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Language Pathways Defined in a Patient with Left Temporal Lobe Damage Secondary to Traumatic Brain Injury: A QEEG & MRI Study

Janelle Lee Bailey

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

Language Pathways Defined in a Patient with Left Temporal Lobe Damage Secondary to Traumatic Brain Injury: A QEEG and MRI Study

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Master of Science

Though the current understanding of language processing is incomplete, it has been established that the left hemisphere is dominant for language in the majority of the population. Damage to language centers of the brain and to white matter tracts connecting these language centers results in a language deficit known as aphasia. Neuroplasticity in the brain can often compensate for these language deficits by strengthening neuronal connections between the right and left hemisphere, or by enhancing the neuronal connectivity of undamaged areas in the left hemisphere. Thus the brain can compensate for damaged language centers by using alternative cortical areas. These compensatory language areas may be homologous areas of the right hemisphere, or other undamaged portions of the left hemisphere. Various imaging techniques have been used to demonstrate this phenomenon. The current neuroimaging technique known as quantitative electroencephalographic brain imaging allows investigators to evaluate the functional anatomical location of language processing. When this mapping is overlaid on a magnetic resonance image, investigators are able to locate areas in the brain of the participant that are electrically activated during elicited speech tasks. This method was used in a single case study to examine the brain of an individual with a unique traumatic brain injury in which the anterior portion of the individual’s left temporal lobe was surgically removed and considerable recovery of language subsequently occurred. The stimulus for the quantitative electroencephalography included identifying syntactically incorrect sentences. Imaging results from the participant with traumatic brain injury were compared to imaging results obtained from an age-matched control. Differences in quantitative electroencephalography between the two participants included a delayed P1-N1-P2 response and an absent P600 in the participant with traumatic brain injury. Behavioral results include an increased number of incorrect responses from the participant with traumatic brain injury as compared to the control participant. These results imply an interesting cortical distribution of language processing that could be further assessed by functional magnetic resonance imaging.

Keywords: Boston Diagnostic Aphasia Examination, language processing, language recovery, left temporal lobe craniotomy, MRI, QEEG, TBI, Wernicke’s aphasia.
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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 research subjects. Appendix B 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 receptive and expressive language skills of the brain are remarkable. Despite centuries of study there is still much to learn about how this intricate process occurs and which portions of the brain’s vast neural network are employed in speech production and perception. Currently, researchers utilize neuroimaging techniques such as functional magnetic resonance imaging (fMRI), diffusion tensor imaging (DTI), and quantitative electroencephalography (QEEG) to better understand the structure and function of language processing. Though it would be an oversimplification to assume that language areas are finite, or that each brain processes speech in an identical manner, studies have shown that the majority of individuals, both right and left handed, process speech predominantly in their left hemisphere, particularly in the left inferior frontal lobe, superior temporal lobe, and inferior parietal lobe (Knecht et al., 2000; Parker, 2005). When these language centers are disrupted through damage incurred by stroke or traumatic brain injury (TBI), aphasia is a common result and recovery is variable (Damasio, 1992). This study will investigate the brain’s ability to compensate for the partial removal of a left temporal lobe, secondary to TBI, in an individual originally diagnosed with severe Wernicke’s aphasia. This individual (participant TB) was able to make significant recovery of language abilities over the course of 3.5 years. This study utilized QEEG overlaid on a structural MRI to describe the alternate pathways used by this individual to compensate for anatomical damage to language areas of the brain.

Language and Aphasia

Language is the means by which thoughts are translated into an acoustic code and the way that the acoustic code is translated into thoughts (Damasio, 1992). Language also involves nonverbal communication, such as gestures and sign language, and written communication.
Early investigations in language identified two main areas of language processing in the brain: Broca’s area in the left posterior frontal lobe and Wernicke’s area in the posterior left superior temporal gyrus (STG; Berker 1986; DeWitt & Rauschecker, 2013). In the mid 1800s Broca identified a region of the brain thought to be associated with motor speech. This area, which encompasses the pars triangularis and pars opercularis in the inferior frontal lobe of the left hemisphere, was damaged in the patients whom Broca studied. In 1865, after careful observation of these patients, Broca concluded (as cited by Berker, 1986)

What is missing in these patients is only the faculty to articulate the words; they hear and understand all that is said to them, they have all their intelligence and they emit easily vocal sounds. What is lost is therefore not the faculty of language, is not the memory of the words nor is it the action of nerves and muscles of phonation and articulation, but something else ... the faculty to coordinate the movements which belong to the articulate language, or simpler, it is the faculty of articulate language. (p. 1066)

Based on observations made by Broca, Broca’s area became associated with the motor functions of speech production. Deficits in spoken language are often translated into written language as well. Individuals affected by Broca’s aphasia demonstrate written language disorders that are similar to the speech disorders. Their written language is telegraphic in nature, predominantly containing content words, such as nouns and verbs. Function words, such as prepositions and conjunctions, are frequently absent in the written language as well as the spoken language of patients with Broca’s aphasia (Berker, 1986).

Lesion studies by Wernicke in 1874 (as cited by DeWitt & Rauschecker, 2013) identified a second language area in the STG. With regard to patients with damage to this area, Wernicke noted: “Apart from lack of understanding, the patient [with sensory aphasia] has aphasic
phenomena in speaking, owing to an absence of unconscious correction exerted by the speech sound image” (DeWitt & Rauschecker, 2013, p 23). By *aphasic phenomena in speaking*, Wernicke refers to what are currently known as paraphasias (DeWitt & Rauschecker, 2013). According to DeWitt and Rauschecker (2013), the STG can be divided into two sections with different functional designs. The posterior region of the STG is associated with monitoring speech output, the disruption of which is evidenced by the production of paraphasias in individuals with Wernicke’s aphasia (DeWitt & Rauschecker, 2013). DeWitt and Rauschecker assert that the anterior portion of the STG is the auditory word form recognition area, in which phonemic processing and word recognition occur.

The white matter fiber tracts of the brain are essential to language processing and production. White matter connections between Broca’s and Wernicke’s areas were typically thought to exist exclusively through a dorsal pathway via the arcuate fasciculus and superior longitudinal fasciculus (Parker, 2005). Recent studies have demonstrated that a second ventral pathway may exist via the ucinate fasciculus and/or the extreme capsule (Kummerer, 2013; Parker, 2005). Parker’s (2005) study identified this ventral pathway in the left hemisphere only in 45% of healthy subjects. Other studies have demonstrated that language lateralization may be affected by the microstructure of the connecting white matter fiber tracts. A study by Perlaki et al. (2013) used fMRI and DTI to identify the language lateralization in comparison to white matter microstructure of 16 left handed, female college students. The results showed that 10 of the 16 subjects exhibited left hemisphere language dominance, one demonstrated bilateral language lateralization and five demonstrated right hemisphere dominance. It was found that higher microstructural organization (high fractional anisotropy, low mean diffusivity) of the left superior longitudinal fasciculus (SLF), the left angular gyrus white matter, and left superior
parietal lobe white matter was associated with left hemisphere language dominance. Lower microstructural organization (low fractional anisotropy, high mean diffusivity) was associated with atypical, right hemisphere language dominance (Perlaki et al., 2013). These results indicate that the organization of white matter microstructure has an effect on language lateralization in both the left and right hemispheres of the brain. In another study conducted by Powell et al. (2006), a comparison was made between the white matter fiber tracts in the left hemisphere and the white matter fiber tracts in the right hemisphere. Researchers concluded that the white matter tract volume was significantly greater on the left hemisphere than on the right hemisphere in both the frontal and temporal lobes. The connectivity pattern between the left and right hemispheres was asymmetric, indicating language lateralization to the left hemisphere.

These studies have provided further evidence supporting the concept that language functions are primarily left hemisphere dominant in the majority of the population (Parker, 2005; Perlaki et al., 2013; Powell et al., 2006). Other studies have presented additional evidence of left hemisphere language dominance. In a study conducted by Knecht et al. (2000), 92.5% of 188 right-handed healthy individuals displayed left hemisphere language dominance. Hence, the left hemisphere, particularly Broca’s and Wernicke’s areas, is a critical area of the brain for language processing.

Aphasia is typically a consequence of stroke, TBI, or disease. In an isolated case of aphasia, the movement of the articulators is preserved, though aphasia can co-occur with dysarthria and apraxia. Aphasia is not a disorder of the intellectual thought process (Damasio, 1992). Pure aphasia specifically affects the ability to understand language, and produce language, leaving other cognitive abilities intact. Depending on the site of lesion, different types of aphasia occur and have generally been identified as Broca’s, Wernicke’s, global, transcortical
motor, and conduction aphasias. The present study will explore the characteristics and neuroanatomy of Wernicke’s aphasia in a participant with left temporal lobe damage.

Wernicke’s aphasia. Wernicke’s aphasia is characterized by relatively fluent speech, but with frequent semantic and phonologic errors (Glasser & Rilling, 2008). Prosody, syntax, and rate of speech remain relatively intact, but speech is mostly meaningless. As stated above, paraphasias are common in Wernicke’s aphasia, including neologistic paraphasias (use of pseudowords, e.g., *karn* for *street*), phonologic paraphasias (substitution of a single phoneme, e.g., *dat* for *cat*), and verbal paraphasias (substitution of a semantically related real word, e.g., *watch* for *clock*; Damasio, 1992). Naming and repeating are often difficult for patients with Wernicke’s aphasia, and they also have poor auditory comprehension. Despite the irregularity of their speech, persons with Wernicke’s aphasia often appear to be unaware of their deficits (Damasio, 1992). Wernicke’s aphasia may be caused by left STG lesions (Brodmann’s area 22) and lesions to the insular cortex (Damasio, 1992; Kreisler, 2000).

Recovery from aphasia can vary greatly depending on lesion size, site, and other factors (Damasio, 1992). At times, it is impossible to predict the potential recovery in patients with aphasia. It is known, however, that the brain is able to recreate neuronal connections and strengthen previously underused connections in the capacity known as neuroplasticity. Through the process of neuroplasticity, some recovery can be expected, but the extent of recovery is unknown and varies widely from person to person.

Neuroplasticity. Neuroplasticity is “the capacity of a system to respond to normal or aberrant developmental or lesion-induced changes in the internal or external environments by adopting new, stable, developmentally appropriate phenotypes and/or restoring old phenotypes” (Dennis et al., 2013, p. 2761). This term has been used to define a number of different
phenomena, including alterations in neuronal pathways that establish habits, the regenerative capacities of both the peripheral and central nervous systems, and chemotropic activities that promote new synaptic functions (Dennis et al., 2013). Neuroplasticity can refer to various molecular, cellular, neural or behavioral systems that achieve novel functions, and can occur on both a micro level (e.g., the fine tuning of prewired circuits through activation of certain cells in the cerebellum) and a macro level (e.g., changes in an approach to memory; Dennis et al, 2013). Neuroplastic changes occur in damaged brains resulting in varying degrees of functional communication gains (Fridriksson, Richardson, Fillmore, & Cai, 2012). In a study by Fridriksson et al. (2012), more than half of 30 subjects presenting with chronic aphasia as a result of stroke demonstrated increased naming ability after 30 hours of training. This is a behavioral example of neuroplastic changes occurring in the damaged brain. Neuroplasticity can also occur at a neuronal level (Dennis et al., 2013; Schlaug, Marchina, & Norton, 2009; Tivarus, Starling, Newport, & Langfitt, 2012). Schlaug et al. (2009) studied six patients with Broca’s aphasia secondary to left sided stroke. The patients underwent DTI studies before and after 75 sessions of intense melodic intonation therapy. This type of therapy is designed to assist the brain in activating abilities traditionally attributed to the right hemisphere, such as prosody and singing, in order to facilitate expressive language. The pre and post DTI studies revealed a significant increase in the number of fibers in the right arcuate fasciculus. This indication of neuronal plasticity suggests that neuronal pathways of the right hemisphere can be enhanced in persons with damage to the left hemisphere.

Though lesion studies conducted by Broca and Wernicke have provided insights into language processing, current neuroimaging techniques have given researchers the means to investigate the role of brain structures in healthy as well as impaired individuals in vivo. Images
of healthy and damaged brains obtained through techniques such as MRI and DTI facilitate predictions about which parts of the brain are responsible for specific functions, such as speech. Further, researchers are not only able to obtain structural images of the live brain, but techniques such as QEEG and fMRI allow the viewing of brain activity during a specific task. These neuroimaging techniques provided a means of identifying functional language activation patterns in healthy persons and persons with damaged brains.

**Neuroimaging and Patterns of Activation**

**Diffusion tensor imaging.** DTI is a technique which uses the principle of water diffusion to create a digital picture representation of white matter fiber tracts that connect gray matter in the brain. When fluid is not restricted in any direction, as in cerebrospinal fluid (CSF), movement is random, and equal in every direction. The same principles of movement apply to water when it is restricted equally in every direction, as in cell bodies. In both instances, this is referred to as isotropic movement. White matter consists of bundles of axons. When water is moving along an axon its movement is restricted to one direction, the path of the fiber tract. This movement is called anisotropic movement (Parker, 2005). DTI measures the direction of water molecule movement in the brain, and thus is able to distinguish between cell bodies, CSF, and white matter fiber tracts (Jang, 2013). In individual white matter damage, DTI can be used to detect the extent of the abnormality (Jang, 2013). Through the use of DTI and diffusion tensor tractography (DTT), three dimensional reconstructions of fiber tracts is possible, thus allowing for identification of areas of the tracts damaged by injury or disease (Glasser & Rilling, 2008). Consequently, it is possible to identify how a focal injury may disturb neural networks connected by underlying white matter. Wilde, Hunter, and Bigler (2012) suggested a brain injury to the left frontal region may have far reaching effects on the right parietal lobe via white matter
connections. This information may be important to the rehabilitation clinician, and in the future may guide rehabilitation decisions. Information from DTI about which fiber tracts are damaged can be used to help assess deficits a patient might experience. Thus clinicians’ rehabilitation methods may become more specific for each patient (Wilde et al., 2012). As stated previously, DTI is also used as a way to identify physical neuronal evidence of neuroplasticity as a result of therapy by using before and after comparisons of DTI studies (Schlaug et al., 2009).

**Functional magnetic resonance imaging.** fMRI provides information about functional language activation patterns. This technique is based on the principle that there is a difference in the magnetic properties of oxygenated and deoxygenated blood. Because of this difference, it is possible to track a hemodynamic response when a magnetic field is applied to brain tissue. This allows researchers to estimate which parts of the brain are receiving increased blood flow during a language specific task. This technique asserts that increased blood flow is evidence of increased cerebral activation (Lee, 2006). Various studies have used fMRI to determine which anatomical areas of the brain are activated during language processing tasks in individuals with damaged language areas in the left hemisphere (Bonelli et al., 2012; Lee, 2006; Tivarus et al., 2012; Voets et al., 2006). Some studies have concluded that these individuals utilize right hemisphere regions homologous to the language areas (specifically Wernicke’s and Broca’s areas) in the left hemisphere (Tivarus et al., 2012). Other studies have concluded that right hemisphere areas activated during language tasks are not simple homologous representations of left hemisphere language areas (Voets et al., 2006). Tivarus et al. (2012) studied activation patterns in seven patients with epilepsy with right hemisphere speech dominance (as determined by Wada testing), 10 patients with epilepsy with left hemisphere language dominance, and 14 healthy control individuals. All patients with epilepsy had undergone a left temporal lobectomy
at least five years before the study. The study measured activation patterns in four different
language tasks (verb generation, passive sentence reading, definition naming, and semantic
decision). Tivarus et al. (2012) found that the activation maps for the right hemisphere dominant
patients revealed a network mirroring activation in the inferior frontal gyrus, or Broca’s area, and
in the posterior temporal lobe, including Wernicke’s area. Other regions of the brain that
facilitate language processing were also found to have homotopic activation in the right
hemisphere. The left hemisphere dominant group also exhibited some evidence of partial transfer
to the right hemisphere by activation in the right inferior frontal gyrus. This area (right inferior
frontal gyrus) was not activated in healthy controls. Researchers concluded that when language
transfers to the right hemisphere, it transfers primarily to homotopic areas (Tivarus et al., 2012).
Although participant TB, who participated in the current research project, did not have a
complete lobectomy, a portion of his temporal lobe was removed, and thus his language
activation pattern can be expected to be similar to these patients with epilepsy. In contrast, the
2006 study by Voets et al. concluded that activation of the right inferior frontal gyrus did not
mirror that of the left hemisphere. It is currently debated whether right hemisphere language
reorganization is homotopic in nature. In the current study, this discussion is viewed through the
lens of another neuroimaging technique, QEEG, to provide further evidence on functional
language activation patterns in the brain.

**Quantitative electroencephalography.** QEEG is a brain mapping technique that uses
surface electrodes to measure the cortical electrical activity of the brain during specified tasks,
such as listening to speech generated stimuli. This brain mapping method was selected for this
study because it provides increased temporal resolution compared to the fMRI (Friederici, 2004).
It is an analytical technique applied to the mathematical and statistical analysis of brainwave
activities and provides an analytical ability to view and describe dynamic changes in brainwave activity. Changes in brainwave activity arise from internal endogenous responses leading to cortical activities engaged in sensory and other types of brain processing (Bagic & Sata, 2007; McPherson, 1996). It also permits a comparison of brainwave activity across individuals and allows for the establishment of databases (Bagic & Sata, 2007). The use of QEEG primarily involves measurements of power (strength of the of brainwave activity), spectrum (the frequency bands of the brainwave activity), asymmetry (the spatial distribution of the power spectrum of brainwave activity), coherence (what areas of the brain are communicating with each other), and phase (the temporal aspect of brainwave activity). Furthermore, when isopotential contours are created from these types of analyses, a map of brainwave activity across the scalp may be created. (Congedo, John, DeRidder, Prichep, & Isenhart, 2010; Mathewson et al., 2012).

Studies investigating the correlation between the temporal aspect of QEEG and language processing have associated time-locked waveforms with specific aspects of language processing which is a measure of postsynaptic neural activity of large neuronal populations, millisecond by millisecond (Friederici, 2002). This neural activity is referred to as an event related brain potential (ERP) when it is associated with the presentation of a stimulus (Friederici, 2004). Studies of ERP waveforms have been associated with aspects of language processing. For example, the N400 component is associated with semantic processing, the early left anterior negativity (ELAN) is associated with early sentence structure building, the closure positive shift (CPS) is associated with prosody, and the P600 is associated with syntactic processing. (Friederici, 2002). The P600 wave will be of particular interest in this study because it is associated with conscious manipulation rather than automatic responses, and the anatomical location from which this waveform is generated is also of interest (Friederici, 2002; Hahne &
Friederici, 1999). In a study by Hahne and Friederici (1999), subjects were presented with syntactically correct and syntactically incorrect sentences. It was found that ELAN was associated with highly automatic responses and that the P600 component was associated with controlled responses (Hahne & Friederici, 1999). Hahne and Friederici stated (1999):

An early left anterior negativity was elicited and equally pronounced under both proportion conditions, supporting the idea that the early structure-building processes are rather independent of the participants’ conscious expectancies and strategic behavior and can therefore be claimed to be automatic in nature. In contrast, we observed a P600-component for a low proportion of syntactically incorrect sentences only. In case of a high proportion of incorrect sentences we did not find a P600 component. For a high error proportion the effect even seemed to reverse, although this effect was not statistically significant. We take these results as evidence that the late positive component reflects processes that are under the control of the participant. (p. 199)

Therefore, the P600 component is activated when the subject consciously manipulates the sentence, whereas the ELAN is activated in automatic sentence processing. Friederici (2002) stated that syntactic processing, including activation of the P600 component, has a functional neuroanatomical location within the anterior STG. Friederici further reported that damage to this area may result in the absence of the P600 component (Friederici, 2002). In this case study, the anterior portion of the STG in TB’s left temporal lobe was removed, and the P600 component was affected.

QEEG has been used to demonstrate neuroplasticity in persons with aphasia. In a study conducted by Sarasso et al. (2013), QEEG measures demonstrated changes in the sleep slow wave activity (SWA) of persons with left hemisphere lesions secondary to ischemic strokes that
resulted in aphasia. The study measured the SWA of 13 participants the night before and the night after they participated in 3.5 hours of an intense computer based imitation therapy program. Results demonstrated an increase in SWA, predominately in the right hemisphere. These results indicated plasticity due to intense therapy, and provide support for the theory of right-sided lateralization in the event of left hemisphere lesions. Additional QEEG studies have also been performed to determine the lateralization of language in patients with aphasia due to damage to the left hemisphere. In a study conducted by Spironelli, Manfredi, and Angrilli (2013), a group of 11 participants with aphasia and a group of 11 control participants were compared with QEEG to assess language laterality. The group of patients with aphasia had exhibited significant gains in linguistic recovery, demonstrated by their performance on the Italian version of the Aachener Aphasie Test. High-beta frequency bands (18-30 Hz) of the QEEG were found to occur during cortical arousal of language related processing and there was greater right hemisphere lateralization in patients with aphasia than control participants using phonologic and semantic tasks (Sarasso et al., 2013; Spironelli et al., 2013).

Advancing techniques in brain imaging, including fMRI, DTI, and QEEG are furthering the current understanding of language processing in typical and damaged brains. Though the left hemisphere is most often dominant for language, it is unclear which regions of the brain are utilized when damaged language centers require the brain to activate alternate pathways. Although it is obvious that there are differences between typical and damaged brains, how these brains differ in terms of the QEEG provides insight into how and where the brain may be processing language. The current study investigated differences in the QEEG waveform of participant TB, an individual with extensive temporal lobe damage and remarkable recovery from Wernicke’s aphasia, and an age-matched control.
Method

Participants

This study included two participants: one with TBI (TB) with a partially removed left temporal lobe as a result of the injury, and an age-matched control (CP). Data collected from the QEEG of each participant were compared and differences in activation patterns were noted.

Participant with Traumatic Brain Injury. Participant TB is a 45 year old male who sustained a TBI at the age of 41 years. The premorbid education level of TB was 12th grade, completed when he was 18 years of age. He was self-employed as an electrical contractor and master electrician prior to the TBI. He had no reported neurologic, neuropsychiatric, or language deficit history prior to the TBI. He was admitted to a local hospital after sustaining blows to both the left and right sides of the head during an assault. He presented with bilateral skull fractures, with the left fracture being depressed and comminuted in the anterior temporal region, the right being linear, beginning in the posterior temporal region and extending into the posterior parietal region. Figure 1 shows TB’s initial neuroimaging, including a CT scan performed on the day of trauma (left image), and an MRI performed six weeks post trauma (right image). In the lower right quadrant of the CT scan, the depressed skull fracture can be viewed. In the MRI, the dark spot in the lower right quadrant is indicative of a partially removed left temporal lobe. These images are in radiologic view.
Figure 1. Initial neuroimaging of TB. Day of trauma CT scan (left image). Six weeks post trauma MRI (right image). The dark spot in the bottom right quadrant of the MRI is indicative of a partially removed left temporal lobe.

Details of the trauma. Upon arrival at the emergency room of the local hospital, TB’s initial Glasgow Coma scale rating was 13. Within the first few hours of injury, multiple neurosurgical procedures were required. An initial CT scan of the brain demonstrated significant intracranial hemorrhage, including an acute epidural hematoma on the right and an acute subdural hematoma on the left. Because the right sided epidural hematoma was more life threatening, it was evacuated first. The release of pressure caused by the evacuation of the right sided epidural hematoma resulted in a more massive hemorrhage associated with the left sided subdural hematoma, temporal lobe contusion, and intraparenchymal hemorrhage. Subsequently, the left subdural hematoma was evacuated. Part of the left temporal lobe was macerated, due to the depressed and penetrating skull fracture; thus a partial left temporal lobectomy was performed. The portion of the temporal lobe surgically removed included the entire temporal pole, sparing the medial temporal lobe and hippocampal area. These surgeries were performed within one day post trauma. Within two days post trauma a left orbitotomy was performed with drainage of the hemorrhage and a left medial wall decompression. Approximately two months post trauma TB underwent follow up CT scans and MRI which demonstrated cerebral atrophy,
marked temporal lobe encephalomalacia (localized softening of the brain substance), and ventriculomegaly (dilation of the lateral ventricles). All of these symptoms are consistent with defects associated with the brain injury. TB was admitted to the rehabilitation unit of the hospital 16 days post trauma. He was discharged home from the rehabilitation unit 28 days post trauma. Figure 2 presents 3-D recreations of the left and right skull fractures.

Figure 2. CT scan 3-D recreation of skull fractures in TB (left images). CT scans depicting left sided depressed fracture and right-sided epidural hematoma under linear fracture (right images).

As a result of the injury, TB suffered extensive damage to the white matter of his brain. Figure 3 depicts an axial fluid attenuate inversion recovery (FLAIR) image at the base of the brain showing extensive destructive lesions involving the left frontal and temporal lobe regions, with deep white matter damage affecting the superior and middle temporal gyri, arcuate
fasciculus and corpus callosum, as well as other structures as depicted. Figure 4 depicts multiple white matter hyperintense (WMH) abnormalities along with ventricular dilation. WMH lesions affect the arcuate fasciculus, corpus callosum cingulum bundle and other tracts as shown. Both images were taken 6 weeks post trauma.

Figure 3. Axial fluid attenuate inversion recovery (FLAIR) image of TB. FLAIR image (right image) at the base of the brain showing extensive destructive lesions involving the left frontal and temporal lobe regions, with deep white matter damage affecting the superior and middle temporal gyri, arcuate fasciculus and corpus callosum, as well as other structures as depicted. Image was taken 6 weeks post trauma. Brain atlas with color coded white matter fiber tracts (left image) retrieved from (Catani & Thiebaut de Schotten, 2012). Image on left published with permission.
Figure 4. FLAIR of TB showing multiple white matter hyperintense (WMH) abnormalities. This image also depicts ventricular dilation (right image). WMH lesions affect the arcuate fasciculus, corpus callosum cingulum bundle and other tracts as shown. Image taken 6 weeks post trauma. Brain atlas with color coded white matter fiber tracts (left image) retrieved from (Catani & Thiebaut de Schotten, 2012). Image on left used with permission.

**Handedness.** An atypical, ambidextrous handedness pattern was reported by TB in a history given prior to neuropsychological testing conducted six months post trauma. From his youth, TB presented with a congenital absence of pectoral muscle development on the right side of his body. While he used his right hand for writing, because of the absence of a normal left pectoral muscle, TB compensated by using his left hand for other motor skills. For example, when playing baseball, he throws and bats left handed. On simple grip strength, grip is equal bilaterally, with no increased grip strength on the right as is typically observed in right handed
individuals. He does not appear to have residual lateralized motor deficits and has adequate finger oscillation movement bilaterally.

**Language deficits, rehabilitation and recovery.** According to speech pathology notes dated 16 days post trauma, during his first visit from a speech language pathologist, TB responded less than 30% of the time and was in a state not appropriate for formal evaluation. He was informally assessed using selected questions from the Boston Diagnostic Aphasia Examination (BDAE; Goodglass, Kaplan, & Baressi, 2001) demonstrating severe receptive aphasia with a 0/5 severity, also demonstrating no usable speech or comprehension. In a subsequent visit 19 days post trauma, the SLP reported that there was no change from the last visit made three days previously. Initially, TB was diagnosed with severe Wernicke’s aphasia and received speech therapy during his 28 day stay at the hospital. Upon discharge 28 days post trauma, TB was formally assessed with the BDAE (Table 1).

The overall severity rating on the BDAE was 1 on a 5 point scale. The speech pathology discharge summary 28 days post trauma reads as follows:

Patient is able to understand and ID a few pictures, does very well with numbers and letters and colors. Naming results in paraphasia and extended paraphasia with rare accuracy even after cueing. Repetition is more intact, but not usually accurate on the first try. Reading is moderately impaired. Patient was able to demonstrate some comprehension of words and short sentences. He has prolific paraphasia and seems unaware of this. Patient does not respond to repetition [of paraphasias] by others, [nor does he respond to] trial recordings of himself [producing paraphasias].

After discharge from the hospital, TB began to be seen at the hospital’s speech and language pathology outpatient clinic three times a week for 50 minutes per session. In the first of these
Table 1

*Boston Diagnostic Aphasia Examination: Participant TB, 28 Days Post Trauma*

<table>
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<td>Narrative Writing</td>
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</table>
outpatient sessions, the speech language pathologist noted mild improvement since the time of discharge. Notes dated 35 days post trauma stated:

There have been small improvements in just the past six days, with improvement in sentence length in spontaneous utterances. Improvement in repetition is most pronounced. There is some mild improvement in comprehension, particularly of identification of nouns, but also with more complex yes/no questions. There is improvement in automatic speech. There are no overt changes in naming of nouns; however, the patient clearly names letters at this time, which he was unable to do prior. There are small improvements in reading ability, particularly word to picture matching, which improved dramatically, but also comprehension and oral reading have improved mildly.

During this session, TB was asked to describe the Cookie Theft Picture as a part of the BDAE (Figure 5).

*Figure 5. Cookie Theft Picture taken from the Boston Diagnostic Aphasia Examination (Goodglass, Kaplan, & Baressi, 2001). A verbal description of the picture, produced by TB 35 days post trauma and a written description produced six months post trauma, were recorded.*
A transcription of TB’s verbal response when asked to describe the Cookie Theft Picture from the BDAE, depicted in figure 5, during TB’s first outpatient speech session 35 days post trauma, reads as follows:

Well she’s got her // supelin ladys reaking all over the sandals/ the birds sleeping over the top and the evelins getting tigh into a play coveerse so they can get into a plesterin// condie. So it’s just a big mess. That’s it. She’s doing one/ thing of sandiv super // right in front of the / sendive slindos her/ tartblackfor. Little boy and a little girl are using that // ah/ tanor with the sando to get the crust n sand. She’s erleventh; she can’t see what’s real and what’s happening.

A written description of the same picture was elicited from TB six months post trauma. It reads as follows:

Mother at kitchen sink and daughter and son at cookie jar on top of the crow and mother in water problem. She is washing diceses [sic]. She can’t see them. The boy is stealing the cook’s. If he is not careful the stool will fall.

Upon discharge from the hospital, TB received outpatient therapy at the local hospital to treat his language and cognitive deficits. A formal discharge from speech therapy was never reached, but the speech therapist reports that TB stopped attending outpatient speech therapy sessions eight months post trauma.

Current levels of functioning. At the time this study was conducted, 3.5 years post trauma, TB was self-employed as an electrician, which was his pre-trauma employment. Anecdotal evidence reports that TB continues to display executive functioning deficits, including organization and prioritization. He also reports difficulty with word finding and repetition of complex sentences. Paraphasias are no longer present and speech is fluent and coherent.
Age-matched control subject. CP is a 48-year-old, right handed native speaker of English with no reported history of neuropsychological or language deficits. CP was assessed with the BDAE, and results indicated no aphasic language deficits.

Prior to hearing and QEEG testing, each participant read and signed an informed consent document approved by the Institutional Review Board at Brigham Young University (Appendix A). In addition to meeting the ethical requirements set by Brigham Young University, this study also met the ethical requirements as stated in the Declaration of Helsinki (World Medical Association, 2008).

Hearing testing. Hearing testing was completed on both participants using guidelines set forth by ASHA (American Speech-Language-Hearing Association, 1990). Pure-tone thresholds for octave intervals between 250-8000 Hz are seen in Table 2.

Table 2

<table>
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<tr>
<th>Frequency (Hz)</th>
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<td>Left Ear</td>
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</table>

Quantitative Electroencephalography Testing

Stimulus preparation. Sentences were recorded using a Larson Davis Laboratories 1.27 cm model 2541 microphone attached to a Larson Davis Laboratories model 900 microphone preamplifier. A three inch foam windscreen was used on the microphone at 0 degrees azimuth. The microphone preamplifier was attached to a Larson Davis Laboratories model 2200
preamplifier power supply. Speech was digitized at 44.1 kHz using a 24 bit quantization and stored on a hard disk for later editing. SADiE disk editor was used to edit the digital recordings and write them on to a compact disk by dithering from 24-bit to 16-bit.

**Instrumentation for hearing screening.** Instrumentation used for the hearing screening included a Grason-Stadler model GSI-1761 audiometer with Etymotic EA-3 insert phones for hearing testing. Also, during data acquisition the test stimuli were presented to the participant via a Grason-Stadler audiometer. All testing was completed in a double-walled, sound-treated test booth. Noise levels were within the limits as specified by ANSI S3.1-1999 R2008 Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms for ears uncovered.

**Quantitative electroencephalography data collection.** Participants were fitted with an electrode cap (Electro-Cap International, 2003) having 64 silver-silver chloride electrodes resting against the scalp and distributed according to the 10-20 International System (Juracak, Tsuzuki, & Dan, 2007). In addition to the scalp electrodes, six electrodes were placed on the right and left mastoid process (linked-mastoid references), the outer cantha of the right and left eyes, and one above and below the supraorbital foramen of the left eye to monitor eye movement and facial muscles. Electrode impedances did not exceed 5000 ohms. The streaming EEG was recorded using a band pass filter of 0.1 to 30 Hz (McPherson & Ballachanda, 2000; Picton, 2011). A code was placed on the EEG at the beginning of the syntactically correct or syntactically incorrect critical verb each time a stimulus was presented in order to facilitate post hoc signal averaging. The two stimulus types had their own unique code. Compumedics Curry 7 software (2008) was used for EEG data collection and analysis. NeuroScan Stim 2 software was used for stimulus presentation.
Stimuli. The QEEG stimuli consisted of correct sentences mixed with sentences containing syntactic errors. One hundred and two sentences were used to create the stimuli. Two versions of each sentence were used. One version of the sentences was correct and the other version contained a syntactic error. Syntactic errors included one of the following: (a) a plural noun syntactic error, (b) a past tense –ed verb syntactic error, (c) a past tense irregular verb syntactic error, or (d) a third person verb syntactic error. All syntactic errors occurred in the final word of the sentence. The correct and incorrect versions of the same sentence were randomized and never occurred consecutively. Each participant listened to a total of 225 sentences. Each participant was given a five-minute training period in which they were instructed to listen carefully to each sentence, decide if the sentence was correct or incorrect, and push the corresponding response button (a smiley-face was attached to the button for a correct or good sentence and a frowny-face was attached to the button for an incorrect or bad sentence). Answers were recorded for later analysis. Examples of the sentences are listed below.

No Syntactic Error

1. The sleeves covered both hands.
2. The girl laughed.
3. The doorbell rang.
4. The wind blows.

Four Types of Syntactic Error

1. The sleeves covered both hand (plurality error).
2. The girl laugh (past tense regular verb error or omission of auxiliary “be” followed by progressive –ing).
3. The doorbell ringed (past tense irregular verb error).
4. The wind blow (third person verb error or past tense irregular verb error).

The sentences were presented at 65 dB HL, bilaterally, with a minimum of a 1000 ms interstimulus interval and a maximum of 1500 ms.
Data Analysis

ERPs were created post hoc following artifact removal of eye movement and other contaminants, such as muscle movement, from the streamed EEG. ERPs were obtained by averaging on the specific stimulus type for each of the participants, individually. ERP components for the P1-N1-P2 and the P600 were obtained from the Cz electrode. A common average reference was used to compare activity at each electrode site. The Curry 7 neuroimaging software was used to determine dipoles, cortical sites to which the source of electrical activity were traced within the cortex for all individual averaged ERP files. Locations for each dipole from TB were compared to each dipole from CP. Behavioral error rates (for example, a subject falsely reporting a grammar error) were determined for each condition for each participant. A Chi-Square statistic was used to calculate differences in error rates.

Results

Language Testing

Both participants were assessed using the BDAE. The results are presented in Tables 3 and 4 below. TB improved significantly from his BDAE that was given 28 days post trauma and no longer presented with severe Wernicke’s aphasia (Table 3). The tasks that were most difficult for TB were repetition of words and sentences, confrontational naming, matching written words with pictures, and writing names of pictures. Paraphasias were no longer present in the speech of TB. No signs of aphasia were exhibited by CP (Table 4) and the results of the BDAE were normal.
Table 3

*Boston Diagnostic Aphasia Examination: Participant TB, 3.5 Years Post Trauma*

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As part of the BDAE, TB was again asked to describe the Cookie Theft picture. The following is a transcription of his verbal response:

I’m looking at the white picture. In the picture there is a mother, a son, and a daughter. The mother is doing the, washing the dishes. Right now she is washing the sink, er sorry, a plate and at that time the water is draining out of the sink. She hasn’t turned that off, so it is running and it’s draining out of that to the floor and making a mess. She’s not looking at her, at her son and daughter that are behind her. And behind her, her son is standing on a stool to get up to and grab the cookie jar out of the cabinets. And because of that, he could fall over. And so he’s grabbing the cookies and giving one to his sister.

The description given by TB is remarkably improved from his first attempt 35 days post trauma. There are no paraphasias present in his description. There is one instance of circumlocution (its draining out of that to the floor) and one naming error (she is washing a sink, er sorry, a plate). The comparison of these transcripts is evidence of TB’s marked recovery of language. Though TB’s recovery is not complete, a lay person would most likely not detect any language deficit in conversing with TB.

Quantitative Electroencephalography Testing

The time distributed waveform (Figure 6) shows the P1-N1-P2 complex and the P600 for both stimulus conditions in the two participants. The P1-N1-P2 responses appear to originate from sources near the posterior regions of the temporal lobe with the majority of the response seen on the lateral aspect of the superior temporal gyrus. Figure 6 show the responses obtained from CP with the latencies for this complex between 78 and 163 ms for the syntactically correct sentences (Figure 6A), and between 117 and 282 ms for the syntactically incorrect sentences (Figure 6B). This is contrasted in participant TB where the P1-N1-P2 latencies for the
syntactically correct sentences occur between 158 and 245 ms (Figure 6C), and for the syntactically incorrect sentences between 221 and 296 ms (Figure 6D). Note that latencies for each of the components (syntactically correct versus syntactically incorrect) are prolonged both within and between participants.

Differences in the P600 for the two conditions in CP are seen in Figure 6A (syntactically correct) and Figure 6B (syntactically incorrect). Figure 6B (syntactically incorrect) shows an increase in latency and reduced amplitude for the P600 response. The dipoles for the P600 are distributed throughout the left hemisphere of CP (Figure 7) and absent in TB.

Figure 6. Time distributed waveform for CP and TB. Time distributed waveform for the syntactically correct (A and C) and syntactically incorrect (B and D) sentences in both participants (A and B, CP; C and D, TB). The waveforms were measured at the vertex (Cz).
Figure 7. The dipole distribution of the P600 in CP. This dipole distribution is for the syntactically correct sentences (A and B) and for the syntactically incorrect sentences (C and D).

Figure 8. The dipole distribution of the P600 in TB. Figures A and B are for the syntactically correct sentences and Figures C and D are for the syntactically incorrect sentences. No dipole sources were observed for TB within the time period of the P600.
Behavioral Testing

A Chi-Square statistic was completed on response (correct versus incorrect) by participant for a 2x2 matrix. A significant difference was observed between the number of errors in identifying syntactically incorrect sentences occurring in TB versus CP; \( \chi^2 (1, N = 2) = 17.713, p < .001 \). Figure 9 is a bar chart showing the number correct and incorrect responses for each participant. Further analysis shows that for TB there were significantly more errors; \( \chi^2 (1, N = 2) = 5.647, p < .017 \) in identifying the syntactically incorrect sentences as being incorrect than for the syntactically correct sentences. This was not the observation seen in CP, in which no differences in the error rate between syntactically correct versus syntactically incorrect were observed; \( \chi^2 (1, N = 2) = .128, p > .721 \). These findings are illustrated in Figure 10.

Figure 9. Bar chart showing the number of errors in identifying syntactically incorrect sentences occurring in TB versus CP.
**Figure 10**: Bar chart showing the number of errors for TB and CP for each type of sentence. This includes both syntactically correct and syntactically incorrect sentences.

**Discussion**

**Language Recovery and Handedness**

As indicated by performance on the BDAE and anecdotal evidence, TB made a significant recovery in terms of language. Significant improvement was noted one month and six months post trauma, as well as 3.5 years post trauma. Though the recovery of language in patients with TBI is not entirely unexpected, the recovery demonstrated by TB is extremely unusual given the location and extent of the damage received from the injury. A possible explanation for this dramatic improvement in language is that TB’s language was established in the right hemisphere premorbidly. As stated previously, TB is ambidextrous. It has been demonstrated that left handed and ambidextrous individuals exhibit higher rates of right-sided language lateralization than those who are right handed (Szafarski, 2002). In an fMRI study by Szafarski (2002), the incidence of atypical language lateralization in normal left-handed and
ambidextrous subjects was 22%; whereas, in normal right-handed subjects it was 4-6%.

Therefore, it is possible that TB experienced right-sided language lateralization prior to the TBI. The remarkable recovery of language in TB, given the extent of damage received to the left temporal lobe, could be due to this phenomenon of language laterality. Although neuroplasticity of the right hemisphere was likely involved, it is possible that TB was able to access language centers already established in the right hemisphere when the language center in the anterior left temporal lobe was partially removed. It is unknown if language processing in TB was transferred directly to homologous areas of the right hemisphere, though this would be a study of interest in the future, and could be investigated through an fMRI study. The results of this study would suggest that this may not be the situation since homologous areas in the right hemisphere were not identified using QEEG in TB.

**Behavioral Results**

During the QEEG testing, TB exhibited more errors than CP when processing syntactical information. TB exhibited greatest difficulty in identifying syntactically incorrect sentences. This may indicate that the pathways employed by TB’s brain to compensate for loss of language function on the left side of the brain are not accurate. The results of the BDAE indicated that TB had difficulty following multi-step verbal commands, repeating multisyllabic words and minimally complex sentences, naming simple pictures, matching pictures with written words, and writing the names of pictures. The tasks related to verbal stimuli (following multi-step verbal commands and repeating multisyllabic words and minimally complex sentences) rely on the basic language process of phoneme discrimination. If the brain is unable to detect the subtle changes in phonemes, it may be unable to detect the changes to words that might make a sentence syntactically incorrect. For instance, if the brain in unable to detect the difference
between *cat* and *cats*, the participant may mark a sentence as syntactically correct when it is syntactically incorrect. Hence, the behavioral results from the BDAE are consistent with the behavioral results from the QEEG testing.

**P1-N1-P2**

The P1-N1-P2 waves are derived from the lateral and posterior regions of the supratemporal plane. The N1 is activated by the auditory cortex and the lateral aspect of the superior temporal gyrus. The P2 is mainly generated on the superior surface of the temporal lobe (Picton, 2011). The amplitudes of the P1-N1-P2 complex in Figure 6 are typical for recordings obtained in normal individuals using sentence material (Tremblay, Shahin, Picton, & Ross, 2009). Figures 6C and 6D show an increase in the latency of the P1-N1-P2 complex for TB. This increase in latency maybe attributed to delays seen in decision-making when syntactically incorrect sentences are presented to the listener.

Tremblay et al. (2009) have shown improvement in the P1-N1-P2 complex following training. Figures 6C and 6D show very clear and well-defined waveforms; however, the latencies are prolonged when compared to those obtained in CP. The prolonged latencies may be secondary to a general slowing of perceptual and conceptual processes in TB. The improvement seen in the morphology of the P1-N1-P2 complex is consistent with that observed by Tremblay et al. (2009) following training. Since the P1-N1-P2 appears to be a mixed process, it can only be concluded that some learning has occurred in TB. Although the analysis may be slowed as demonstrated by delayed latencies in both conditions and the accuracy as exemplified in the behavioral data is decreased, some type of neural plasticity has occurred. Because this study only made a single observation following intense intervention, it is not possible to fully understand the dynamics of this process of adaptation or plasticity.
The P600 in CP (Figure 6B) shows increased amplitude in the presence of syntactic violations (Friederici, 2004). The dipole shifts from a left centroparietal orientation near the cingulate gyrus-corpus callosum to a more left lateralized position near the inferior temporal gyrus (Hahne & Friederici, 1999). The P600 was absent in TB (Figure 8). This result is expected due to the absence of the anterior portion of the left temporal lobe and is consistent with that reported by Friederici (2004).

The P600 is a positive wave occurring at approximately 600 ms, and is associated with violations of “structural preferences, outright syntactic violations, and difficulty of syntactic integration” (Freiderici, 2004, p. 468). In patients with lesions in the anterior temporal lobe, the P600 has been found to be absent. Another interesting point to note is that the P600 has also been found to be selectively reduced or absent in patients with lesions in the basal ganglia. According to Freiderici, this suggests that “the early structure-building processes are supported by a temporal-frontal network involving the left anterior portion of the STG and the left inferior frontal gyrus, whereas late processes of syntactic repair seem to involve the basal ganglia” (Freiderici, 2004, pp. 468-469). Therefore, TB may have basal ganglia damage, as evidenced by the absence of the P600. What is somewhat surprising is that no language activity in the time frame of the P600 was noted in TB in the right hemisphere, which would have suggested a homologous transfer of left hemisphere language processing.

Limitations and Further Research

This study has provided some preliminary insights into the adaptive language processes occurring in TB. Some limitations of this study include the narrow range of analyses conducted
on TB. Additional language testing, fMRI testing, and DTI testing may provide further insight into this unique case.

Further language testing may provide insight into additional areas of language and executive function that are difficult for TB. The language test performed on TB, the BDAE, is a diagnostic test, and does not provide details about TB’s deficits. Its purpose is rather to identify the presence of aphasia. More in depth language assessment focusing on TB’s deficits, such as repetition and confrontational naming, may reveal patterns in tasks that are difficult for TB. This information may help researchers understand more specifically what TB is lacking in terms of language, and correlate this with the observable damage to TB’s left and right hemispheres.

To better understand the structure of white matter fiber tracts in the brain of TB, it would be of interest to conduct research using DTI and DTT. Through the use of DTT it is possible to visualize the white matter fiber tracts of the brain. In TB’s brain, it is expected that the white matter fiber tracts (including the arcuate fasciculus and the superior longitudinal fasciculus) connecting Wernicke’s and Broca’s areas have extensive damage due to the portion of TB’s temporal lobe that was removed. It is unknown which other fiber tracts experienced damage, nor the extent of damage they experienced. Because TB suffered trauma to the right side of the head as well as to the left side, it could be expected that there are fiber tracts on the right side that have been damaged. Information regarding which of TB’s fiber tracts are been damaged and which remain intact could provide insight into TB’s current functioning. Research of interest would also include an evaluation of the integrity of the white matter fiber tracts involved in connecting the areas homologous to Wernicke’s and Broca’s areas in the right hemisphere. If these fiber tracts consisted of high microstructural organization (high fractional anisotropy, low mean diffusivity), this may provide additional evidence that TB is processing language in his right
hemisphere in areas homologous to language centers in the left hemisphere. Also, dichotic speech processing coupled with DTI analysis should provide additional information as to the processing of auditory information within the corpus callosum.

Because of the spatial accuracy of fMRI, research might also be done to identify the regions used by the brain during specific speech task. In developing fMRI protocols, researchers could test aspects of language that are weak for TB, such as picture naming. The protocols that targeted TB’s weak language skills could be compared to protocols that targeted strong language skills. Information from this type of fMRI would provide accurate spatial information for the location of language processing in TB’s brain.

The language recovery experienced by TB is truly remarkable. This recovery is not only noteworthy due the location of the damage in the anterior left temporal lobe, but also due to the extent of the damage incurred. As this case continues to be studied, researchers are sure to gain additional insights into the brain’s capacity to adapt.
References


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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
The purpose of the proposed research project is to study is to compare the cortical location of language processing in with damage to a primary language center and in a typical brain of an age matched control.

Procedures
You have been asked to participate in this study by Janelle Bailey, B.S., a student conducting research under the direction of David L. McPherson, PhD. The study will be conducted in room 111 of the John Taylor Building on the campus of Brigham Young University. The testing will consist of one session including orientation and testing and will last for no more than 3 hours. You may ask for a break at any time during testing. Basic hearing tests will be administered during the first half-hour of the session.
Surface electrodes (metal discs about the size of a dime) will be used to record electrical activity of your brain. These discs will be applied to the surface of the skin with a liquid and are easily removed with water. Blunt needles will be used as a part of this study to help apply the electrode liquid. They will never be used to puncture the skin.

Acoustic and linguistic processing will be measured using an electrode cap, which simply measure the electrical activity of your brain and does not emit electricity; no electrical impulses will be applied to the brain. These measurements of the electrical activity are similar to what is known as an “EEG” or brain wave testing. These measurements are of normal, continuous electrical activity naturally found in the brain.

You will wear the electrode cap while you listen to different sentences and you will be asked to determine whether these sentences are correct according to your knowledge of the English language, and press a button to indicate your response. During the time of your responses, the electrical activity of your brain will be recorded on a computer. The sentences will be presented through insert earphones at a comfortable, but not loud listening level. You will be seated comfortably in a sound treated testing room. You will be asked to give responses during the hearing test and portions of the electrophysiological recording by pressing a series of buttons.

The procedures used to record the electrophysiological responses of the brain are standardized and have been used without incident in many previous investigations. The combination of sounds presented is experimental, but the recording procedure is not.

**Risks/Discomforts**

There are very few potential risks from this procedure, and these risks are minimal. The risks of this study include possible allergic reactions to the liquid used in applying the electrodes. Allergic reactions to the liquid are extremely rare. There is also a possibility for an allergic reaction to the electrodes. If any of these reactions occur, a rash would appear.

Treatment would include removing the electrodes and liquid and exposing the site to air, resulting in removal of the irritation. If there is an allergic reaction, testing procedures would be discontinued. Another unlikely risk is a small abrasion on the scalp when the blunt needle is used to place electrode gel. Treatment would also include removing the electrode and gel, exposing the site to air and testing procedures would be discontinued.
Benefits

You will receive a copy of your hearing assessment at no charge. You will be notified if any indications of hearing loss are found in this area. The information obtained from this study may help to further the understanding of language processing, which will be beneficial to professionals involved in treating speech and hearing disorders.

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 in aggregate form without individual identifying information.

Compensation

You will be given $50 compensation at the completion of this portion of the study; you will receive this compensation whether or not you complete the study in its entirety.

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.
Other Considerations

There are no charges incurred by you for participation in this study. There is no treatment or intervention involved in this study.

The procedures listed above have been explained to me by: _____________________________ in a satisfactory manner and any questions relation to such risks have been answered.

I understand what is involved in participating in this research study. My questions have been answered and I have been offered a copy of this form for my records. I understand that I may withdraw from participating at any time. I agree to participate in this study.

Printed Name: ____________________________

Signature: ____________________________

Date: ____________________________
Appendix B

Annotated Bibliography


**Objective:** The purpose of this study was to outline Broca’s findings in regards to aphasia based on clinical studies. Based on post mortem studies, patients who presented with aphasia had lesions in the left hemisphere, specifically in the third left frontal convolution. Patients with right hemisphere lesions rarely demonstrated aphasic symptoms. Observations of patients with lesions to Broca’s area did not exhibit deficits associated with the action of articulatory muscles or the nerves that innervate them. These patients could hear and understand what was said to them, and could emit vocal sounds, but were not able to coordinate the movements needed for articulatory speech. These patients with Broca’s aphasia also demonstrated deficits in their written expression, exhibiting telegraphic writing much like their speaking. Although most patients examined seemed to use the third left frontal convolution for speech, there were exceptions. In one patient with epilepsy, post mortem studies found that the third left frontal convolution was underdeveloped, not as a result of lesion, but as a result of atrophy. This patient was left handed, and was able to use language to express herself well. In this case, it appears that her language had been transferred to the right hemisphere. **Conclusions:** Broca concludes that the ability to produce language is tied to the third left frontal convolution in most persons. He asserts that both hemispheres of the brain are identical anatomically, and are not responsible for different functions per say, but the left hemisphere tends to become dominate for complex functions such as speech and language because persons favor the left hemisphere by using the right hand. Persons learn in childhood to use the right hand, and thus the left hemisphere of the brain develops for complex functions as a result. But although the left hemisphere is dominant for language, because the right hemisphere is symmetrical anatomically, the right hemisphere is capable of producing language. **Relevance to the current work:** This paper concludes that Broca’s area is used for speech output and also claims that the right hemisphere is capable of taking over the function of Broca’s area in the event of damage. In the current work TB is able to produce language despite the partial removal of the left temporal lobe. It is also important to note that TB is ambidextrous. According to this paper by Broca, this may be a partial reason for his extensive language recovery. **Level of evidence:** Level IV.


**Objective:** The purpose of this study was to investigate the reorganization of language in left hemisphere dominant patients before and after anterior temporal lobe resection as a treatment for temporal lobe epilepsy. This study also investigated whether preoperative fMRI predicts postoperative naming decline and the efficiency of postoperative language networks. **Study sample:** Forty-four native English speaking patients with medically refractory temporal lobe
epilepsy (TLE) due to unilateral hippocampal sclerosis participated in this study. Twenty-four participants had left TLE. **Methods:** Subjects underwent testing using the McKenna Graded Naming Test. This test requires the subject to name 30 black and white line drawings of increasing difficulty. For the verbal fluency test, patients were asked to produce as many words as possible beginning with the letter “S.” These tests occurred before and four months post anterior temporal lobe removal. Postoperative-preoperative changes in scores were correlated with preoperative and post-operative fMRI activation patterns to assess language processing location and fMRI ability to predict postoperative language deficits. During the verb-generation task, concrete nouns were presented visually every 3 seconds in blocks of 10 contrasted by 30 seconds of crosshair fixation at rest. Subjects were instructed to either covertly generate verbs associated with these nouns (indicated by the letter ‘G’ preceding the noun) or silently repeat the nouns presented (indicated by the letter ‘R’ preceding the noun) during the activation time. **Results:** The left TLE patients had significantly lower naming scores as compared to the right TLE patients, both pre and post operatively. There was also a significant reduction of preoperative vs. postoperative naming scores in patients with left TLE. There was no significant difference in mean verbal fluency scores between patients with left and right TLE pre or postoperatively. For naming, 14/24 (statistically significant) left TLE patients and 7/20 (not statistically significant) patients with right TLE exhibited a decline in naming scores. For verbal fluency, 9/24 (statistically significant) left TLE patients and 10/20 (statistically significant) right TLE patients exhibited a decline in verbal fluency scores. The preoperative fMRI exhibited significant activation for verbal fluency in the left inferior frontal gyrus and the middle frontal gyrus. Postoperative fMRI exhibited significant activation for verbal fluency bilaterally in the inferior frontal gyrus and the middle frontal gyrus for the left TLE patients and was found in the left middle and inferior frontal lobe for right TLE patients. Left TLE patients demonstrated significantly less postoperative than preoperative activation in the left inferior and middle frontal gyri, and in the left posterior hippocampus. **Conclusions:** Reorganization of language processing to the contralateral hemisphere within four months post resection of the anterior temporal lobe was found in this study. This suggests that multiple systems in the brain support language and are able to compensate, though not perfectly, in the event of damage or removal. Postoperatively, patients with left TLE with no significant naming decline relied on the recruitment of the residual left posterior hippocampus for word retrieval, whereas patients demonstrating a decline showed greater reliance on the contralateral frontal lobe. This implies that reorganization within four months of left temporal lobe resection to the contralateral lobe is less effective, whereas reorganization involving the ipsilateral posterior hippocampus is more effective in preserving naming function. This study presents continued evidence on left hemisphere dominance, as activation changes in right anterior temporal lobe resection were not significant. **Relevance to the current work:** This study identified alternative areas of activation on fMRI scans in the event of left anterior temporal lobe resection, specifically in the right inferior and middle frontal gyrus. Greater hippocampal activation was associated with greater preservation of naming ability. As in this study, the current work examines the language processing of an individual with left temporal lobe removal (TB). **Level of evidence:** Level IIIb.
Objective: The objective of this book is to provide an anatomical atlas of the brain and the white matter connections that connect these areas. Relevance to the current work: FLAIR images from this book were used with permission in this thesis to gain a better understanding of the white matter damage in TB’s brain. Level of evidence: Level IV.


Objective: The purpose of this study was to study the coherence profile of eye-closed resting EEG sources, using two large normative data bases, and to assess the usefulness of group blind source separation (BSS) on resting state networks. Study sample: Two normative databases (N = 57; age range 17–30) and (N = 84; age range 18–30) participated in this study. Methods: About 3–5 min of EEG was continuously recorded from the databases while participant sat with their eyes closed on a comfortable chair in a quiet and dimly lit room. Analysis of group BSS was performed to assess the coherence profile between the two databases. Results: The coherence profile displayed peaks occurring at nearly identical frequencies in the two databases, although with inconsistent relative amplitude. The components measured are organized in two independent (both in-phase and out-of phase) networks, whereas significant out-of-phase crosstalk exists within each network. Conclusions: Group BSS can be purposefully used in EEG as group and a set of seven components can be replicated with nearly identical spatial and spectral content. The organization of these components in networks communicating by specific frequency and time-lag protocols is replicable. Relevance to the current work: This provides a review of important EEG principles that were applied in the current work. Level of evidence: Level IIIa.


Objective: The purpose of this study was to provide a definition of aphasia and outline the deficits associated with each type of aphasia, namely Broca’s, Wernicke’s, Transcortical, Conduction, and Global aphasias. Conclusions: Aphasia is a disturbance of the comprehension and production of language caused by focal brain damage. Aphasia occurs across languages and is even present in sign languages. It can affect naming, syntax, prosody, morphology, and semantics. Aphasia is not a disorder of speech perception, nor is it a disorder of movement or intellect. Aphasia can be caused by any neurologic condition, but is most commonly a result of stroke or TBI. Lesions associated with aphasia are typically located in the hemisphere dominate for language, which is most often the left hemisphere. The presence of aphasia has often been used as a diagnostic tool for brain damage location. Aphasia has been studied by psychologist, neuroscientist, and psycholinguists. Much development has come as a result of neuroimaging studies, such as MRI. Wernicke’s aphasia is most often caused by damage to the posterior section of the left auditory cortex, or Brodmann’s area 22. It can also involve Brodman’s areas 37, 39, and 40. Patients with Wernicke’s aphasia typically have poor repetition, and naming.
Speech is mostly fluent with a normal or faster rate, though is marked by the production of paraphasias. Speech comprehension is poor. Though Wernicke’s area is not the center for auditory comprehension, it is the processor of speech sounds that allows sounds to be mapped as words. **Relevance to the current work:** This article defines the general characteristics of aphasia, and specifically the characteristics of each type of aphasia. The current work involves a case history of TB, who was diagnosed with Wernicke’s aphasia. **Level of evidence:** Level IV.


**Objective:** The purpose of this study was to examine the relation of young age to plasticity by reviewing human pediatric brain disorders, as well as selected animal models, and human developmental and adult brain disorder studies. **Conclusions:** Neuroplasticity is the ability of a system to respond to changes in the internal or external environment by adopting new phenotypes or restoring old phenotypes. It can occur on a micro level or a macro level. Although plasticity is for the most part beneficial, it is neutral in regards to outcome. It can be both adaptive and maladaptive. The idea that young age leads to a greater capacity of plasticity has been overstated. Plastic changes occur in conjunction with homeostatic mechanisms regulating change throughout the lifespan. The same mechanisms that propel developmental change expose the immature brain to adverse events, making it more difficult for the immature brain to sustain equilibrium between plasticity and homeostasis; this disequilibrium results in a poor outcome in neurodevelopmental disorders and childhood acquired brain insults. **Relevance to the current work:** This article provides a foundational explanation of neuroplasticity needed to better understand what processes have occurred within TB’s brain that have enabled him recover language abilities. **Level of evidence:** Level IV.


**Objective:** The purpose of this study was to present an analysis of speech processing within the auditory cortex in an attempt to clarify the neural substrates of auditory word form recognition. **Conclusions:** Although classical models of language comprehension have associated the posterior superior temporal (ST) cortex with word recognition, studies performed on macaque monkeys and fMRI studies on humans have demonstrated that the anterior ST cortex is associated with word recognition, or monkey calls, and the posterior ST cortex is associated with sound localization. Work with nonhuman primate electrophysiology and early functional imaging have identified two main language processing pathways: a dorsal stream that is used primarily for sensorimotor integration and spatial processing, and ventral stream that is used for object or pattern recognition. The ventral stream is characterized by the posterior ST region, and the dorsal stream is characterized by the anterior superior temporal gyrus (STG). In a functional brain imaging study conducted by DeWitt and Rauschecker (2012), it was concluded that analysis of phonemes occurred in the mid-STG, lateral to Heschl’s gyrus, word recognition occurred in the anterior STG, and phrase processing occurred in the anterior superior temporal sulcus. This differed from the classical model of language organization proposed by Geschwind (1970) which located word form recognition in the posterior ST. Original conclusions made by
Wernicke suggested that the entire STG made up Wernicke’s area, and that Wernicke’s area, in addition to word form recognition, included a corrective role, which monitors speech output for errors. Wernicke concluded that this role was disrupted in patients with Wernicke’s aphasia, as demonstrated by what are known today as paraphasias. A contemporary understanding of functional anatomy suggests that Wernicke’s area, as it is functionally defined, appears to consist of two areas: an auditory word form area in the anterior STG and an “inner speech area” in the posterior STG. 

**Relevance to the current work:** This article provides a greater understanding of functional abilities that are attributed to Wernicke’s area. This area has been damaged TB’s brain, whose language is studied in the current work. 

**Level of evidence:** Level IV.


**Objective:** The purpose of this study was to determine the locus (that of the perilesional cortex to that of the residual language network in the left hemisphere) for brain changes that occur as a result of treated anomia in patients with chronic stroke-induced aphasia. A second objective was to analyze the relationship between cerebral blood flow and brain activation prior to treatment, and improved ability to name pictures following treatment. 

**Study sample:** Thirty patients (16 female, 14 male, and age range 33-81 years) participated in this study. Each had incurred a single stroke and presented with aphasia according to results from the Western Aphasia Battery.

**Methods:** Patients received 3 hours of anomia treatment per weekday for 2 weeks, for a total of 30 hours of treatment. Treatment targeted oral naming with cueing, which relied on a hierarchy of semantic and phonemic cues. Patients were presented with an overt naming task in which patients attempted to name a presented picture. Results from two pretreatment and two post treatment fMRI sessions were compared. Patients viewed 120 randomly presented pictures, 80 of which depicted real objects for overt naming and 40 of which were abstract pictures requiring no response. Analysis contrasted the two fMRI sessions before treatment with the two fMRI sessions administered upon treatment completion, creating a single statistical map for each patient that represented the change in cortical activation from pre-treatment to post-treatment.

Pulsed arterial spin labeling was used to acquire regional cerebral blood flow. 

**Results:** Slightly fewer than half of the patients demonstrated little or no improvement in naming whereas the remaining patients were able to name at least 10 more pictures (out of 80 total) than they were able to name at baseline following treatment completion. A comparison of pre and post treatment naming performance across the whole group revealed a statistically significant increase in naming. The perilesional frontal lobe was the most robust predictor of improved naming. Increased blood flow was statistically significant, a general pattern indicating that the level of baseline cortical activation and anomia treatment did not emerge.

**Conclusions:** Functional brain changes in physiologically defined areas in the perilesional cortex, especially in the frontal lobe, predict improvement in correct naming following anomia treatment in patients with aphasia post-stroke. Further research is needed to determine if anomia treatment results in greater cerebral blood flow. 

**Relevance to the current work:** This study attempted to identify location of cortical activation after treatment of anomia, and examined the relationship between anomia treatment and increased blood flow in patients with aphasia. This is an example of behavior induced neuroplasticity. In the current study, TB experienced neuroplasticity that may be behavior induced. 

**Level of evidence:** IIIb.

**Objective:** To provide a review of the four relevant language related components in event-related brain potentials, which are the N400 component, the early left anterior negativity (ELAN), the P600 component, and the closure positive shift (CPS). This review will focus on the N400 component and the P600 component due to their relevance to the present study. **Conclusions:** The N400 is a negative waveform peaking at around 400 ms after the onset of the critical stimulus. It is associated with lexical-semantic processing. The amplitude of the N400 is greater when words that are semantically unrelated are presented one after the other. Amplitude is also affected by the general frequency with which the word is used in the target language. Studies have demonstrated that the N400 is associated with lexical integration and may be associated with some aspects of automatic spreading activation as well as meaning integration. Data from a study with intracortical recordings suggest that the superior temporal sulcus and additional frontal areas are involved in the generation of the N400. This is in partial agreement with brain imaging studies that report activation in the left STG, posterior and anterior to the Heschl's gyrus for lexical-semantic processes. Syntactic processes are functionally subdivided into different phases. First, initial phrase structure-building processes around 200 ms are supported by the anterior portion of the left STG and the frontal operculum. Second, left processes of assigning the grammatical relations between words and their thematic roles are reflected in a LAN between 300 and 500 ms. Later processes of syntactic integration and repair are reflected by the P600 component present beyond 600 ms. The P600 is a positive wave after 600 ms, and has been observed with violations of structural preferences, outright syntactic violations, and difficulty of syntactic integration. The P600 has been found to be absent in patients with lesions in the left anterior cortex and in those with lesions in the anterior temporal lobe. The P600 has also been found to be selectively reduced or absent in patients with lesions in the basal ganglia. This suggests that the early structure-building processes are supported by a temporo-frontal network involving the left anterior portion of the STG and the left inferior frontal gyrus, whereas late processes of syntactic repair seem to involve the basal ganglia. **Relevance to the current work:** In this review, researchers have concluded that the P600 component is absent in the event of left anterior temporal lobe damage. The current work found similar results in TB. **Level of evidence:** Level IV.


**Objective:** The purpose of this study was to provide a review establishing the neural basis of auditory sentence processing. **Conclusions:** Evidence from numerous studies has lead researchers to conclude that a bilateral temporo-frontal network sub serves auditory sentence comprehension. Both syntactic and semantic information are processed predominantly in the left hemisphere. A neurocognitive model of sentence comprehension is proposed which contains temporal characteristics consisting of three phases. Phase 1 (100-300 ms) is the time period in which the initial syntactic structure is formed on the basis of information about the word category. In phase 2 (300-500 ms), lexical-semantic and morphosyntactic processes take place with the goal of thematic role assignment. In phase 3 (500-1000ms) the different types of information are integrated. Studies on functional neuroanatomy of syntactic processing demonstrate the
involvement of the inferior frontal cortex and the anterior portion of the temporal cortex. Anterior and posterior temporal activation has been reported, but most consistently, the anterior STG has been most active in syntactic processing. This is accompanied by substantial activation of the inferior frontal gyrus or minimal or no activation in Broca’s area, though activation in the left frontal operculum is sometimes observed. The P600 component correlates with obvious syntactic violations with garden path sentences that require syntactic revision. Temporal regions are involved in syntactic processing in the left anterior STG, semantic processing in the left MTG, and prosodic processing in the right posterior STG. Timing of syntactic processing precedes and is initially independent of semantic processing, though both interact during a later processing phase. Prosodic processes influence syntactic processes. Relevance to the current work: This article states the function of the P600 component as relating to later, conscious (not automatic) syntactic processing. It also defines the functional neuroanatomy of syntactic processing in the left STG. This area was removed in TB, and as a result, the P600 was not present in the TBI participant. Level of evidence: Level IV.


Objective: This study uses DTI to track the connections between the arcuate fasciculus and cortical regions, including the superior temporal gyrus (STG) and the middle temporal gyrus (MTG), as implicated by phonologic, lexical-semantic, and prosodic processing. The goal of the study was to assess the degree of laterality of the arcuate fasciculus. The study expected to find bilateral STG connections and asymmetric MTG connections, favoring the left side. The study then compared tractography results with activation coordinates from prior functional neuroimaging studies of phonology, lexical-semantic processing, and prosodic processing. The study interpreted these results and compared them to a recent model of language processing and tested this model against some of the aphasia types reported in the literature. Study sample: Twenty right-handed male subjects, aged 18-50 (mean: 23.75, SD 7.1) participated in this study. Methods: The arcuate fasciculus was tracked with the following approach: A single region of interest (ROI) was drawn on a coronal slice of the DTI color map to select the fibers of the arcuate fasciculus in the left and right hemisphere. This ROI defines fibers oriented in an anterior-posterior direction, including neighboring fibers such as the superior longitudinal fasciculus. All fibers pass through this bottleneck, making it an ideal region to localize the pathway. The tractography derived from this ROI reveals two regions of arcuate terminations within the temporal lobe and non-arcuate termination in the parietal lobe. Both arcuate and non-arcuate terminations are found within the frontal lobe. To separate the arcuate from other tracts and divide it into the STG and the MTG, a 2-ROI approach was used. Results: The STG pathway: The pathway connecting the STG to the frontal lobe was found in 17/20 subjects in the left hemisphere, and 4/20 in the right. The left hemisphere pathway connected Brodmann’s Area 22 to Brodmann’s Area 44 and 6. The right hemisphere pathway also connected BA 22 to Ba 44 and 6. The volume of the pathway in the left was an average of 2724 mm³ (±438 mm³) on the left and 516 mm³ (±240 mm³) on the right, exhibiting a highly asymmetric volume, favoring the left hemisphere. Conclusions: The connection of the arcuate fasciculus, which links both the STG and the MTG with the inferior frontal lobe, is asymmetric, favoring the left hemisphere. In comparison with activations from functional neuroimaging experiments, the left STG pathway is involved in phonological processing and the left MTG pathway is involved in lexical-semantic
processing. The right MTG pathway is involved in prosodic processing. 

Relevance to the current work: This study supports the notion that white matter fiber tracts, in particular the arcuate fasciculus are of higher volume in the left hemisphere as compared to the right hemisphere, further supporting the idea of left hemisphere dominance for language. The current work found an atypical pattern of activation in the left hemisphere, support the idea that residual language functioning is taking place in the right hemisphere. 

Level of evidence: Level IIIb.


Objective: The object of this examination is to determine the existence and level of aphasia in individuals with damage to the brain. Relevant to the current work: This examination was used to assess TB and CP. Level of evidence: Level IV.


Objective: The purpose of this study was to examine the properties of the processes involved in the structural analysis of sentences using event related brain potential measures. Previous research had shown two ERP components to correlate with phrase structure violations: an early left anterior negativity (ELAN), which is assumed to reflect first-pass parsing processes, and a late parietal distributed positivity (P600), assumed to reflect second-pass parsing processes. It was hypothesized that the first-pass parsing processes are highly automatic, whereas second-pass parsing processes are more controlled. Study sample: Twenty right-handed college students (8 male, age range 20 to 29 years, mean 24 years) participated in this study. All were native speakers of German and had normal or corrected to normal vision and no known hearing deficit. Methods: Participants were presented with combination syntactically correct and syntactically incorrect sentences via headphones. Participants were asked to indicate if the sentences were correct or incorrect via push buttons. In this study, researchers varied the proportion of correct and syntactically incorrect sentences across two experimental sessions. In one session, 20% of the sentences contained a phrase structure violation, whereas in the other session, there were 80% phrase structure violations. Correct sentences consisted of a noun phrase, an auxiliary, and a past participle (Das Baby wurde gefüttert—The baby was fed). Syntactically incorrect sentences contained a word category error. In these sentences, a preposition appeared after the auxiliary and was directly followed by a past participle (Die Gans wurde im gefüttert—The goose was in the fed). Because the preposition indicates the beginning of a prepositional phrase necessarily consisting of a preposition and a noun phrase, this sequence of words creates a clear phrase structure violation. It was predicted that if the early left anterior negativity reflects an automatic process, it should be present and equally pronounced under both proportion conditions because an automatic process should not be influenced by strategic behavior as induced by the varying proportion of incorrect sentences. It was additionally predicted that if the late positivity reflects a more controlled process of secondary parsing, it would diminish in the case of a high proportion of incorrect sentences compared to a low proportion of incorrect sentences. Results: Phrase structure errors elicited an early anterior negativity that was more pronounced over the left than
over the right hemisphere. This effect was independent of the proportion of incorrect sentences. By contrast, the proportion manipulation clearly affected the late positive component. Syntactic violations in the 20% violation condition elicited a late parietal distributed positivity, whereas this effect seemed to be reversed in the 80% violation condition. **Conclusions:** the early structure-building processes are independent of the participants’ conscious expectancies and strategic behavior and can therefore be claimed to be automatic in nature. In contrast, a P600 component was observed for a low proportion of syntactically incorrect sentences only. **Relevance to the current work:** In this study, researchers conclude that the P600 component is a result of conscious thought, not an automatic response. In the current work, the P600 component was absent in TB, possibly indicating that the participant had decreased conscious ability to interpret syntactic information, due damage in the left temporal lobe. **Level of evidence:** Level IIIb.


**Objective:** The purpose of this review is to explain the details of DTI and DTT, to explain the advantages and limitation of DTI in aphasia research, and to examine previous DTI studies on the arcuate fasciculus in stroke patients with regard to the usefulness for diagnosis, prediction of prognosis, and recovery of aphasia. **Conclusions:** The following is a list of advantages of researching aphasia using DTI. First, DTI has unique value in its ability to diagnose hidden or ambiguous lesions that cannot be easily detected on conventional brain. Second, serial DTI scanning of the arcuate fasciculus allows for estimation of changes of an injured arcuate fasciculus, for example, regeneration, degeneration, or resolution of peri-arcuate fasciculus edema of an injured. Third, asymmetry of the arcuate fasciculus between the right and left hemispheres on DTT can provide another parameter for evaluation of an injured. Fourth, other neural tracts involved in language function can be analyzed along with the arcuate fasciculus and compared with the state of the arcuate fasciculus. There are also several limitations to DTI. First, the fiber tracking technique is operator-dependent. Therefore, results can be misleading. Second, DTI may underestimate or overestimate fiber tracts. The problem associated with kissing fiber in regions of fiber complexity can prevent full reflection of the underlying fiber architecture by DTI. Many recent studies have attempted to solve this limitation using probabilistic tractography. Third, DTT cannot determine the exact cortical origin and termination of fibers; therefore, it can only define the territories of fiber projection. Studies using a combination of functional neuroimaging techniques can compensate for this limitation of DTI. **Relevance to the current work:** In the current work, details of DTI and their application to brain lesions are related in the introduction. **Level of evidence:** Level IV.


**Objective:** The purpose of this study was to evaluate the effectiveness of 10/20-derived systems in the light of head-surface-based positioning systems. **Study sample:** Seventeen healthy volunteers (9 males, 8 females; aged 22 to 51 years) participated in this study. **Methods:** Head and brain images were extracted from the MRI data sets of the 17 subjects to produce isotropic
images of $1 \times 1 \times 1$ mm voxels in size containing 8-bit continuous-tone data. These were subsequently converted to 2-bit data. The 10/20, 10/10, and 10/5 positions were determined according to the distance between landmarks over the head surface. The distance between a set of points over the head surface in a virtual space were calculated by defining a plane using three landmark positions. Head surface points which comprised a cross-section between the plane and the head surface were extracted and a reference curve utilizing the extracted points was drawn. When only two points were given, the shortest distant search algorithm was used. This set numerous planes intersecting the two points. Among the cross-sections between the planes and the head surface, the one that gave rise to the shortest path along the head surface was chosen.

After multi-subject data for a given landmark position was expressed in MNI space, the mean coordinate locations across subjects were calculated. The mean coordinate location provided the most likely estimates of the given point. The SD provided the measure for its variability across subjects within a given system. Results: There were inter-system variabilities between 10/10 positions defined in different methods. Specifically, choice of hemispheric or anterior/posterior divisions and of coronal reference curves causes non-negligible differences in the locations of 10/10 positions. These observations clearly demonstrate the need to clarify which branch of 10/20-derived systems is used to set scalp landmarks in order to describe their locations explicitly. On the other hand, intra-system variabilities were at similar levels. Conclusions: It was found that as long as a detailed rule for a particular method is provided, it will yield precise landmarks. Landmarks set by any system can be probabilistically described.

Relevance to the current work: the 10-20 international system was used in QEEG testing for TB and CP. Level of evidence: Level IIIa.


Objective: The purpose of this study was to determine the percentage of left hemisphere language dominant individuals using functional transcranial Doppler- ultrasonography (fTCD). Study sample: In this study, 188 healthy volunteers, 111 women, 77 men participated. Methods: Subjects were asked to perform a word fluency task in which they were presented with a letter of the alphabet and asked to silently generate words beginning with that particular letter. Letters were presented for 2.5 seconds and subjects were given 15 seconds to generate words silently. Subjects were then given five seconds to repeat the words they had silently generated. Patients continued this pattern for 23 letters. Changes in cerebral blood flow velocity were measured as an indicator of increased metabolic activity downstream. Dual fTCD was then performed on the middle cerebral arteries. Results: Of the 188 subjects who participated, 7.5% exhibited right hemisphere language lateralization, whereas 92.5% exhibited left hemisphere language lateralization. Conclusions: Language lateralization is predominantly left lateralized in healthy, right handed individuals. Relevance to the current work: This study upholds the notion that language is largely left lateralized. This emphasizes the uniqueness of TB’s ability to access the right side of his brain for language tasks. Level of evidence: Level IIIb.

**Objective:** The purpose of this study was to determine the lesion locations associated with various types of aphasia in patients affected by stroke. **Study sample:** In this study, 107 patients participated (mean age 56 years; range 17 to 86; 54% men). Ninety-six patients were right-handed, five were left-handed, and six were ambidextrous. The index stroke was a cerebral infarct in 88 patients and a cerebral hemorrhage in 19 patients. Fifty-six patients had motor weakness of the preferred hand. **Methods:** Patients were assessed for language using the Montreal-Toulouse battery and some subtests of the Boston Diagnostic Aphasia Examination within four weeks of stroke. Each patient underwent an MRI within three months after stroke. The images were rated by three independent examiners blind to language examination. **Results:** Broca’s aphasia was associated with anterior and insular lesions, Wernicke’s aphasia with temporoparietal, and insular lesions, global aphasia with large antero-posterior lesions usually involving the cortex. Subcortical lesions were associated with subcortical, transcortical motor, and Broca’s aphasia, but never global, transcortical sensory, or Wernicke’s aphasia. Age did not differ significantly across aphasic syndromes. **Conclusions:** This study supports the close association between aphasic disorders and specific lesion sites. **Relevance to the current work:** This study suggests temporoparietal lesions are associated with Wernicke’s aphasia. The same results were found in the case study of TB. **Level of evidence:** Level IIIb.


**Objective:** The purpose of this study was to determine how well acute impairments of repetition and comprehension correlate with lesions of either the dorsal or ventral stream in patients with aphasic stroke. The dorsal stream connects the temporoparietal with frontal premotor regions through the superior longitudinal fasciculus and arcuate fasciculus and integrates sensorimotor processing, as in repetition. The ventral stream connects the temporal and prefrontal regions via the extreme capsule and facilitates meaning, as in auditory comprehension. **Study sample:** One hundred adults (mean age 62 years, 67 male, six left handed) with acute aphasia caused by ischemic stroke participated in this study. **Methods:** Damage to patients’ ventral and dorsal fiber tracts was quantified using voxelwise lesion behavior maps derived from the average fiber tracts that connect activated cortical regions in repetition and comprehension in healthy subjects. The patients were given the repetition and auditory comprehension subtests of the Aachen Aphasia Test to determine presence of repetition or auditory comprehension deficits. **Results:** Repetition impairments were mainly associated with lesions located in the posterior temporoparietal region and were associated with damage to the superior longitudinal and arcuate fasciculus. Lesions associated with comprehension deficits were found more ventral anterior in the temporoprefrontal region and were associated with damage to the extreme capsule in the ventral pathway. **Conclusions:** Language is organized along two segregated dorsal-ventral streams and damage to these streams can cause repetition and comprehension deficits respectively. **Relevance to current work:** This study comes to conclusions about the function of specific fiber tracts between the language centers of the brain. It is clear from MRI evidence that TB has damage to both the superior longitudinal fasciculus and the arcuate fasciculus, and thus experiences deficits similar to those stated above. **Level of evidence:** Level IIIb.

**Objective:** The purpose of this review was to explain the physiological details of several different neuroimaging techniques, including fMRI and DTI. The second purpose was to examine the contribution of neuroimaging to the study of aphasia. **Conclusions:** This review gives a broad overview of the techniques used in studying language, ranging from structural imaging such as CT, standard MRI and DTI, to functional techniques such as PET and fMRI. Ideally, complementary methodologies should be used to investigate how language is represented and processed in the brain. For example, functional “activation” imaging (e.g., PET or fMRI) can be used to reveal the areas of the brain engaged during a specific language process, and DWI and PWI of acute stroke patients with dysfunctional tissue in these areas (along with language testing at nearly the same time) can be used to test whether these areas are essential for the process. New imaging methods are being refined, including optical imaging of blood flow, molecular MRI, and PET studies of receptors and transporters. These methods are likely to reveal new insights regarding language processing and recovery from aphasia in the near future. **Relevance to the current work:** This study provides greater understanding for the physiologic details of fMRI and DTI that are explained in the introduction to this study. **Level of evidence:** Level IV.


**Objective:** The purpose of this study was to determine whether regional EEG power and coherence in the resting state would differ between adults with autism spectrum disorder (ASD) and matched controls in both eyes closed and eye open resting conditions. **Study sample:** In this study, 15 adults (12 males) with a confirmed DSM-IV diagnosis of autism spectrum disorder participated. Ages ranged from 18.8 to 51.6 years ($M = 35.5, SD = 7.6$). A control group of 16 adults (12 males), ranging in age from 22.6 to 47.8 years ($M = 35.7, SD = 10.6$) also participated. **Methods:** Researchers measured EEG data during a 6-min resting baseline condition with alternating eyes-open and eyes-closed intervals of one minute each as instructed by the experimenter. Both EEG alpha power and EEG alpha coherence were measured. Isopotential contours were created and a map of brainwave activity across the scalp was created. **Results:** The alpha power in each region was greater in the ASD group than in control participants. Like resting alpha power, resting alpha coherence differed by condition and region, but appeared to be quite similar in both groups. **Conclusions:** Adults with ASD exhibited higher levels of posterior alpha activity during eyes-open rest than matched controls. This is apparently due to lower levels of alpha suppression in the ASD group. Within the ASD group, individual differences in posterior resting alpha power and right centro-parietal connectivity in the alpha network reflected the degree to which adults with ASD reported being captivated by detailed information. These relations suggest that there are functional differences and differences in the micro-circuitry of the autistic brain and that these differences may influence attention-related behavior in this population. The capacity to manage cortical excitability and signal integration may be limited by functional changes in connectivity. **Relevance to the current work:** This study used methods to create a map of functional brain activity in a similar way that was used in the current work. **Level of evidence:** Level IIIb.
Objective: The purpose of this study was to investigate the connection between regions of the human auditory language system in healthy brains using diffusion weighted imaging. The study aimed at determining which, if either hemisphere, demonstrated a greater volume of white matter tracts connecting Broca’s and Wernicke’s areas in the left hemisphere, and homologous areas in the right hemisphere. The study also sought to determine if there exists a ventral connection, via the uncinate fasciculus or extreme capsule, in addition to the dorsal connection via the arcuate fasciculus and superior longitudinal fasciculus. Study sample: In this study, 11 right handed typical volunteers (six male, five female) participated. Methods: The Brodmann’s area 44 (Broca’s area) and Brodmann’s area 22 (Wernicke’s area) were identified on each subject by a neurologist. Homologous areas were identified in the right hemisphere. Volumes of interest (VOI) were traced and were defined to include the grey matter relating to each area and the neighboring white matter to allow for white matter fiber tracking. Tracking began from the center of each voxel in the brain that was an order of two or greater and the pathway was accepted only if it passed through both regions (Broca’s and Wernicke’s on the left, their homologues on the right). The voxels encountered by an accepted pathway were identified to be along the route, and the number of times each voxel was encountered throughout the experiment was recorded. The individual maps were then averaged for the group of participants. A lateralization index was then calculated to determine which, if either hemisphere averaged greater volume in their connecting tracts. Two sets of data were eliminated due to failure to show any connection between the target areas. This was attributed to failure in the voxel classification stage of the data processing due to poor signal to noise ratio. Results: The volumes of the VOIs defined for both Broca’s and Wernicke’s areas were significantly larger in the left hemisphere. The dorsal connection involving the arcuate fasciculus between Broca’s and Wernicke’s areas were present in both hemispheres. A ventral connection to the superior temporal gyrus was only present in the left hemisphere. More connecting voxels were identified in the left than in the right. Four of the 11 (45%) participants exhibited the connection between Broca’s and Wernicke’s areas. It passed either through the uncinate fasciculus or the slightly superior portion of the external capsule. Conclusions: These results reaffirm many studies exhibiting a strong connection between Broca’s and Wernicke’s areas via the arcuate fasciculus. It also provides evidence for a second ventral pathway, as has been suggested in other studies. The volume of the pathways was larger in the left hemisphere as compared to the right, implying more extensive connectivity. The second ventral route was only found in the left hemisphere, consistent with other studies that demonstrate predominately left hemisphere activation for processing speech. It is possible that the other 55% of the subjects did also demonstrate the ventral pathway, but it was not detected due to low sensitivity thresholds. It is also possible that the ventral pathway also exists in the right hemisphere, but is also not seen due to low sensitivity thresholds. It can be assumed however, that large tract volume in the ventral pathway can be found in the left hemisphere. Relevance to the current work: This study investigates the language pathways of the healthy brain, with results providing further evidence of left hemisphere dominance for language, due to the greater white matter connectivity in the left hemisphere. Both ventral and dorsal white matter fiber tracks of TB have been damaged, affecting his language ability. Level of evidence: Level IIb.

**Objective:** The purpose of this study was to determine the effects of white matter microstructure on language lateralization by investigating language lateralization and white matter microstructure in healthy left handed individuals at the whole brain level, through the use of fMRI and DTI. **Study sample:** In this study, 16 healthy, left-handed, Caucasian, female, graduate or postgraduate university students between age of 20 and 25 without history of brain disorders (mean age: 21.8 ± 1.7; range: 20–25 years) participated. Left handed subjects were used because they exhibit greater instances of atypical hemisphere dominance for language. **Methods:** The verbal fluency fMRI paradigm consisted of seven 30 second active periods, interspersed with 30 second rest periods. During the active period, subjects were presented with a letter, via headphones and asked to silently generate words beginning with the given letter. Subjects were asked to remain still and with eyes closed throughout the course of the stimulus. A language asymmetry index (AI) was calculated using the LI toolbox. Positive AI values represented left hemisphere language dominance, negative AI values represented right hemisphere language dominance. DTI image analysis was carried out using Tract-Based Spatial Statistics (TBSS). Data collected from TBSS were tested for linear correlations between diffusion characteristics mean diffusivity (MD), fractional anisotropy (FA) and language lateralization. **Results:** Ten of the 16 subjects exhibited left hemisphere language dominance. One demonstrated bilateral language lateralization and five demonstrated right hemisphere dominance. It was found that higher microstructural organization (high FA, low MD) of the left superior longitudinal fasciculus (SLF), the left angular gyrus white matter (AnG-WM) and left superior parietal lobe white matter (SPL-WM), were associated with left hemisphere language dominance, whereas lower microstructural organization (low FA, high MD) was associated with atypical, right hemisphere language dominance. **Conclusions:** Left SLF and left superior parietal lobe white matter are associated with language lateralization in left handed women. This may support the hypothesis that reduced white matter integrity in the left-sided language related tracts are closely linked to the development of right hemispheric language dominance. **Relevance to the current work:** The goal of this study was to determine the effect of white matter integrity on language lateralization, and concluded that in the event of reduced left hemisphere language integrity, particularly in the left superior longitudinal fasciculus and the left superior parietal lobe white matter, right hemisphere language dominance can occur. The white matter of TB’s brain is damaged, thus right hemisphere language dominance is possible. **Level of evidence:** Level IIIb.


**Objective:** The purpose of this book is to summarize the contribution of human auditory evoked potentials to the understanding of normal and atypical hearing. **Conclusions:** Information regarding the N1 and P2 waves was used in this thesis. The N1 can be defined as the maximum negative peak within the latency range of 50 to 150 ms and P2 the maximum positive peak between N1 and 250 ms. The N1 and P2 waves are derived mainly from the more lateral and posterior regions of the supra-temporal plane. The dipoles of N1 and P2 originate in the temporal lobes. The P2 typically increases dramatically as subjects learn to discriminate stimuli that they
previously found to be indistinguishable. The P2 is generally maintained on the superior surface of the temporal lobe with a location anterior to that of the N1 generator, which is centered on the planum temporale regions posterior to the primary auditory cortex. P2 follows N1, suggesting that the two waves represent two different stages in information processing. \textit{Relevance to the current work:} The P1-N1-P2 was evaluated in the QEEG testing of TB and CP. \textit{Level of evidence:} Level IV.


\textbf{Objective:} The purpose of this study was to use fMRI and MR topography (DTI) to examine the white matter connectivity between language areas of the frontal and temporal lobes in the left hemisphere and compare this connectivity with homologous areas in the right frontal and temporal lobes. It is hypothesized that connectivity would be stronger (evidenced by greater tract volumes) between the language areas of the left hemisphere than between homologous areas of the right hemisphere. \textit{Study sample:} In this study, 10 right-handed, native English-speaking, healthy volunteers participated. Ages ranged from 23-50 years, mean age 29.5. \textit{Methods:} Subjects completed tasks for verbal fluency, verb generation, and reading comprehension. Tasks were presented in blocked experimental design with 30 second task blocks followed by 30 seconds of rest over five minutes and 30 seconds. For the verbal fluency task, subjects were asked to silently generate different words beginning with a specified letter, which were presented visually. The rest block consisted of visual fixation on a crosshair. For the verb generation task, concrete nouns were presented every three seconds in blocks of 10 nouns. Subjects were instructed to covertly generate verbs from the nouns during the task block and to silently repeat the nouns during the rest block. For the reading comprehension task, subjects were presented with a baseline task. In the baseline condition, subjects attentively viewed 9-word sentences after all the letters were transformed into false fonts. This baseline controlled for visual input but not lexical, semantic, or syntactic content. Blocks of six sentences were interleaved with blocks of six false font sentences. Sentences and false fonts were presented one word at a time at a fixed rate (word duration, 500 ms; sentence duration, 5000 ms; block length, 30 s). To evaluate structure function relationships, correlations between the lateralization of fMRI activation and of the lateralization of the derived connections were noted, mean fractional anisotropy (FA) of left and right hemispheres were calculated, as well as mean tract volumes in the left and right hemispheres. \textit{Results:} Tract volume was significantly greater on the left than on the right in both the frontal and temporal lobes. For the frontal lobes, mean FA was higher in the left than in the right hemisphere. For the temporal lobes, there was no overall significant difference between the left and the right. There was a significant correlation between the degree of lateralization of mean FA and lateralization of fMRI activation for verb generation in the frontal lobes, and for reading comprehension in the temporal lobes. \textit{Conclusions:} There is asymmetry in the pattern of connectivity between the left and the right hemispheres. There are greater connections between frontal and temporal lobes on the left, reflecting the lateralization of language function. \textit{Relevance to the current work:} This study establishes left hemisphere dominance in language, and demonstrates greater tract volume in the left hemisphere. This further illustrates the uniqueness of the language recovery of TB in the current work. \textit{Level of evidence:} Level IIIb.
Objective: The purpose of this study was to assess changes in brain plasticity in participants with aphasia after a single, intense exposure to an imitation based computer therapy technique by measuring EEG sleep slow wave (SWA) activity. Study sample: In this study, 13 right handed patients (eight male; mean 52 ± 10.9 years; mean age at stroke = 46 ± 10.6) participated. These participants presented with previous left hemisphere stroke and resulting aphasia, as assessed by performance on the Western Aphasia Battery (WAB) and identification on MRI scans. Methods: Language assessment occurred prior to the first night of sleep and after the second night of sleep. Participants were assessed using the Apraxia Battery for Adults-2 (subtests 1, 2A, 2B, 5), the Boston Naming Test, and the WAB (Part 1; AQ). Participants underwent an MRI scan to determine the precise location and extent of lesion prior to EEG testing. Participants completed an intense session of therapy using IMITATE, an intensive physiologically based therapy, which uses more than 3000 unique video clips of words and phrases spoken by six different standard American English speakers. During the therapy session, participants viewed videos of six different speakers uttering an identical word or phrase, followed by a 20-s period during which they were asked to produce the same word or phrase as many times as they could. This program is normally used over a period of six weeks for 90 minutes a day. In this study, participants participated in a single day in two sessions, three hour session, followed by a .5 hour session. The EEG SWA was recorded the night before the treatment and the night following the treatment. Results: Most patients (8 out of 10) had lesions located over the left-precentral regions (inferior frontal gyrus, pars opercularis, and insula) and over the left-postcentral regions (inferior parietal lobule), whereas fewer patients had lesions involving a broad range of cortical regions of the left hemisphere. Speech assessment before and after the therapy demonstrated no significant change in standardized scores, consistent with researcher expectation. The average SWA was calculated for each non-REM sleep episode during both the night before treatment and the night after treatment. In the first 30 minutes of non-REM sleep (characterized by highest SWA and previously used to demonstrate plasticity-related SWA changes), a significant local increase (14% compared with baseline) in SWA was found across the right-central sulcus. Average SWA was calculated for each NREM sleep episode. This was also found during the entire first, second, and third non-REM sleep cycles. Conclusions: Plastic changes occur in areas activated during the execution of IMITATE, possible indicating effectiveness of the program. Changes induced by IMITATE were most consistently found over the right hemisphere, suggesting the possibility of reorganization of imitation function to the right hemisphere in the presence of damage to the left hemisphere. Relevance to the current work: This study provides evidence that neuroplasticity can be measured by EEG. It also provides evidence of reorganization of language function to the right hemisphere in the presence of left hemisphere damage. In the current work, neuroplastic changes in TB’s brain are evident due to his recovery of language functioning. It is possible that lateralization has shifted to the right hemisphere. Level of evidence: Level IIIa.

**Objective:** The purpose of this study was to determine whether or not the arcuate fasciculus in the undamaged right hemisphere of patients with chronic Broca’s aphasia would show structural changes as a result of intensive, long term treatment with melodic intonation therapy. **Study sample:** In this study, participants consisted of six right handed patients with moderate to severe nonfluent aphasia with relatively preserved comprehension and at least one year since their first left hemisphere stroke. **Methods:** Patients underwent high resolution MRI studies that included DTI acquisition before and after 75 sessions of melodic intonation therapy. The fiber tracts of the arcuate fasciculus were recreated. Two DTI studies were performed prior to therapy to rule out the possibility of increased number of fibers due to scan to scan variability. Differences in the number of fibers between these two scans were not significant. Speech measures such as correct informational units per minute while eliciting spontaneous speech through conversations with the patient and description of complex pictures as well as common procedures, the picture-naming test, and the number of syllables per phrase were measured before and after treatment. **Results:** All six patients showed a significant increase in the absolute number of fibers in the right arcuate fasciculus comparing post- versus pretreatment DTI studies (paired $t$-test, $p = 0.04$). One patient showed not only an increase in the absolute fibers of the right arcuate fasciculus, but also an increase in the fiber length after therapy. All six patients demonstrated increase in speech measures. In a regression analysis comparing correct information units per minute and the change in the fiber numbers of the arcuate fasciculus, a strong trend was found that did not reach significance. **Conclusions:** Intense speech therapy, such as MIT can impact the neuroplasticity of the right arcuate fasciculus by increasing its volume and the overall number of fiber tracts in patients with damage to the left sided language centers of the brain, and the left sided arcuate fasciculus. **Relevance to the current work:** This study supports the idea that neuroplastic changes have also occurred in TB’s brain. **Level of evidence:** Level IIIb


**Objective:** The purpose of this study was to investigate the functional reorganization of language in right handed patients with former non-fluent aphasia who had made linguistic recovery and a group of age matched controls using recordings looking at the high-beta band in an EEG. The high-beta band is an indication of cortical arousal. **Study sample:** Eleven patients with aphasia, three females, eight males who suffered from a single cerebrovascular accident around the perisylvian cortex participated in this study. Each had been diagnosed with non-fluent aphasia at the time of the injury and had demonstrated substantial recovery of linguistic functioning as assessed by the Italian version of the Aachener Aphasie Test. The control group consisted of 11 right handed, healthy adults matched for sex and age. **Methods:** Participants participated in three tasks while EEG testing was conducted; a phonological task, a semantic task, and an orthographic/visuoperceptual task. In all tasks, the participants were presented with two target
words on a screen. Buy pushing a button on a keyboard using the left index finger or middle finger, participants were asked to decide whether word pairs rhymed, whether they fit into the same category, and whether they were written in the same case. Correlation analysis of the high-beta bands was performed in order to determine whether the language reorganization occurred in the left hemisphere or the right. Results: Results of behavioral testing revealed a significant difference on tasks between the group of patients with aphasia and the control group. EEG analysis demonstrated that patients with aphasia demonstrated greater levels of high-beta rhythm in intact sites located anterior to the participants’ lesion sites. In the anterior cluster of electrodes, patients with aphasia had greater left versus right locations during the orthographic/visuo-perceptual and the phonological tasks, but not during the semantic task, which elicited a bilateral distribution of high-beta percentage. In frontal sites, control participants had significantly greater high-beta activity than participants with aphasia on right hemisphere scalp sites during phonological and orthographic/visuo-perceptual task and they showed bilateral greater high-beta activity during the semantic processing. At central sites, patients had greater right versus left high-beta percentage during the linguistic tasks, whereas controls exhibited greater left versus right high-beta percentage in the same tasks. Therefore, at central sites, groups showed inverted patterns of lateralization, participants with aphasia being right lateralized, control participants being left lateralized. During the orthographic/visuo-perceptual task, both groups revealed a similar bilateral distribution of high beta activity. Group differences revealed that controls had significantly greater high-beta activity than patients with aphasia on the left (but not right) scalp sites regardless of task. At posterior locations, regardless of task, patients with aphasia exhibited greater high-beta percentage in the right versus left sites, whereas controls showed an overall bilateral distribution of high-beta activity. Conclusions: The comparison of high-beta activity between the participants with aphasia and the control participants indicated reorganization of language activity over left prefrontal sites anterior to Broca’s area, which was partially damaged. The results demonstrated greater right hemisphere activity than left in the patients with aphasia as compared to the controls. This suggests reorganization of language in the right hemisphere in the presence of left hemisphere damage. Relevance to the current work: This study exhibited the location of reorganization of language in participants with aphasia secondary to left hemisphere damage who had recovered some linguistic functions using EEG. The current work also used EEG to discover patterns of language reorganization in TB. Level of evidence: Level IIIb.


Objective: The purpose of this study was to determine the incidence of atypical language distribution in non-right handed individuals. Study sample: Fifty healthy non-right handed adults with no history of neurologic or psychiatric problems. Non–right-handedness was defined as a handedness quotient based on the Edinburgh Handedness Inventory, between100 and 50. Twenty-four were male, 26 were female, and the average age was 27. Methods: Participants underwent a control task and a semantic decision task in order to determine laterality. In the control task (tone decision), subjects heard trains of three to seven 150-ms tones of either 500 or 750 Hz frequency. The subjects were instructed to press a button each time they heard a train containing two high-pitched (750 Hz) tones. In the language task (semantic decision), subjects heard names of animals (e.g., horse) and were instructed to press a button for animals they considered to be both “found in the United States” and “used by humans.” The tasks were matched for average stimulus intensity, stimulus duration, and frequency of positive targets. The
voxel count of 22 regions of interest was recorded. Results: Activation was predominantly right hemispheric in 8% (4/50), symmetric in 14% (7/50), and predominantly left hemispheric in 78% (39/50) of the subjects. Lateralization patterns were similar for all hemispheric regions of interest. Conclusions: The incidence of atypical language lateralization in normal left-handed and ambidextrous subjects is higher than in normal right-handed subjects (22% vs 4–6%). These whole-brain results confirm previous findings in a left-handed cohort studied with fMRI of the lateral frontal lobe. Associations observed between personal handedness and LI and family history of handedness and LI may indicate a common genetic factor underlying the inheritance of handedness and language lateralization. Relevance to the current work: Participant TB is ambidextrous. According to these findings, because of his handedness, it is more likely that he experienced right sided language activation prior to his TBI. Level of evidence: Level IIIb.


Objective: The purpose of this study was to assess the language reorganization of language to the right hemisphere after early left hemisphere injury in patient with left temporal lobe epilepsy through the use of fMRI. Study sample: Seven patients with epilepsy exhibiting right hemisphere language dominance and 10 epilepsy patients with left hemisphere language dominance participated in this study. All patients had had a left anterior temporal lobectomy at least five years before the study. Fourteen right handed healthy volunteers served as controls. Methods: The subjects were tested using four different language tasks. For verb generation, subjects were presented with a noun and asked to silently generate a verb every three seconds. Blocks of 10 nouns alternated with control blocks consisting of a string of symbols (#) matched to the length of the nouns. For semantic decision, subjects heard the name of an animal and were asked to press a button if the animal is found in the United States and used by people. For the control block, subjects heard a sequence of low and high tones and were asked to press a button for any sequence containing two high tones. For definition naming, subjects were given a description of an object and asked to push a button when they had covertly named the object. For the control condition, subjects pushed the button when they thought they heard a specific complex sequence of sounds within a longer sequence. For the passive sentence reading, subjects were presented with 30 nine-word sentences. The control block consisted of 30 false font sentences. Results: The patterns of activation for the control group were similar to those patterns previously published in the literature. For the left hemisphere patient group, activation was similar to that of the control group. For the right hemisphere group, activation was found in homologous areas of the right hemisphere. Overall, the extent of activation was smaller in both patient groups as opposed to the control group. Conclusions: This study concluded that when language transfers to the right hemisphere, it does so primarily to homotopic areas. Relevance to the current work: This study exhibited reorganization of language function to the right hemisphere with activation of right hemisphere structures homologous to left hemisphere language areas. The current work seeks to identify the functional activation patterns in TB, who experienced damaged left hemisphere. Level of evidence: Level IIIb.

**Objective:** The purpose of this study was to determine if enhanced cortical activity was specific to the trained voice-onset-time (VOT) stimuli ‘mba’ and ‘ba’, or whether it generalized to the control stimulus ‘a’ that did not contain the trained cue. **Study sample:** Thirteen young normal-hearing, mono-lingual English speaking, right-handed adults (age 21–30 years) participated in this experiment. They were in good general health, reported no history of otologic or neurologic disorders. **Methods:** Each individual participated in eight sessions. A pre-training test session on day one, was followed by six training sessions (days 2–7) and a post-training test session on day eight. The participants were trained to identify a 10 ms VOT cue that differentiated the two experimental stimuli. Event-related potentials (ERPs) evoked by three different speech sounds ‘ba’ ‘mba’ and ‘a’ were recorded before and after six days of VOT training. P1, N1, and P2 amplitudes were determined for each participant, each stimulus type, and each recording condition (pre- and post-testing) for each hemisphere using a 40 ms window centered about the group defined peak for each condition. **Results:** The ability to identify the two sounds improved ($t = 4.75$, $df = 1,12$, $p = 0.0005$). In the EEG testing it was found that the larger a person’s pre-training N1 amplitude, the greater the perceptual change following training. Significant increases in P2 amplitude were seen for both the experimental and control stimuli. But the distribution of P2 change was different for the control and experimental stimulus conditions. Whereas increases in P2 amplitude were seen across both hemispheres for the control stimulus ‘a’, post-training P2 responses were larger over the left hemisphere for the experimental stimuli. Although changes in perception did not significantly correlate with changes in P2 amplitude in all stimulus conditions, the amount of P2 change over the left hemisphere for the control stimulus did significantly correlate with the amount of perceptual improvement. Another significant finding was that people with smaller N1 amplitudes were less affected by training, showing little or no perceptual gains following training. **Conclusions:** Both stimulus-specific and general effects of training can be measured in humans. An individual’s pre-training N1 response might predict their capacity for improvement. In regards to the P2, if enhanced P2 responses reflect heightened awareness or attention resulting from passive listening during ERP recordings, it might be expected that there would be similar stimulation patterns of brain activity for all of the stimuli being tested. Yet in this study, the distribution of P2 change was different for the control and experimental stimulus conditions. One interpretation is that enhanced P2 activity seen for all stimulus types and is therefore not stimulus specific, reflects general processes (such as arousal, awareness) that are activated during the experiment. In contrast, the lateralization effects seen only for the trained stimuli could have been shaped by task-dependent attention to the acoustic feature (VOT), activated during training. In this respect, focused attention to the voiced VOT cue could have enhanced temporal encoding in the left hemisphere, similar to the asymmetrical hemispheric specializations reported in humans, described earlier. **Relevance to the current work:** Diminished amplitudes of P2 in TB’s brain could be related to lack of processing in the left hemisphere. **Level of evidence:** Level IIIb.
**Objective:** The purpose of this study was to define the role of the right inferior frontal gyrus (RIFG) in functional language reorganization following injury to the left language network, as is seen in left hemisphere epilepsy patients. The first goal of the project was to determine whether patients and controls activate the same anatomical regions of the RIFG during verbal fluency performance. The second goal of the study was to determine whether regions engaged in the RIFG during the tasks are homologous structures to the left inferior frontal gyrus (LIFG). The third goal of the study was to determine location of language–related activation following surgical removal of the left hemisphere in a patient with Rasmussen’s encephalitis. 

**Study sample:** Twelve preoperative right-handed patients with left temporal lobe epilepsy (seven males, mean age 33.4, range 15–53) participated in this study, along with twelve healthy, right-handed, neurologically normal controls (five males, mean age 31.17, range 24–37).

**Methods:** Eleven of the 12 patients underwent Wada testing to determine hemisphere dominance for language. Ten of the 11 were left hemisphere dominant for language and one of the 11 was determined to be bilateral in regards to language function. For the fMRI paradigm for phonemic fluency, the LTLE patients and the controls were scanned during a five minute fluency task. The subjects alternated between 30 seconds of a rest condition (a flashing fixation cross) and 30 seconds of stimulus. The stimulus consisted of a letter of the alphabet. Subjects were asked to silently generate words beginning with the given letter for the duration of its appearance on the screen. For the semantic fluency task, a category name was presented for 30 seconds. Subjects were asked to think of members for the given category. This was alternated with 30 second blocks. Subject completed a trial run of the experiment out loud prior to scanning and the number of words generated during each block was recorded. Region of interest (ROI) analysis and fMRI laterality indexes were calculated. The anatomical regions of pars opercularis, pars triangularis, and pars orbitalis were located in the LIFG and it was determined if activation in the RIFG was anatomically homologous to LIFG activation. 

**Results:** LTLE patients generated significantly fewer words on average than controls in both phonemic (\(t = 4.835, p < 0.001\), mean words) and semantic fluency (\(t = 7.387, p < 0.001\)) tasks. During the phonemic fluency task, the control subjects exhibited left hemisphere activation the inferior frontal gyrus, insular cortex, premotor regions and anterior cingulate gyrus on the left. Right hemisphere activation involved the insula, inferior occipital gyrus and anterior cingulate gyrus. Bilateral thalamic, putamen and cerebellar activation was also observed. Increased activation in controls relative to patients was found in the left thalamus and insular cortex. In LTLE patients, the pattern of significant activation was less left-lateralized than in controls, with activation in the right middle frontal gyrus, bilateral superior temporal gyrus, bilateral precuneus, and right parahippocampal gyrus. Significantly increased activation in patients with LTLE compared to controls was observed in the right medial frontal gyrus as well as bilateral posterior cingulate gyri. 

**Conclusions:** Differences were found in the activation of the RIFG between patients with LTLE and healthy controls in the verbal fluency task. This suggests that verbal fluency following left hemisphere damage does not rely on right hemisphere regions normally engaged by the task, but involves recruitment of a more posterior RIFG site. Activation in the RIFG in patients with LTLE were not homologous anatomical areas of activation in the LIFG, disproving the hypothesis that RIFG activation following left temporal lobe damage involves simple homologous anatomical regions.
of language areas in the LIFG. Longitudinal observations in a patient with Rasmussen’s encephalitis showed similar relative changes in localization of activation in the RIFG after left hemispherectomy. Relevance to the current work: This study concluded that right hemisphere activation following left temporal lobe injury was not simply present in homologous anatomical regions of the left hemisphere. The current work sought to define areas of right hemisphere activation for language tasks following left temporal lobe removal. Level of evidence: Level IIIa.


**Objective:** The purpose of this review was to provide a foundation for neuroimaging fundamentals for neurorehabilitation specialists and to examine the progress in using neuroimaging techniques such as MRI analysis, DTI and fMRI to understand patients with neurologic damage. **Conclusions:** Advances in neuroimaging techniques have allowed for a greater understanding of the neuronal connections inside the brain. Through advances in DTI, it is possible to reconstruct white matter fiber tracts and evaluate their integrity. Thus, it is possible to view which anatomical areas may be affected due to a lack of white matter connectivity. Anatomical areas of the brain that were not directly damaged may be affected due to a loss of connectivity. As these neuroimaging techniques become more common and more advanced it may be possible for rehabilitation specialists to use the neuroimaging data to make predictions about prognosis and rehabilitation strategies for patients with brain damage. Relevance to the current work: This review affirms importance of neuroimaging development in the rehabilitation of future TBI patient similar to TB. Level of evidence: Level IV.