Published in final edited form as:

Neurosurgery. 2008 September ; 63(3): 487–497. doi:10.1227/01.NEU.0000324725.84854.04.

Language reorganization in aphasics:

An electrical stimulation mapping investigation

Timothy H. Lucas II, M.D.^{1,2}, Daniel L. Drane, Ph.D.^{1,3}, Carl B. Dodrill, Ph.D.^{1,3}, and George A. Ojemann, M.D.¹

¹Department of Neurological Surgery, University of Washington, Seattle, Washington

²Department of Physiology and Biophysics, University of Washington, Seattle, Washington

³Department of Neurology and Regional Epilepsy Center, Harborview Medical Center, Seattle, Washington

Abstract

Objective—The purpose of this investigation was to determine whether clinical speech deficits following brain injury were associated with functional speech reorganization.

Methods—Across an 18 year interval, 11 patients with mild to moderate speech deficits underwent language mapping as part of their treatment for intractable epilepsy. These ‘aphasics’ were compared to 14 matched ‘controls’ with normal speech also undergoing epilepsy surgery. Neuroanatomical data were compared to quantitative language profiles and clinical variables.

Results—Cortical lesions were evident near speech areas in all aphasia cases. As expected, aphasics and controls were distinguished by quantitative language profiles. The groups were further distinguished by the anatomical distribution of their speech sites. A significantly higher proportion of frontal speech sites was found in patients with prior brain injury, consistent with frontal site recruitment. The degree of frontal recruitment varied as a function of patient age at the time of initial brain injury—earlier injuries were associated with greater recruitment. The overall number of speech sites remained the same following injury. Significant associations were found between the number of the speech sites, naming fluency and the lesion proximity in the temporal lobe.

Conclusions—Language maps in aphasics demonstrated evidence for age-dependent functional recruitment in the frontal, but not temporal, lobe. The proximity of cortical lesions to temporal speech sites predicted the overall extent of temporal lobe speech representation and performance on naming fluency. These findings have implications for neurosurgical planning in patients with preoperative speech deficits.

Keywords

language mapping; aphasia; plasticity; dominant hemisphere

INTRODUCTION

A clear understanding of the anatomical location of essential speech sites is critical if one is to confidently avoid postoperative speech deficits when performing dominant hemisphere

Address correspondence and reprint requests to THL at the following address: Department of Physiology & Biophysics, and Neurological Surgery Box 357290 University of Washington Seattle, WA 98195 E-mail: tlucas@u.washington.edu (*preferred*) Direct: (206) 422-1379 Office: (206) 543-3570 Fax: (206) 543-8315.

Financial Disclosure

There are no conflicting financial incentives associated with this investigation.

surgery. Electrical stimulation mapping has become a standard technique to identify those sites in individual patients. Using this technique, the organization of speech sites has been well-characterized in adults(40) and children.(43) However, little is known about how language organization is affected by damage to eloquent speech areas.(5,30,54) Such information is valuable for neurosurgeons who encounter patients with preoperative language deficits.

Recent functional imaging and electrophysiological studies suggest that language organization is altered in response to lesions that damage speech areas in adults. Taken as evidence for functional reorganization, cortical language activity may increase locally around the lesion periphery,(32) or may shift to more distant areas in the frontal(12,50,51) or temporal lobes. (1) In addition to the location of language-related cortical activity, the temporal patterns of electrographic language activity also changed in response to lesions.(20,26,49) Such functional changes have been attributed to treatment during the recovery phase of aphasia(13) and may portend a better prognosis.(28) These findings are reminiscent of the functional reorganization seen after injury to the central nervous system in a number of animal models.(3,4,8,21,33,34, 37-39,58)

The present investigation sought to compare speech organization between patients with, and without, preoperative speech deficits. To the best of our knowledge, this is the first published series comparing stimulation mapping between patients with preoperative speech deficits and those with normal speech. We report findings which are consistent with theories of functional reorganization in the frontal lobe following cortical damage. We found no evidence of functional reorganization in the temporal lobe, despite the fact that all patients had some degree of temporal lobe damage. Significant relationships were found in the temporal lobe between the number of the speech sites, naming fluency and the proximity of the cortical lesion, however. These findings have important implications for those who study the functional organization of the dominant hemisphere and are discussed in light of cerebral plasticity literature.

MATERIALS AND METHODS

Subjects

The study population in this investigation consisted of a series of patients presenting with clinical language deficits between January 1, 1985 and December 31, 2003. All patients in this series underwent surgical procedures for the treatment of epilepsy or lesions associated with seizures. Patients with obvious language deficits documented during preoperative neurological examination performed by the senior author (GAO) were considered 'aphasic.' The majority of patients demonstrated expressive aphasia symptoms, although patients varied in the degree and type of specific language deficits. To be enrolled in this investigation, the following inclusion criteria were applied: (1) patients must have been free from pre-existing language deficits prior to a defined neurological insult; (2) the timing and type of neurological insult must have been documented; (3) patients must have completed comprehensive preoperative neuropsychological evaluations, including quantitative language assessments; (4) patients must have sufficient language function to permit reliable intraoperative language mapping (i.e. a confrontational naming baseline performance rate of greater than 70 percent). Patients who did not meet these criteria were excluded.

The aphasic population was compared to a 'control' population matched on operative age, gender, language dominance and side of surgery. In all cases, the operative indication was medically intractable epilepsy secondary to mesial temporal lobe sclerosis. Control patients demonstrated no evidence of preoperative language deficits, nor were cortical lesions present on preoperative imaging. University of Washington Human Subjects Division approved Confidentiality Agreements for the use of clinical data presented in this research investigation.

Neuropsychological Testing

As part of the preoperative evaluation for epilepsy surgery at the University of Washington, patients undergo formal neuropsychological evaluations performed by licensed academic neuropsychologists (D.L.D., C.B.D.). Patients undergo a thorough, well-validated battery of neuropsychological measures. For the purposes of this study, we were most interested in tests tapping general intellectual functioning and language performance. General intellectual functioning was assessed using the Wechsler Adult Intelligence Scale (WAIS or WAIS-III). (55,56) Language assessment included the Aphasia Screening Test from the Halstead-Reitan Neuropsychological Battery(27), the Controlled Oral Word Association Test (COWA),(7) and a standard semantic fluency paradigm (i.e. Animal Naming).(6,48) The Aphasia Screening Test is purported to be the most widely used of the aphasia tests,(48) and includes a range of test items chosen to reflect most basic language functions. The COWA and the animal naming task represent measures of generative verbal fluency. The COWA is a letter fluency task that requires the patient to state as many words as possible beginning with a given letter of the alphabet in a specified time period (i.e., 3 one-minute trials with different letters). The animal naming task is a semantic fluency paradigm requiring the patient to generate exemplars of a specified category within an allotted time span. Performance below published normative ranges signals the presence of a language disturbance. These tests were used to confirm the clinical suspicion of language deficits.

Electrical Stimulation Mapping

Mapping of speech cortex was performed extraoperatively with subdural grids, or intraoperatively during awake craniotomy. The standardized confrontation naming task was identical in both instances. All aphasic patients (100%) and eight of fourteen control patients (57%) underwent extraoperative mapping. Extraoperative mapping consisted of first identifying Rolandic cortex, followed by language mapping. During language mapping, the threshold for afterdischarges was determined for each electrode pair (separated by 1 cm) and stimulus intensities were adjusted to the maximal intensity that did not produce afterdischarges. These currents typically ranged from 1.5 to 10 mA,(41) for both extraoperative and intraoperative mapping techniques. Stimulation consisted of 2.5 ms biphasic square-wave pulses in 4 s trains at a frequency of 60 Hz. For extraoperative mapping, standard 64-contact electrode grid (**1 cm inter-electrode distance**) centered on the sylvian fissure covered areas of suspected language sites and seizure onsets. Electrode selection commenced in pseudo-random order, provided that each contact was stimulated at least once before any individual contact was stimulated a second time, and provided that no two adjacent sites were stimulated back-to-back. This was done to minimize the effects of stimulating the same cortical area multiple times in succession. All stimulated contacts were within the limits of the craniotomy. The location of speech sites were documented and labeled at the time of grid removal with sterile numbered markers. The location of these sites was then photographed.

Six of fourteen control patients (43%) underwent intraoperative mapping. The intraoperative stimulation mapping technique for the localization of essential language cortices has been described in detail previously.(40,42) Briefly, initial anesthesia (Propofol) was administered to allow a large fronto-temporo-parietal craniotomy to be fashioned. Local analgesics (0.5% lidocaine and 0.25% marcaine) were applied along the scalp and dural incisions for patient comfort upon waking. Once the cortex was exposed, anesthesia was discontinued and the patient was allowed to awaken fully. No other medications were administered until after stimulation mapping, which was usually performed 3-4 hours after the operation was begun. Rolandic cortex was identified by stimulation and the threshold for afterdischarges was established with electrocorticography. Language mapping followed in the exposed cortex. Sites for stimulation were selected to sample the full extent of the cortical exposure in approximately 1 cm intervals and labeled with sterile numbered tags. Sites were stimulated in

pseudo-random fashion as with extraoperative mapping. Stimulation was delivered from a constant-current stimulator with 1 mm ball-tip bipolar electrodes separated by 5 mm. Four second trains were applied using the largest current that did not evoke afterdischarges. The stimulation sites, averaging 22.8 ± 9.9 sites per patient, were identified with sterile numbered markers and the location of these markers was recorded photographically.

The language paradigm consisted of the standard confrontation object naming paradigm.⁽⁴⁰⁾ Two separate raters recorded the patients' responses on score sheets. In addition, patient responses were recorded on audiotape. Errors consisted of anomie episodes, production of nonsense words, and use of incorrect object names (e.g. using the word 'fork' to name a 'spoon'). Baseline error rates for each patient were calculated during non-stimulation trials from the ratio of incorrect to total responses. Each stimulation site was tested at least three times during baseline and test conditions, although all sites were tested at least once before repeating any individual site, and no site was tested twice in succession. To make statistical inferences reliable, patients had to demonstrate at least 70 percent accuracy during baseline testing. Baseline error rates were statistically compared to the stimulation-induced error rate for each anatomic site using Fisher's Exact Test. Fisher's Exact Test was chosen because it makes no assumptions about the expected proportion of correct or incorrect responses. Chi square test was used to compare group and lobe differences. Essential speech sites were those where electrical stimulation produced reliable, statistically significant, differences in error rate during confrontational naming when compared to that patient's baseline naming performance. Objects which could not be named during any trial (including at least three baseline trials) were omitted from analysis.

Data Analysis

All patient data were coded with a four digit patient number. A third, blinded investigator reviewed each audiotape and verified score sheet accuracy, without knowledge of preoperative language abilities. Stimulation mapping data and neuropsychological scores were then collated into a common spreadsheet. Statistical analyses were performed using SPSS (SPSS Inc., Chicago, IL). Sites statistically associated with stimulation-induced errors were then identified on intraoperative photographs. The location of these sites was anatomically categorized on the basis of their relationship to the major hemispheric fissures and veins. When obvious cortical lesions were evident, the relationship between the nearest lesion margin and the closest essential language site was measured.

RESULTS

Patient Demographics

Aphasic and control populations were matched on clinical demographics (Table 1). Eighteen patients were retrospectively identified with preoperative language deficits. Of these, 11 satisfied the inclusion criteria outlined above. Seven patients performed below the minimum necessary to undergo reliable language mapping (i.e. greater than 30% error rate on object naming). The study group thus consisted of 8 male and 3 female, originally right handed patients. The mean age at time of operation was 35 ± 7 years. Aphasic patients suffered a variety of speech deficits (Table 2). Four of the eleven exhibited purely expressive aphasia, characterized by impaired speech fluency and naming deficits with intact comprehension. Two of these patients retained some repetition capability (see Table 2, *). Two patients experienced deficits in naming and milder deficits in generative fluency tasks and preserved repetition. These were considered anomie aphasias. Five patients exhibited deficits in semantic fluency, naming, rate of speech. Two of these patients also suffered from deficits in articulation and literacy skills (see Table 2, dysphasia/dysfluency). The control group consisted of 14 patients (4 male, 10 female) with a mean age of 35 ± 10 years. Twelve of the controls were right handed

and two were left handed. All patients were left hemisphere dominant for speech as assessed by sodium amobarbital testing. Mean symptom onset (i.e. age at time of brain insult), duration of illness, age at operation and education are presented in Table 1. For consistency across patients, symptom onset and illness duration data were gathered with respect to clinical seizures. It must be noted, however, that speech deficits were present immediately following brain injury. No patient experienced new speech deficits following surgery. There were no significant differences between the aphasia group and matched control group for the above variables.

Cortical lesions were evident intraoperatively in all aphasia cases during left hemisphere craniotomy (Fig. 1). Scalp and subdural recordings demonstrated that seizure foci were associated with cortical lesions in all cases. Lesions associated with speech disturbances included the following: focal contusions (e.g. following traumatic brain injury) in eight cases (73%), astrocytoma in one case (9%), subarachnoid hemorrhage with focal cerebrovascular accident in one case (9%), and penetrating injury in one case (9%). The lesion location was classified by lobe of involvement. The temporal lobe was involved in every instance (100%). Six of the 11 aphasics (55%) demonstrated isolated temporal lobe lesions, two cases demonstrated fronto-temporal lesions (18%) and the remaining three cases (27%) demonstrated fronto-temporo-parietal lesions. The control group had no apparent cortical lesions intraoperatively.

Quantitative Speech Differences

Aphasic and control patients were distinguished by language performance. Aphasics demonstrated objective speech deficits on a battery of sensitive language tests, including the VIQ, FIQ, the Aphasia Screening Battery, COWA and Animal naming (Fig. 2). For individual patients, performance across these tests was significantly inter-correlated (Table 3). For example, VIQ scores and COWA scores were significantly related (bivariate Pearson correlation coefficient $r = 0.58$, $p < 0.002$). While 'aphasic' patients demonstrated objective language deficits, these deficits were mild-to-moderate in severity, and were not so severe as to preclude intraoperative language mapping. As described in the Methods, patients must have achieved at least 70 percent baseline naming accuracy during intraoperative testing to make statistical inferences for determining essential speech sites reliable.

Aphasics demonstrated objective speech deficits during intraoperative confrontation naming. Intraoperative naming proficiency was assessed by first determining the baseline performance during confrontational naming. Both aphasics and controls performed well on this simple language task, achieving mean scores greater than 95%. Nevertheless, controls significantly out-performed aphasics ($99.2 \pm 1.2\%$ versus $96.0 \pm 4.3\%$, $t = -2.577$, $p = 0.018$). Intraoperative naming performance was highly correlated with VIQ ($r = 0.56$, $p < 0.005$), FIQ ($r = 0.42$, $p < 0.05$), the Aphasia Screening Battery ($r = -0.59$, $p < 0.005$), COWA ($r = 0.47$, $p < 0.05$) and Animal Naming ($r = 0.53$, $p < 0.01$). Performance on all of these tests was independent of such clinical variables as the duration of illness, age of symptom onset, and age at time of surgery for both groups.

Differences in Cortical Speech Representation

The cortical distribution of speech sites distinguished aphasic patients from matched controls. Essential speech sites were significantly redistributed in aphasics, with proportionally more frontal lobe, and fewer temporal lobe, sites than matched controls. In the aphasic group, 19 out of 47 essential language sites (40%) were found in the temporal lobe, whereas, in the control group, 35 of 45 essential language sites (76%) were found in the temporal lobe ($\chi^2 = 11.618$, $p < 0.001$). Aphasics had proportionally more frontal lobe sites than controls (21/47 versus 11/45, respectively; $\chi^2 = 4.15$, $p < 0.05$; Fig. 3). These additional frontal lobe sites were

observed dorsal to the frontal operculum, predominantly occurring along the superior border of the inferior frontal gyrus, as well as along the middle frontal gyrus. This redistribution of speech sites was independent of frontal lobe lesion involvement. Aphasics with lesions involving the frontal lobe averaged 2.2 ± 1 frontal sites and 2.2 ± 1.5 temporal sites, while aphasics without frontal lobe lesion involvement averaged 1.7 ± 2.4 frontal and 1.3 ± 1.5 temporal lobe sites ($p = \text{ns}$). Of note, the **overall** number of essential sites found in aphasics and controls was the same despite the reorganization of sites in aphasics (**47 versus 45, respectively**). This suggests that the overall extent of dominant hemisphere speech representation remained constant. Aphasics averaged 4.3 ± 2.6 language sites per patient, while controls averaged 3.4 ± 3.1 sites ($t = 0.734$, ns). Hence, cortical lesions near eloquent speech cortex which produce clinical speech deficits were associated with a redistribution of essential speech sites favoring the frontal lobe.

The redistribution of frontal speech sites varied as a function of the age of the patient at the time of the initial brain insult. The observed number of frontal lobe sites was inversely related to the age of symptom onset ($r = -0.71$, $p = 0.014$). Figure 4A illustrates the linear association between age of brain insult and the number of frontal lobe sites. Aphasic patients with “early” insults had more frontal speech sites than those with “late” insults (3.5 ± 1.9 versus 1.0 ± 1.2 , respectively; $t = 2.745$, $p = 0.02$; Fig. 4B). The number of frontal lobe sites was also inversely related to the age of the patient at the time of surgery ($r = -0.68$, $p = 0.021$). The number of frontal sites was independent of the duration of illness. Identical analyses were run on temporal lobe speech sites and failed to reveal any associations between the number of sites and the age of brain insult, age at time of surgery, or duration of illness. Control patients, who had no history of speech disturbances, demonstrated no significant relationships relating speech sites and clinical variables.

Lesion Proximity to Speech Cortex Predicts the Number of Essential Speech Sites in the Temporal Lobe

The distance between the cortical lesion and the nearest temporal language site was measured using intraoperative photographs. Essential language sites were located on average 1.1 ± 1 cm from the lesion margin (range 0.1 to 2.5 cm). Eighty two percent (9/11) of aphasic patients had a language site within 2 cm of the lesion margin. At least one speech site was within 2.5 cm of the lesion margin in every case. Interestingly, the distance between the lesion and the nearest language site was negatively correlated with the number of temporal lobe sites ($r = -0.642$, $p < 0.05$). No relation was found between this distance and the number of frontal lobe sites language sites ($p = \text{ns}$), or the overall number of sites ($p = \text{ns}$).

To characterize this relationship further, patients were categorized into three groups on the basis of lesion proximity. The ‘adjacent’ group consisted of patients with a speech site located within 1 cm of the lesion ($n=5$). The ‘near’ group consisted of patients with a speech site between 1 cm and 1.5 cm from the lesion ($n=2$). This distance corresponds to the outer limit of the depolarization effects of electrical stimulation used to induce transient anomia during language mapping.(25,40) The ‘remote’ group consisted of patients with a speech site farther than 1.5 cm from the lesion ($n=4$). Analyses of variance were completed to explore possible group differences on neuroanatomical and neuropsychological data.

Considering neuroanatomical variables first, the number of temporal lobe sites was significantly different among the three groups (ANOVA $F_{2,10} = 7.161$, $p = 0.01$). The ‘adjacent’ and ‘near’ groups had a significantly greater number of temporal lobe speech sites than the ‘remote’ patients (Bonferroni post hoc tests ‘adjacent’ verses ‘remote’, $p = 0.03$; ‘near’ verses ‘remote’, $p = 0.04$; *a priori* contrast ‘adjacent’ and ‘near’ verses to ‘remote’, $p = 0.005$). ‘Adjacent’ and ‘near’ patients were not significantly different from each other. ‘Remote’ patients consisted of patients whose lesions were farther than 1.5 cm from the nearest speech

site. These data, therefore, suggest that fewer temporal lobe sites are found in patients whose sites are more than 1.5 cm from a focal cortical lesion (Fig. 5). Patients with at least 1.5 cm of separation between the lesion and language sites had 0.25 ± 0.5 temporal lobe sites ($n=4$), while those with less than 1.5 cm of separation had 2.6 ± 1.1 temporal lobe sites ($n=7$; $t=3.819$, $p=0.004$). There were no differences between these groups in the number of frontal lobe sites or overall number of sites.

Considering neuropsychological variables, naming fluency was significantly different among the three groups. Patients in the 'near' group out-performed other patients on naming fluency (ANOVA $F_{2,10}=8.960$, $p=0.009$; *a priori* contrast 'near' versus 'adjacent' and 'remote', $p=0.006$; Fig. 6). Post-hoc Bonferroni tests also revealed significantly worse performance in the 'adjacent' group compared to the 'near' group ($p=0.009$). The 'adjacent' and 'remote' groups did not significantly differ on naming fluency performance. These findings suggest that aphasic patients perform better on naming fluency when their lesion is near (i.e. 1 – 1.5 cm) speech sites, than when the lesion is either immediately adjacent to, or apparently quite distant from, speech areas. A possible explanation for the neuroanatomical and neuropsychological findings is discussed below.

DISCUSSION

The purpose of this investigation was to determine whether clinical speech deficits following brain injury were associated with functional speech reorganization. Such information is valuable for neurosurgeons who encounter patients with language deficits in preoperative consultation. To answer this question, we compared intraoperative language maps between epilepsy patients with, and without, preoperative speech deficits. The major findings in this investigation were the following: (1) insults to eloquent speech areas altered the distribution of speech sites by increasing frontal lobe— but not temporal lobe—speech representation; (2) this functional reorganization of the frontal lobe varied as a function of the age of the patient at the time of initial brain insult; and (3) the proximity of the lesion to the temporal lobe speech areas predicted both patient performance on generative naming fluency, as well as the number of temporal lobe speech sites found during mapping.

Lesion-Induced Differences in Cortical Speech Representation: The Frontal Lobe

Frontal lobe speech representation expanded into the superior border of the inferior frontal gyrus and middle frontal gyrus following injury to eloquent speech areas. This finding supports the hypothesis that the frontal lobe retains the ability to functionally adapt to eloquent cortex injury into early adulthood. Several potential models of functional reorganization could explain these findings. First, the appearance of reorganized frontal speech areas may reflect unmasking (15) of diffuse language networks. Damage to an essential language node in this model would result in a shift of the functional load of speech processing to portions of the network previously involved in, but not *essential* for, speech. These unmasked nodes would then become apparent at the time of language mapping. Alternatively, this functional reorganization of frontal speech areas may signify recruitment of areas not previously involved in speech processing. Such functional reshaping has been described following glioma resections in eloquent cortex.(16) Finally, behavioral adaptation, such as the use of alternative linguistic strategies to compensate for speech deficits, could engage alternate cortical pathways which emerge as new speech nodes. While the data collected here support the capacity for frontal lobe functional reorganization, the data do not establish a definitive mechanism of plasticity.

Convergent lines of evidence support the ability of the adult brain to undergo functional reorganization. Evidence from functional imaging studies, including positron emission tomography and functional magnetic resonance imaging, demonstrates reorganization of linguistic functions within the left hemisphere following brain injury. (5,30,54) For example,

frontal lobe lesions alter language activity patterns, resulting in recruitment of additional frontal (12,50,51) and temporal(1) language representation. Electrophysiological evidence of spatial and temporal reorganization occurs during aphasics' recovery from brain injury.(20,26,49) Functional reorganization is seen in amputees with phantom limb pain(19) and focal hand dystonia(17). String instrument musicians, with expert use of their fingers, demonstrate functional reorganization of somatosensory cortices(18).

The potential for functional reorganization has also been convincingly demonstrated in animal models. Cortical reorganization occurs in primates following lesions(58), including focal infarcts(37,39) and sensory deafferentation(21,33,34). Cortical plasticity in the mature brain also occurs in response to advanced behavioral training(3,4,8,38). The capacity of the central nervous system for plastic adaptation, to at least a limited extent, has been demonstrated in both human and animal studies.

Extent of Frontal Lobe Recruitment Is a Function of the Age of Brain Injury

The degree of frontal lobe recruitment varied as a function of the age of the patient at the time of brain insult. Brain damage at earlier ages was associated with the development of significantly more frontal lobe sites. Meanwhile, the duration of patient illness did not influence the degree of frontal lobe recruitment. This suggests that the capacity of the frontal lobe to functionally reorganize may decline with age.

This finding is consistent with other investigations of brain plasticity. The degree of recovery of function following damage to the central nervous system is dependent upon the age of the individual when the lesion is acquired.(11) Coined the 'Kennard effect,'(31) the developing brain has a greater capacity for plasticity than the adult state. This plasticity is confirmed in studies of children who undergo hemispherectomy for intractable epilepsy.(53,57) Children undergoing resection early in life manifest marked functional recovery following surgery when compared to those undergoing resection at an older age.(10,29,35,52,57)

Differences in the rate of maturation of white matter provide one possible explanation for functional adaptation in the frontal lobe, but not the temporal lobe. The average age of brain injury in this population was 24 years old, with the youngest occurring at 9 years of age. It is well described that white matter maturation continues into early adulthood, particularly in the frontal regions.(14,22,44,46) Regional differences in myelination rates may underlie the development of different cognitive functions,(36) as well as regional differences in the response to insult. For instance, working memory performance is strongly associated with white matter development in the superior and inferior left frontal lobe.(36) Similarly, measures of brain growth and cortical gray matter density suggest persistent growth in the frontal lobe, but not temporal lobe, through early adulthood(47). Taken together, these factors suggest that regional differences in brain maturation occur into early adulthood and may explain regional differences in functional adaptation to focal insult found here. Further study in this area is clearly warranted.

Lesion-Induced Differences in Cortical Speech Representation: The Temporal Lobe

Unlike the frontal lobe, temporal lobe speech representation was reduced following injury to eloquent language areas. This is perhaps not surprising given that each of the cortical lesions in this series involved the temporal lobe. Within the temporal lobe, lesions were highly variable in both location and size. This is consistent with other reports of highly variable lesions which result in speech deficits.(2) In fact, aphasic syndromes may result from lesions which spare perisylvian areas.(2) This, too, is not surprising, given that the location of essential speech areas is highly variable, and may occur at locations distant from the classical language areas.(40)

Lesion Proximity Predicts Temporal Lobe Sites and Naming Fluency

A relationship was observed between the organization of speech centers and the proximity of the lesion in the temporal lobe. Using the number of essential speech areas as a measure of the extent of speech representation, we found an inverse relationship between the extent of temporal lobe speech representation and the proximity of the lesion. Temporal lobe speech representation was maximal when the lesion was located ‘adjacent’ or ‘near’ to speech areas (i.e. within 1.5 cm). Conversely, when the lesion was ‘remote’ (i.e. greater than 1.5 cm), the temporal lobe speech representation was diminished. Stratifying patients based on the lesion’s proximity to speech sites confirmed this observation; A significant reduction in the number of temporal lobe sites was found when the lesion was farther than 1.5 cm from speech centers ($p = 0.004$). Lesion proximity modulates the extent of temporal lobe speech representation.

Stratifying patients by lesion proximity also revealed significant differences in naming fluency across the groups. In this analysis, one might hypothesize that naming fluency would improve as the distance between the cortical lesion and nearest speech center increased. As expected, patients with ‘adjacent’ lesions performed worse than those with lesions ‘near’ speech areas. Unexpectedly, however, patients with ‘remote’ lesions performed as poorly as patients with ‘adjacent’ lesions (Fig. 6), with no significant difference between ‘adjacent’ and ‘remote’ performance. Lesion proximity modulates naming fluency.

It is easy to understand how a lesion immediately adjacent to speech sites might disrupt naming abilities. It is perhaps less obvious how lesions that are apparently quite distant from speech areas might disrupt naming abilities.

To answer this question, and reconcile the finding of modulated speech site representation described above, consider the following illustration (Fig. 7). Three potential lesion locations are considered against the background of a typical pattern of temporal lobe speech representation. Lesion proximity is measured as the distance between the lesion and the closest essential speech site (the black circles). In panel A, a lesion occurs in very close proximity (i.e. ‘adjacent’) to a temporal lobe speech site without destroying it. In this case, it is easy to see how significant speech symptoms might result from the lesion’s encroachment upon an essential speech site. Note that the total number of temporal lobe sites remains unchanged (i.e., 3). In panel B, the lesion occurs at a moderate distance from a speech site (i.e. ‘near’). This lesion might produce subtle speech symptoms by encroaching upon the outer limits of the functional radius of a speech site, which is known to be approximately 1–1.5 cm.^(23-25,40) In this case, the number of sites also remains unchanged (i.e., 3). In panel C, the lesion completely destroys the speech site, leaving no functional evidence of its preexisting location. The nearest speech site is seemingly far from the lesion (i.e. ‘remote’). In this instance, speech symptoms obviously result from the destruction of the speech site. When one tallies the remaining temporal lobe sites, the number has decreased to *two*. Hence, the apparent extent of temporal lobe speech representation has decreased. Considering all three examples together, the number of temporal lobe sites is an inverse function of the distance between the lesion and the nearest speech site, thus mirroring the results documented in our patient sample.

Further support for this model comes from the neuropsychological data. The model predicts that patients with a speech site which has been destroyed would perform poorly (cf. group C). Similarly, those with a lesion immediately adjacent to, but not destroying, a speech site would also perform poorly (cf. group A). However, patients with lesions along the outer functional limits of a speech site would perform comparatively better than the other two groups as all speech sites are relatively preserved (cf. group B). The result predicted by this model is precisely what was found in our sample (Fig. 7). The model parsimoniously accounts for the relationships between both the anatomical data and the behavioral data presented here. It serves

as a testable hypothesis against which data from other brain mapping techniques, such as functional imaging, may be compared.

A final word must be said regarding functional reorganization. The degree to which spatial reorganization of speech areas is associated with clinical improvement remains unclear. Most studies have focused on changes in perilesional activation. Some report a correlation between clinical improvement and the magnitude of perilesional language activity.(32) Such activity has been associated with treatment-induced adaptation.(13) Additionally, favorable outcome have been related to re-activation of perilesional areas in longitudinal studies of aphasics.(28) Yet, it remains undetermined whether perilesional activity represents focal reorganization, functional sparing, or restoration of typical activity patterns.(45) Our findings suggest the presence of reorganization in frontal areas in response to lesions involving the dominant temporal lobe.

LIMITATIONS

Several important factors must be considered when analyzing these results. First, this investigation was structured to address the practical clinical question, are speech deficits following brain injury associated with functional speech reorganization in a neurosurgical population? Our purpose was not to strictly identify the neuroanatomical correlates of specific aphasic syndromes, nor was it to compare patients with isolated frontal lesions versus those with isolated temporal lesions. This limited study population is heterogeneous in lesion etiology, focus, and magnitude of speech deficits. In this regard, this population mirrors clinical neurosurgical practice populations. Second, the aphasics studied here suffered mild-to-moderate speech deficits; severe speech deficits preclude language mapping and are not included in this investigation. Third, nature of electrical stimulation mapping only allows for data to be collected during a brief period of time in the course of the patient's disease. These data are cross-sectional. The relationship between the presence of eloquent cortex lesions and altered speech maps must therefore infer causality. Inferences about causality are indirect and must be interpreted with caution. Finally, every attempt was made to map the full extent of cortex exposed through large fronto-temporo-parietal craniotomies. The possibility that additional sites were located beyond the limits of the craniotomy, or in the opposite hemisphere, cannot be ruled out in these investigations. Future investigations should include functional mapping methods, such as functional magnetic resonance imaging, as other investigators have noted contralateral language activation in stroke (50) and tumor populations. (9)

CONCLUSION

The purpose of this investigation was to determine whether clinical speech deficits following brain damage were associated with functional speech reorganization. We found evidence for function reorganization in the frontal lobe, but not the temporal lobe. This reorganization varies as a function of the age of the patient at the time of brain injury. In the temporal lobe, the spatial relationship between the lesion and speech areas predicts naming fluency and the number of temporal lobe speech areas found. We offer an anatomical model to explain these findings. Collectively, these findings are important for planning neurosurgical resections in patients with preoperative speech deficits. Particular care should be applied to identify speech areas in these patients.

Acknowledgments

This work was supported by NIH grants NS 36527 and EB 02663 (G.A.O.), McDonnell-Pew Cognitive Neuroscience Grant (G.A.O.), and Institutional National Research Service Award PA-02-109 (T.H.L.). We wish to acknowledge Ettore Lettich, R.E.E.G.T., for his help with the data collection and retrieval.

REFERENCES

1. Angrilli A, Elbert T, Cusumano S, Stegagno L, Rockstroh B. Temporal dynamics of linguistic processes are reorganized in aphasics' cortex: an EEG mapping study. *NeuroImage* 2003;20:657–666. [PubMed: 14568442]
2. Bang OY, Heo KG, Kwak YT, Lee PH, Joo IS, Huh K. Global aphasia without hemiparesis: lesion analysis and its mechanism in 11 Korean patients. *J Neurological Sciences* 2004;217:101–6.
3. Bao S, Chang EF, Davis JD, Gobeske KT, Merzenich MM. Progressive degradation and subsequent refinement of acoustic representations in the adult auditory cortex. *J Neurosci* 2003;23(34):10765–75. [PubMed: 14645468]
4. Beitel RE, Schreiner CE, Cheung SW, Wang X, Merzenich MM. Reward-dependent plasticity in the primary auditory cortex of adult monkeys trained to discriminate temporally modulated signals. *PNAS* 2003;100(19):11070–5. [PubMed: 12941865]
5. Belin P, VanEeckhout P, Zilbovicious M, Remy P, Francois C, Guillaume S, Chain F, Rancurel G, Samson Y. Recovery from non-fluent aphasia after melodic intonation therapy. *Neurology* 1996;47:1504–11. [PubMed: 8960735]
6. Benson, DF.; Ardila, A. Aphasia: A clinical perspective. Oxford University Press; NY: 1996.
7. Benton, AL.; Hamsher, K.; Sivan, AB. Multilingual Aphasia Examination. AJA Associates; Iowa City, IA: 1983.
8. Blake DT, Strata F, Churchland AK, Merzenich MM. Neural correlates of instrumental learning in primary auditory cortex. *PNAS* 2002;99(15):10114–9. [PubMed: 12119383]
9. Cao Y, Vikngstad EM, George KP, Johnson AF, Welch KM. Cortical language activation in stroke patients recovering from aphasia with functional MRI. *Stroke* 1999;30:2331–40. [PubMed: 10548667]
10. Chugani HC, Shewmon D, Peacock W, Shields W, Mazziotta J, Phelps M. Surgical treatment of intractable neonatal-onset seizures: the role of positron emission tomography. *Neurology* 1988;38:1178–88. [PubMed: 3261000]
11. Chugani HT, Muller R-A, Chugani DC. Functional brain reorganization in children. *Brain and Development* 1996;18:347–356. [PubMed: 8891228]
12. Cohen R, Döbel C, Berg P, Koebbel P, Schonle PW, Rockstroh B. Event-related potential correlates of verbal and pictorial feature comparison in aphasics and controls. *Neuropsychologia* 2001;39(5):489–501. [PubMed: 11254931]
13. Cornelissen K, Laine M, Tarkiainen A, Jarvinsivu T, Martin N, Salmelin R. Adult brain plasticity elicited by anomia treatment. *J Cogn Neurosci* 2003;15(3):444–61. [PubMed: 12729495]
14. De Bellis MD, Keshavan MS, Beers SR, Hall J, Frustaci K, Masalehdan A, Noll J, Boring AM. Sex differences in brain maturation during childhood and adolescence. *Cereb Cortex* 2001;11:552–557. [PubMed: 11375916]
15. Duffau H. Acute functional reorganization of the human motor cortex during resection of central lesions: a study using intraoperative brain mapping. *J Neurol Neurosurg Psychiatry* 2001;70:506–513. [PubMed: 11254775]
16. Duffau H, Denvil D, Capelle L. Long term reshaping of language, sensory and motor maps after glioma resection: a new parameter to integrate in the surgical strategy. *J Neurol Neurosurg Psychiatry* 2002;72:511–16. [PubMed: 11909913]
17. Elbert T, Candia V, Altenmüller E, Rau H, Sterr A, Rockstroh B, Pantev C, Taub E. Alteration of digital representations in somatosensory cortex in focal hand dystonia. *Neuro Report* 1998;9:3571–3575.
18. Elbert T, Pantev C, Wienbruch C, Rockstroh B, Taub E. Increased cortical representation of the fingers of the left hand in string players. *Science* 1995;270:305–7. [PubMed: 7569982]
19. Flor H, Elbert T, Knecht S, Wienbruch C, Pantev C, Birbaumer N, Larbig W, Taub E. Phantom limb pain as a perceptual correlate of cortical reorganization following arm amputation. *Nature* 1995;375:482–4. [PubMed: 777055]
20. Friederici AD, Yves von Cramon D, Kotz SA. Language related brain potentials in patients with cortical and subcortical left hemisphere lesions. *Brain* 1999;122:1033–1047. [PubMed: 10356057]
21. Garraghty PE, Kaas JH. Large-scale functional reorganization in adult monkey cortex after peripheral nerve injury. *Proc Natl Acad Sci U S A* 1991;88(16):6976–80. [PubMed: 1871112]

22. Giedd JN, Blumenthal J, Jeffries NO, Castellanos FX, Liu H, Zijdenbos A, Pauls T, Evans AC, Rapoport JL. Brain development during childhood and adolescence: A longitudinal MRI study. *Nat Neurosci* 1999;2:861–863. [PubMed: 10491603]
23. Haglund M, Ojemann GA, Hochman D. Optical imaging of epileptiform and functional activity in human cerebral cortex. *Nature* 1992;358:668–671. [PubMed: 1495561]
24. Haglund MM, Berger MS, Shamseldin M, Lettich E, Ojemann GA. Cortical localization of temporal lobe language sites in patients with gliomas. *Neurosurgery* 1994;34(4):567–576. [PubMed: 7516498]
25. Haglund MM, Ojemann GA, Blasdel GG. Optical imaging of bipolar cortical stimulation. *J Neurosurg* 1993;78:785–793. [PubMed: 8468609]
26. Hagoort P, Brown CM, Swaab T. Lexical-semantic event-related potential effects in patients with left hemisphere lesions and aphasia, and patients with right hemisphere lesion without aphasia. *Brain* 1996;119:627–649. [PubMed: 8800953]
27. Halstead WC, Wepman JM. The Halstead-Wepman Aphasia Screening Test. *J Speech Lang Hear Res* 1959;14:9–15.
28. Heiss W-D, Karbe K, Weber-Luxemburger G, Herholz K, Kessler J, Pietrzak U, Pawlik G. Speech induced cerebral metabolic activation reflects recovery from aphasia. *J Neurol Sci* 1997;145(2):213–17. [PubMed: 9094051]
29. Hoffman HJ, Hendrick EB, Dennis M, Armstrong D. Hemispherectomy for Sturge-Weber syndrome. *Child's Nerv Sys* 1979;5:233–48j.
30. Karbe H, Thiel T, Weber-Luxemburger G, Herholz K, Kessler J, Heiss WD. Brain plasticity, in post-stroke aphasia: what is the contribution of the right hemisphere? *Brain Lang* 1998;64:215–230. [PubMed: 9710490]
31. Kennard MA. Reorganization of motor function in the cerebral cortex of monkeys deprived of motor and premotor areas in infancy. *J Neurophysiol* 1938;1:477–96.
32. Meinzer M, Elbert T, Wienbruch C, Djundja D, Barthel G, Rockstroh B. Intensive language training enhances brain plasticity in chronic aphasia. *BMC Biol* 2004;2(1):20. [PubMed: 15331014]
33. Merzenich MM, Kaas JH, Wall J, Nelson RJ, Sur M, Felleman D. Topographic reorganization of somatosensory cortical areas 3b and 1 in adult monkeys following restricted deafferentation. *Neuroscience* 1983;8(1):33–55. [PubMed: 6835522]
34. Merzenich MM, Kaas JH, Wall JT, Sur M, Nelson RJ, Felleman DJ. Progression of change following median nerve section in the cortical representation of the hand in areas 3b and 1 in adult owl and squirrel monkeys. *Neuroscience* 1983;10(3):639–65. [PubMed: 6646426]
35. Muller F, Kunesch E, Binkofski F, Freund HJ. Residual sensorimotor functions in a patient after right-sided hemispherectomy. *Neuropsychologia* 1991;29:125–45. [PubMed: 1902915]
36. Nagy Z, Westerberg H, Klingberg T. Maturation of white matter is associated with the development of cognitive functions during childhood. *J Cogn Neurosci* 2004;16(7):1227–1233. [PubMed: 15453975]
37. Nudo RJ, Milliken GW. Reorganization of movement representations in primary motor cortex following focal ischemic infarcts in adult squirrel monkeys. *J Neurophysiol* 1996;75(5):2144–9. [PubMed: 8734610]
38. Nudo RJ, Milliken GW, Jenkins WM, Merzenich MM. Use-dependent alterations of movement representations in primary motor cortex of adult squirrel monkeys. *J Neurosci* 1996;16(2):785–807. [PubMed: 8551360]
39. Nudo RJ, Wise BM, SiFuentes F, Milliken GW. Neural substrates for the effects of rehabilitative training on motor recovery after ischemic infarct. *Science* 1996;272(5269):1791–4. [PubMed: 8650578]
40. Ojemann G, Ojemann J, Lettich E, Berger M. Cortical language localization in left, dominant hemisphere. An electrical stimulation mapping investigation in 117 patients. *J Neurosurg* 1989;71(3):316–26. [PubMed: 2769383]
41. Ojemann GA. Cortical Organization of Language and Verbal Memory Based on Intraoperative Investigations. *Progress in Sensory Physiology* 1991;12:193–230.
42. Ojemann, GA. Awake operations with mapping in epilepsy. In: Schmidek, HH.; Sweet, WH., editors. *Operative Neurosurgical Techniques*. W.B. Saunders Co.; Philadelphia: 1995. p. 1317-1322.

43. Ojemann SG, Berger MS, Lettich E, Ojemann GA. Localization of language function in children: results of electrical stimulation mapping. *J Neurosurg* 2003;98(3):465–70. [PubMed: 12650415]
44. Reinis, S.; Goldman, JM. The development of the brain: Biological and functional perspectives. C. Thomas; Springfield: 1980. p. 400
45. Rosen HJ, Petersen SE, Lineweber MR, Synder AZ, White A, Chapman L, Dromerick AW, Fiez JA, Corbetta M. Neural correlates of recovery from aphasia after damage to left inferior frontal cortex. *Neurology* 2000;55(12)
46. Schmithorst VJ, Wilke M, Dardzinski BJ, Holland SK. Correlation of white matter diffusivity and anisotropy with age during childhood and adolescence: A cross-sectional diffusion-tensor MR imaging study. *Radiology* 2002;222:212–218. [PubMed: 11756728]
47. Sowell ER, Thompson PM, Tessner KD, Toga AW. Mapping continued brain growth and gray matter density reduction in dorsal frontal cortex: Inverse relationships during postadolescent brain maturation. *J Neurosci* 2001;21(22):8819–8829. [PubMed: 11698594]
48. Spreen, O.; Strauss, EH. A compendium of neuropsychological tests. Vol. Second. Oxford University Press; NY: 1998.
49. Swaab T, Brown CM, Hagoort P. Spoken sentence comprehension in aphasia: event-related potential evidence from a lexical integration deficit. *J Cogn Neurosci* 1997;9:39–66.
50. Thiel T, Herholtz K, Koyuncu A, Ghaemi M, Kracht LW, Habedank B, Heiss W-D. Plasticity of language networks in patients with brain tumors: a positron emission tomography activation study. *Ann Neurol* 2001;50(5):620–9. [PubMed: 11706968]
51. Thomas CG, Altenmüller E, Marckmann G, Kahres J, Dichgans J. Language processing in aphasia: changes in lateralization patterns during recovery reflect cerebral plasticity in adults. *Electroencephalogr Clin Neurophysiol* 1997;102:86–97. [PubMed: 9060859]
52. Tinuper P, Andermann F, Villemure JG, Rasmussen T, Quesney LF. Functional hemispherectomy for treatment of epilepsy associated with hemiplegia: Rationale, indications, results and comparison with callosotomy. *Ann Neurol* 1988;24:27–34. [PubMed: 3137858]
53. Verity CM, Strauss EH, Moyes PD, Wada JA, Dunn HG, Lapointe JS. Long-term follow-up after cerebral hemispherectomy: neurophysiologic, radiologic, and psychological findings. *Neurology* 1982;32(6):629–39. [PubMed: 7201093]
54. Warburton E, Price CJ, Swinburn K, Wise RJ. Mechanisms of recovery from aphasia: evidence from positron emission tomography studies. *J Neurol Neurosurg Psychiatry* 1999;66:155–161. [PubMed: 10071093]
55. Wechsler, D. Wechsler Adult Intelligence Scale--Revised (WAIS-R): Administration and scoring manual. The Psychological Corporation; NY: 1981.
56. Wechsler, D. Wechsler Adult Intelligence Scale -- Third Edition (WAIS-III): Administration and scoring manual. The Psychological Corporation; San Antonio, TX: 1997.
57. Wilson PJE. Cerebral hemispherectomy for infantile hemiplegia: A report of 50 cases. *Brain* 1970;93:147–80. [PubMed: 5418398]
58. Xerri C, Merzenich MM, Peterson BE, Jenkins W. Plasticity of primary somatosensory cortex paralleling sensorimotor skill recovery from stroke in adult monkeys. *J Neurophysiol* 1998;79(4):2119–48. [PubMed: 9535973]

Figure 1.

Speech Sites in Patients with Language Deficits

Speech sites (yellow circles) are shown in relation to the cortical lesions (*). Panel A was a 42 year old female who suffered a traumatic brain injury and cortical contusion. Mapping demonstrated a speech site on the frontal operculum in a typical location, as well as a speech site more dorsally on the inferior frontal gyrus. Panel B was a 33 year old male who suffered a traumatic brain injury. Mapping demonstrated multiple speech sites along the frontal operculum (arrow). Panels C and D demonstrate temporal lobe speech sites at varying distances from the lesion margin. Panel C was a 39 year old female with traumatic brain injury. The photograph illustrates the evacuated cavity from a cerebral contusion. Panel D is a 36 year old male with subarachnoid hemorrhage. The photograph depicts the resection cavity following resection of epileptic focus. Bars represent 1 cm.

Figure 2.

Language Test Performance by Patient Group

Aphasics (shown in black) performed significantly worse than controls (shown in gray) across language tests. *T*-score and *p*-value for each test were as follows: VIQ, $t = -3.169$, $p = 0.004$ (Panel A), FIQ, $t = -2.13$, $p = 0.04$ (Panel B), Aphasia Screening Test, $t = 4.361$, $p = 0.001$ (Panel C; Higher scores reflect worse performance, lower scores reflect better performance), Animal Naming, $t = -2.941$, $p = 0.007$ (Panel D), and COWA, $t = -4.021$, $p = 0.001$ (Panel E). Y-axis is raw score for each respective test. Bars represent mean performance. Error bars represent SEM.

Figure 3.

Reversal of Speech Site Distribution

The proportion of speech sites found in the frontal lobe (black) and temporal lobe (gray) is shown on the y-axis. The typical proportion of speech sites found in the frontal and temporal lobes is reversed in patients with temporal lobe lesions involving eloquent speech areas. Aphasics had proportionally fewer temporal lobe sites than controls (*, $\chi^2 = 11.618$, $p < 0.001$) and proportionally more frontal sites (*, $\chi^2 = 4.15$, $p < 0.05$). A — aphasic group; C — control group. Bars represent comparisons between control and aphasic groups.

Figure 4.

Frontal Lobe Sites Decline with Age of Brain Insult

In Panel A, the number of frontal lobe sites are plotted as a function of the age of the patient at the time of initial brain insult. The number of sites was significantly inversely correlated with age of brain insult ($r = -0.71$, $p = 0.014$). This finding was independent of frontal lobe lesion involvement. Patients with frontal lobe involvement shown in circles; those without shown in triangles. Lines represent linear regression with 95% mean prediction interval ($r^2 = 0.51$, $F = 9.266$, $p = 0.014$). Panel B demonstrates the comparison between early and late brain injury patient. The mean number of frontal lobe sites is shown for patients with 'early' brain injury (younger than 19 years of age) and for those with 'late' brain injury (older than 19 years of age). $T = 2.745$, $p = 0.02$. Error bars represent standard deviation.

Figure 5.

Temporal Lobe Sites by Lesion Proximity

The number of temporal lobe sites varied as a function of the distance between the lesion and the nearest speech site. Patients with lesions beyond 1.5 cm from the nearest speech site (i.e. 'remote' lesions) had significantly fewer sites (ANOVA $F_{10,2} = 7.161, p = 0.01$). Bars represent mean value, error bars represent standard deviation.

Figure 6.

Naming Fluency by Lesion Proximity

Performance on the Animal Naming test is shown across lesion proximity groups as in Figure 5. Patients with ‘near’ lesions (i.e. between 1 –1.5 cm), significantly outperformed the other patients (ANOVA $F_{10,2} = 8.960$, $p = 0.009$).

Figure 7.

Model Relationship Between Temporal Lobe Sites and Lesion Proximity

Three potential lesions illustrated against the background of a typical pattern of temporal lobe speech representation. Lesion proximity to the nearest speech site (black circles) is measured. (Panel A) An 'adjacent' lesion occurs within 1 cm of a speech site without destroying it. Significant speech symptoms result from the lesion's encroachment upon the speech site. Note that the total number of temporal lobe sites remains unchanged (i.e., 3). (Panel B) A 'near' lesion occurs at a moderate distance from a speech site (i.e. between 1-1.5 cm). This lesion produces mild speech symptoms by damaging only the outer limits of a speech site. The number of sites remains unchanged. (Panel C) The 'remote' lesion destroys the speech site, leaving the next closest speech site intact. Significant speech deficits result from the destruction of the speech site. Only two temporal lobe sites remain and the distance between the lesion and next closest speech site is greater than 1.5 cm.

Table 1

Patient Clinical Variables. There were no differences between aphasics and matched control patients on demographic variables. Means and standard deviations shown.

Clinical variables	Aphasia (mean $\pm$ std)	Control (mean $\pm$ std)	t-score	p-value
Age at operation	34 $\pm$ 7.1	35.1 $\pm$ 9.7	-0.168	ns
Age at brain injury	23.9 $\pm$ 10	18.3 $\pm$ 10.1	1.351	ns
Symptom duration	10.0 $\pm$ 7.9	14.2 $\pm$ 10.7	-1.125	ns
Education	12.0 $\pm$ 2.1	12.8 $\pm$ 1.9	-1.047	ns

Table 2

Diagnosis and Speech Disorders of Aphasics Eleven aphasics were included in this investigation. Their diagnosis, etiology of brain injury, and speech disorder are listed. Two patients with expressive aphasia exhibited only mild forms of impaired repetition. These patients fall on the diagnostic spectrum between classical expressive aphasia and transcortical motor aphasia.

Case	Age (yrs)	Sex	Handedness	Diagnosis	Etiology	Speech Disorder
1	36	M	R	epilepsy	SAH/CVA	expressive aphasia*
3	32	M	R	epilepsy	Glioma	dysphasia
4	25	M	R	epilepsy	TBI	dysphasia with anomia
5	32	M	R	epilepsy	TBI	dysphasia / dysfluency
6	37	M	R	epilepsy	TBI	expressive aphasia*
7	42	F	R	epilepsy	TBI	expressive aphasia
8	30	M	R	epilepsy	TBI	anomic aphasia
9	39	F	R	epilepsy	TBI	anomic aphasia
10	45	M	R	epilepsy	TBI	dysphasia
11	34	F	R	epilepsy	GSW	expressive aphasia
13	33	F	R	epilepsy	TBI	dysphasia / dysfluency

Table 3

Language Tests Significantly Inter-correlated. A correlation matrix of language tests demonstrates that language performance across tests was significantly inter-correlated. Pearson's *r* shown as top number in each cell. *P-value* shown as bottom number in italics. VIQ – Verbal Intelligence Quotient; FIQ – Full-Scale Intelligence Quotient; COWA – Controlled Oral Word Association test (a.k.a. 'F.A.S.' test). The Aphasia Battery score represents error rates; higher values represent worse performance while lower values represent better performance.

Neuropsych Variables	OR Naming	VIQ	FIQ	Aphasia Battery	COWA
VIQ	-0.585 0.003	–	–	–	–
FIQ	0.417 0.05	0.936 0.001	–	–	–
Aphasia Battery	-0.585 0.003	-0.67 0.001	-0.626 0.001	–	–
COWA	0.474 0.02	0.577 0.002	0.502 0.01	-0.61 0.001	–
Animal Naming	0.526 0.01	0.631 0.001	0.572 0.002	-0.488 0.01	0.535 0.005