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Analysis of Naming Errors during Cortical Stimulation Mapping: Implications for Models of Language Representation

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Abstract

This study reports on the characteristics and distribution of naming errors of patients undergoing cortical stimulation mapping (CSM). During the procedure, electrical stimulation is used to induce temporary functional lesions and locate ‘essential’ language areas for preservation. Under stimulation, patients are shown slides of common objects and asked to name them. Cortical stimulation can lead to a variety of naming errors. In the present study, we aggregate errors across patients to examine the neuroanatomical correlates and linguistic characteristics of six common errors: semantic paraphasias, circumlocutions, phonological paraphasias, neologisms, performance errors, and no-response errors. Aiding analysis, we relied on a suite of web-based querying and imaging tools that enabled the summative mapping of normalized stimulation sites. Errors were visualized and analyzed by type and location. We provide descriptive statistics to characterize the commonality of errors across patients and location. The errors observed suggest a widely distributed and heterogeneous cortical network that gives rise to differential patterning of paraphasic errors. Data are discussed in relation to emerging models of language representation that honor distinctions between frontal, parietal, and posterior temporal dorsal implementation systems and ventral-temporal lexical semantic and phonological storage and assembly regions; the latter of which may participate both in language comprehension and production.

Keywords

cortical stimulation mapping; paraphasias; temporal lobe epilepsy

Complementing the results of neuroimaging and lesion studies, cortical stimulation mapping (CSM) provides a rare and valuable opportunity for mapping language function to neuroanatomy (G. A. Ojemann, 1991). CSM is an invasive procedure used to identify the language, sensory, and motor cortices, so that these critical regions may be preserved during

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surgical resection. The technique was originally employed to identify the sensory-motor cortices in patients with medically intractable seizure disorders. Penfield and colleagues later extended the procedure to identify eloquent language cortex by implementing an object-naming task (Penfield & Roberts, 1959). Subsequent studies have demonstrated that visual naming under stimulation can successfully identify resection boundaries that preserve functionally important language areas (Haglund, Berger, Shamseldin, Lettich, & Ojemann, 1994; G. A. Ojemann, 1983), though some controversy remains (e.g., Seeck et al., 2006).

CSM is one of the few techniques that allow direct observation of language dysfunction at an extremely localized neural level. However, the technique is limited by its own unique constraints. As a surgical procedure, intraoperative mapping is limited in time, with most testing typically lasting 0.5 h to 3 h (Gordon, Boatman, Hart, Miglioretti, & Lesser, 2001). Cortical stimulation sites are limited to the regions exposed by the craniotomy (Roux et al., 2004). Typically there is an unequal sampling of cortical sites within the exposed region. Moreover, patients have just come out of general anesthesia and may be lethargic and therefore not alert or in the most optimal state for testing (Gordon et al., 2001). In addition, neurologically compromised patients, especially those with an early-age epilepsy onset, may have undergone cortical reorganization (Thompson, 2005). Aside from these procedural constraints, some controversy remains over the extent to which electrical stimulation spreads to adjacent cortex (G. A. Ojemann, 1983). Some studies of non-human primates have reported greater than expected spread of current in visual cortex (Tolias et al., 2005), though other studies have reported a lack of activation in adjacent cortex (Haglund, Ojemann, & Blasdel, 1993).

Despite these challenges, cortical stimulation studies over the past three decades have provided valuable evidence of the cortical organization of language. Although lesion studies have identified classic perisylvian regions in language processing, CSM studies have shown that language cortex may involve extra-sylvian regions, though these are variable across patients. Although most language sites are distinctly defined by sharp boundaries, some regions have been reported to include a “fuzzy” transition zone where cortical stimulation induces only occasional naming disruption (Whitaker & Ojemann, 1977). CSM studies comparing early and adult lesion onset (G. Ojemann, Ojemann, Lettich, & Berger, 1989) and patients with fast growing tumors reveal a highly similar pattern of language organization, suggesting that this mosaic of language function spread across perisylvian regions is likely reflective of the general population and is not simply an artifact of language organization in a clinical epileptic population.

CSM studies have provided evidence that cortex can exhibit functionally specific vulnerabilities for language functions. Direct cortical stimulation has given rise to specific and differentiated errors associated with reading, verbal memory, semantic classes, and differential object naming in bilinguals (G. A. Ojemann, 2003). Evidence of selective disruption of verb versus noun naming has been reported (Corina et al., 2005), as well as dissociations of reading and object naming (Roux et al., 2004). An anterior to posterior distribution for auditory versus visual naming has also been reported (Hamberger, McClelland, McKhann, Williams, & Goodman, 2007). A number of CSM speech perception studies have identified discrete regions in the middle-posterior superior temporal gyrus that subserve phonological processing of consonants but not vowels (Boatman, Hall, Goldstein, Lesser, & Gordon, 1997; Boatman, Lesser, & Gordon, 1995).

In the present study, we add to this body of literature a characterization of the type and distribution of naming errors observed during CSM. Specifically, we examine the neuroanatomical correlates and linguistic characteristics of six common naming errors:

semantic paraphasias, circumlocutions, phonological paraphasias, neologisms, performance errors, and no-response errors.

2. Materials and Methods

2.1 Patients

The present study queried a database of 110 patients (57 female, 53 male; age range 15-61) undergoing CSM as part of intractable epilepsy surgery or tumor resection at the University of Washington Medical Center. Patients were included in this study if (a) they produced one or more stimulated errors of our five primary error types (i.e. semantic, phonological, neologism, circumlocution, or performance) and (b) imaging data was available to conduct site localization. This procedure identified 37 patients, one of which was excluded due to an unusually high unstimulated baseline error naming rate which was uncharacteristic of the remaining subjects. The 36 patients (21 female, 15 male; age range 18-58) who contribute data to the present analysis are described in Table 1. Each subject gave informed consent to participate in this study, with the study and methods annually reviewed by the University of Washington Institutional Review Board. Patient verbal IQ ranged from 66 to 125, with a mean of 89. Cortical stimulation was always performed on the language dominant hemisphere as determined by Wada test. Of the 36 patients, 34 showed left hemisphere (LH) dominance, while two showed right hemisphere (RH) dominance¹. The intraoperative mapping procedure was performed on all patients; eleven subjects additionally underwent preoperative grid testing and these data are included for analysis. The number of cortical regions sampled per patient ranged from 2 - 13 (mean 7.5) and the number of stimulated trials ranged from 20 - 140 (mean 60).

2.2 Protocol

During the CSM procedure, patients were asked to name common objects presented as black and white line drawings based on the Snodgrass and Vanderwart (1980) images. The images consisted of exemplar members of a number of different semantic categories (e.g. animals, body parts, fruits and vegetables, furniture, etc.). Stimuli were presented to patients via a slide carousel of approximately 60 slides. Prior to cortical mapping, patient familiarity with the slides was established in order to ascertain a baseline level of object familiarity. For each individual, incorrectly named and unfamiliar slides were removed from the carousel prior to brain mapping. This accounts for slight differences in stimuli number and order of presentation between patients.

During the procedure, under general anesthesia, patients underwent craniotomy to expose the suspected epileptic focus and adjacent lateral cortex. After this procedure patients were allowed to emerge from general anesthesia and stimulation thresholds were established on a per patient basis by finding the highest level achievable without causing after discharge as recorded by EEG. Patients were positioned on their left or right side, as determined by the proposed side of resection. Slides were presented for a duration of four seconds on a screen positioned approximately 0.5 meters from the patient. On stimulated trials, cortical stimulation occurred simultaneously with slide onset and was maintained until the patient correctly named the object or the next slide was presented. Stimulated trials were always immediately followed by unstimulated trials, and unstimulated trials continued until the patient could correctly name the slide indicating that naming had returned to baseline.

During CSM, patient responses were audio or video taped for later offline coding and analysis. Four raters evaluated object naming responses from the 36 patients according to an

¹The distribution and numbers of errors observed in two RH dominance patients were unremarkable.

11-point coding scheme that classifies errors by major type (Corina et al., 2005). Trials were additionally coded according to the temporal characteristics of the response (e.g., short/long delays in speech and word searching “umm...”) and whether the patient made repeated attempts or approximations of the target form. Trials could additionally be tagged as after discharge (AD) or following stimulation error (FSE) – a non-stimulated error that immediately follows a stimulated trial. The present analysis excludes errors associated with AD or labeled as FSE. For our analysis, we examined the linguistic characteristics and the aggregate distribution of five different types of paraphasic *naming* errors: semantic paraphasias, circumlocutions, phonological paraphasias, neologisms and performance errors. In addition, we consider stimulation trials that resulted in a lack of naming response, here termed as “no-response” errors. In contrast to paraphasic naming errors, the presence of a no-response error offers little opportunity to infer the nature of underlying mechanisms in naming. For this reason, we choose to treat no-response errors separately from audible *naming* response errors.

2.3 Error Categories

Semantic paraphasias are errors in which the patient substitutes a semantically related or associated word for the target word. Iconic examples of semantic paraphasias include producing the word ‘horse’ for the target image COW, or producing the word ‘car’ when the correct target is TRAIN. A schema based on Snodgrass and Vanderwart (1980) was used to sub-classify semantic paraphasias into one of six categories: coordinate – a response that is a different exemplar from the same category (e.g., LION → ‘tiger’); associate – a response that is related to the target, but which does not share semantic features with the target (e.g. FOOT → ‘shoe’); superordinate – a hyponym response in which a more general term is produced in lieu of the basic term (e.g., PEAR → ‘fruit’); subordinate – a hypernym response in which a term more specific than the basic level is produced (e.g., FLOWER → ‘rose’); part-whole – a meronym response in which the part term is produced instead of the whole (e.g. HAND → ‘finger’) or a holonym in which the whole is produced in lieu of the intended part (e.g., FOOT → ‘leg’); and visual – a response that has a vague or tenuous semantic relationship to the target but which shares visual features (e.g., NAIL → ‘knife’).

Circumlocution errors are responses in which the subject talks about or ‘around’ the target in lieu of naming it. The subject may describe attributes of the target, describe its use (e.g., CHAIR → ‘sit down’), or talk about the target in a roundabout manner (e.g., SHOE → ‘cover foot’). Circumlocutory responses differ from semantic paraphasias in that they are typically multiword responses for a single word target (e.g., COUCH → ‘something I lay on besides my bed’). A single word semantic paraphasia is seen as an “unintended” error, but a circumlocution is considered a deliberate “approximation to [the] intended idea because of... word-finding difficulty” (Goodglass & Kaplan, 1972; but see Nickels, 2001).

Phonological paraphasias are characterized by unintended phonemic epenthesis, omission, substitution, metathesis, and repetition. In production models of language, phonological paraphasias are believed to involve phoneme selection. Unlike neologisms, phonological paraphasias bear a resemblance to the intended target. Our classification of these errors follows Code’s (1989): substitution - clear phonological substitution (e.g., WAGON → ‘ragon’); epenthesis – insertion of a segment into the target form (e.g., PANTS → ‘plants’); deletion – omission of one or more segments (e.g., SPOON → ‘poon’) and transposition – changes involving intralexical phonological errors. Transpositions consist of segment-level anticipations (e.g., APPLE → ‘papple’) and perseverations (e.g., BANANA → ‘babana’ as well as metathesis, or the full exchange of segments (e.g., DESK → ‘deks’). We also included the subcategory ‘other’ to classify phonological errors that did not fall neatly into the aforementioned categories.

Neologisms (e.g., FISH → ‘herp’) are form-based errors which are “possible but nonexistent words” that generally follow the phonotactics of the language (Blumstein, 2001). With neologistic errors, the relationship between the target and the produced form is “more remote” than in phonological paraphasias (Dell, Schwartz, Martin, Saffran, & Gagnon, 2000). While the relationship between phonological paraphasias and neologisms may be inherently gradient, following Nickels (2001), we set a cut-off criterion of 50% for separating the two error types. That is to say, if a response shared 50% or more phonemes with the target it was classified as a phonological paraphasia; otherwise, it was classified as a neologism.

Performance errors include form-based distortions that are slurred, stuttered, or imprecisely articulated. In our data, these may include both dysarthric speech production and errors more typically considered apraxic. Apraxia of speech (AOS) is characterized by reduced rate of speech, disrupted prosody, syllable segregation, articulatory groping, and repeated, successive approximation of the target form (Square, Roy, & Martin, 1997) While the distinction between AOS and dysarthria is theoretically motivated, in practice, especially in the context of CSM data, it is often difficult to differentiate these error types fully (see McNeil, Robin, & Schmidt, 1997). We use the cover term “performance error” to acknowledge this difficulty.

No-response errors are cases in which stimulation leads to the lack of naming response. We differentiate these no-response errors from errors of speech arrest that occur due to stimulation of ventral motor regions associated with speech articulation. In clinical practice, these latter areas are determined by having the patient perform an automatic counting task. In these cases, stimulation is used to identify regions that reliably halt the otherwise fluent counting. The results from the speech arrest counting procedure are not discussed in this paper; however, regions identified by this procedure did not necessarily preclude testing for additional naming errors. Unlike audible errors, which allow for more detailed inferences regarding functional neuroanatomy and confrontation naming, no-response errors do not. As such, no-response errors are more speculatively assessed by their underlying distribution in relation to other error types. For this reason, we begin with an analysis of paraphasic errors followed by an assessment of no-response errors.

2.4 Anatomical Localization

The location of stimulation sites was determined by using a cortical parcellation system (CPS) that uses the terminology of the NeuroNames hierarchy (Bowden & Martin, 1995) in the Foundational Model of Neuroanatomy (R. F. Martin, Mejino, Bowden, Brinkley, & Rosse, 2001). Described in Corina et al. (2005), this system divides the surface of the cortex (by using landmarks and projections) into 37 distinct regions. Stimulation sites are identified in the system by using 3D MRI reconstructions, as well as intraoperative photographs and schematic drawings of grid placements. Site localization was directed by the primary author of the CPS (i.e. Martin) with no knowledge of the error types associated with the sites. Anatomical terms and abbreviations are provided in Table 2. For analysis, we utilized a suite of data-querying and imaging tools developed by the Structural Informatics Group at the University of Washington (Brinkley et al., 2006).

2.5 Data Analysis

As previously noted, the CSM procedure is used to identify eloquent language regions for consideration of surgical planning. Rather than a description of these specific regions (see for example, Ojemann et al., 1989), the intent of this paper is to focus upon errors that are observed throughout the course of the stimulation procedure, some of which may fall within or beyond the eloquent language regions identified for surgical purposes. Because CSM

studies are ultimately constrained by surgical concerns that limit the extent of mapping, the temporal lobes (especially the middle and posterior aspects of the superior and middle temporal gyri) are over-sampled in our data compared to frontal, parietal, and occipital regions. We address these issues by considering error ratios (ER) – the ratio of a specific error type to the total number of naming errors in a specific region. Thus, in determining prominent regions for a specific error type (see following discussion), we only consider regions in which stimulation evoked five or more total naming errors.

In consideration of regional effects of *naming* errors, as the number of data points was often insufficient for standard non-parametric analysis at this level of granularity, we report descriptive statistics based on the number of errors observed and include a reporting of the patient ratio (PR) – the number of patients with one or more target errors over the total number of patients that incurred stimulation in that region. We consider cortical region X “prominent” for a specific error type Y if: (1) region X demonstrates an unusual distribution of error type Y as defined by the following formula: # Y errors \geq (total # naming errors observed / 5) * 1.5 (rounded to the next whole integer) and (2) at least three of the patients tested in region X elicited one or more Y errors. For example, region pMTG exhibits 17 naming errors. If this region is non-selective for error type, we would expect a relatively even distribution of our five error types (i.e. excluding no-response errors), specifically 3.4 occurrences of each of our five naming errors. Conservatively, if we find an error type exceeding 5.1 errors (3.4 * 1.5), we flag this as potentially “prominent.” As “partial” errors are not possible, this number is further rounded to the next higher whole integer to produce the threshold value (in this case, 6). In addition we require at least three individual subjects to have exhibited this form of error during stimulation to this region. As shown in Table 3, only semantic errors satisfy this dual constraint (8 semantic errors out of 17 total errors; 7 of 20 subjects exhibiting this form of error). In our reporting, we specify this as follows: pMTG (^6, 8/17, 7/20). When considering error types with relatively small numbers (i.e., phonological paraphasias, neologisms, and circumlocutions), we report the relative prominence of regions with respect to each other and consider higher patient ratios to be more important than error rates.

In our discussion of *no-response* errors, we report the total number of no-response errors over the total number of errors for each region. Likewise, we also report the number of patients demonstrating this error. Given the abundance of these errors we treat as prominent those regions that show an error ratio of over 50% based upon trial data and at least 50% of subjects showing errors of this form.

3. Results

3.1 Error Types

Regarding error type, the most frequently observed errors were no-response errors (54.0%), followed by performance errors (16.4%) and semantic paraphasias (15.1%). Less frequent errors included phonological paraphasias (7.4%), neologisms (4.0%), and circumlocutions (3.1%). Table 3 presents the raw error data by region and type for all cortical regions and it shows the number of patients observed to have made one or more target errors during electrocortical stimulation.

3.2 Semantic Paraphasias

Semantic paraphasias were one of the most prevalent naming errors. Of the CSM trial errors, n=49 were classified as semantic paraphasias – errors in which the patient substitutes a semantically related or associated word for the target. These errors were distributed across 24 patients (mean 2.0 errors). The distribution of errors across patients was relatively even,

with the exception of one patient (#127) who contributed seven errors. In this section, we report the frequency of the different semantic paraphasia subtypes and present the semantic error ratios by cortical region.

Semantic paraphasias were classified according to the semantic relationship between the produced response and target response. The most frequent paraphasias observed were coordinate-level errors (LION → ‘tiger’) at 73.5%. Part-whole (FINGER → ‘hand’) errors accounted for 14.3%, while associate errors (FOOT → ‘shoe’) accounted for an additional 6.1%. The remaining error types appeared relatively infrequent: superordinate errors (APPLE → ‘fruit’) at 4.1%, visual errors (NAIL → ‘knife’) at 2.0%. No subordinate errors (FLOWER → ‘daisy’) were observed.

Semantic paraphasias occurred following stimulation to 18 different cortical regions (Figure 1A). Prominent regions of semantic paraphasias were found in both parietal and temporal cortex, including mPOG (^2, 3/5, 3/4), aSMG (^4, 6/12, 5/19), and pMTG (^6, 8/17, 7/20) (see regions with bolded borders in Figure 1A). Regions approaching prominence included mMTG (^5, 4/15, 4/25) and parietal site vPoG (^3, 3/9, 2/13) (see regions with stippled border in Figure 1A).

3.3 Performance Errors

Performance errors were also quite frequent (n=53) and occurred across 23 patients (mean 2.3 errors). Of these, 24.6% were stutters, 37.7% were slurs, and the remaining coded as ‘other’ (which included cases of segmentation, slowed speech, etc.). 84.6% of the stutters were word-initial stutters. Performance errors occurred following stimulation to 14 regions (Fig. 1B). Prominent regions of performance errors (see Figure 1B) were found in both parietal and temporal sites including pSMG (^5, 14/16, 4/10), aSMG (^4, 6/12, 5/19), and mSTG (^12, 14/39, 11/29). Regions approaching prominence included mMTG (^5, 4/15, 4/25).

3.4 Phonological Paraphasias

Phonological paraphasias (n = 24) were less frequent than semantic paraphasias and performance errors. These errors were evenly distributed across 18 patients, with no single patient contributing more than three phonological errors. Segment deletion was the most frequent subtype, accounting for 48% of the observed phonological paraphasias. Substitutions were also quite frequent, contributing an additional 32%. Less frequent errors included epenthesis (8%), transposition (4%), and other (8%). Phonological paraphasias were primarily observed following stimulation to temporal regions (Fig. 1C). Reflecting the rarity of this error type, no one region reached our established level of prominence. The errors that were observed tended to be associated with temporal lobe regions, specifically aSTG (^2, 2/5, 2/22), mMTG (^5, 3/15, 3/25), and mSTG (^12, 7/39, 6/29).

3.5 Neologisms

In our study, neologisms (n = 13) were relatively rare, but were evenly distributed across 10 subjects. Considering syllabic similarity between target and response, five pairs shared the same number of syllables; eight responses had a different syllabic structure (five of which had *more* syllables than the target). Neologisms (Figure 2A) occurred following stimulation to parietal and temporal regions, although no single area met our criteria for prominence. Regions that approached prominence included mSTG (^12, 4/39, 4/29) and pMTG (^6, 4/17, 4/20). One subject produced three neologistic responses with stimulation to vPoG (^3, 3/9, 1/13).

3.6 Circumlocutions

In our data, circumlocutions (n=10) were rather infrequent, and unevenly distributed across the four subjects by whom they were produced (i.e., patient #94 produced seven circumlocutions). Stimulated errors were confined to temporal regions (Figure 2B), which included mSTG (~ 11 , 5/39, 3/29) and mMTG (~ 5 , 4/15, 1/25). No regions were considered prominent by our accounting.

3.7 No-Response Errors

No-response trials in which the patient does not verbally respond to the stimulus accounted for over half of the errors observed (n=175). Stimulation to 19 cortical regions elicited no-response errors, and these errors were observed in 30 of the 36 patients tested. Distribution across patients was skewed however, with six patients contributing 50% of these data. The most prominent regions of no-response errors (Figure 2C) include frontal site mPrG (5/6, 2/4), with frontal regions opIFG (17/20, 5/15) and vPrG (15/18, 5/14) approaching prominence. No-response errors were also prominent in more posterior cortex including anG (9/11, 5/9) and mPoG (9/14, 3/4), as well as temporal site pMTG (24/41, 12/20), with adjacent region pSTG (13/18, 8/20) approaching prominence.

Equally interesting are select regions that appear somewhat impervious to stimulation. Anterior and polar regions of the temporal lobe appear to feature a resistance to naming disruptions that lead to a complete lack of response. Region aMTG, for example, had 97 stimulated trials, none of which resulted in a no-response error (and only four naming errors: semantic-2, performance-1, and phonological-1) in any of the 19 patients tested. Theories of neural architecture for language can be informed from consideration of both positive and negative cases.

4. Discussion

4.1 Semantic Paraphasias

Semantic paraphasias were one of the most prevalent naming errors observed. Examining the semantic relationship between target form and error, we found that patients made proportionally more coordinate-level errors (LION \rightarrow 'tiger') than other errors. Regarding the distribution of semantic paraphasias, we observed wide spread regions in the temporal and parietal lobes giving rise to semantic paraphasias, the most prominent of which include mPoG, aSMG, and pMTG.

In most current models of language representation, temporal lobe regions have been implicated in aspects of semantic processing (Binder & Price, 2001; Grabowski et al., 2001; A. Martin & Chao, 2001). Complex effects of global semantic structure and single word meaning have been reported over large temporal regions including the superior temporal sulcus (STS), middle temporal gyrus, and inferior temporal gyrus (Humphries, Binder, Medler, & Liebenthal, 2007), which have been implicated in language comprehension (Dronkers, Wilkins, Van Valin, Redfern, & Jaeger, 2004) and lexical-semantic processing (Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996; A. Martin & Chao, 2001). Recent work has attempted to further differentiate the nature of semantic processing within the temporal lobe, yet widely different claims have been offered.

There is growing recognition of the need to differentiate conceptual semantic processing versus lexical-semantic processing. Price (2000), for example, posits the angular gyrus and anterior inferior temporal regions as key in semantic processing, while Indefrey and Levelt (2004) suggest that lemma retrieval and selection occur in the middle temporal gyrus. Hickok and Poeppel (2004, 2007) propose a role for bilateral posterior middle and inferior

portions of the temporal lobe corresponding to the lexical interface, which is seen to link phonological and lexical (including semantic) information. A study by Cloutman et al. (2009) tested 196 patients with acute left hemisphere stroke and identified a number of regions that were associated with impaired semantics as assessed by picture naming and word/picture verification. Posterior middle and inferior temporal lesions were associated with semantic errors in naming, but not comprehension. In contrast left pSTG and adjacent occipital cortex, and less prominently, the left angular gyrus, the supramarginal gyrus was associated with more global impairment. Especially prominent in our semantic paraphasia data were the contributions of the pMTG, where 7 of the 20 people tested in this region produced semantic paraphasias. This is a region that has been suggested to participate in long-term storage of lexical representations that interface with a semantic network distributed across brain regions (Lau, Phillips and Poeppel (2008); Hickok and Poeppel 2007).

In contrast to some reports, the angular gyrus did not result in an abundance of semantic errors in our single word stimulation paradigm. On the one hand, this may be expected as some researchers have suggested that the angular gyrus' contribution to semantics modulation reflects sentence-level semantic processing (Humphries et al., 2007) and/or integrating information into context (Lau, Phillips, & Poeppel, 2008) or higher order conceptualization (Vigneau et al., 2006). Interestingly, while stimulation to left and anG and pSTG did not produce a large proportion of semantic paraphasias, stimulation to these sites resulted in a large percentage of no-response errors (13/18 and 9/11). We further note the absence of semantic paraphasia associated with more anterior temporal lobe regions, areas that have been implicated in syntactic or combinatorial aspects of processing, rather than single word access (Dronkers et al., 2004; Hickok & Poeppel, 2007; Mazoyer et al., 1993).

A modality-based division of labor for semantic processing has been suggested by Vigneau and colleagues (Vigneau et al., 2006). Based upon their fMRI meta-analysis, they propose a dorsal and ventral network within the left temporal lobe subserving semantic function with the ventral component attuned to visual information and a dorsal component sensitive to auditory and speech based information. The aggregates of sites giving rise to semantic errors within pMTG map to MNI coordinates (-57, -52, 2.6). This appears to lie between two sites identified in the meta-analysis of Vigneau T2p (-40, -63, 5) and T2ml (-57, -37, 2), which were noted to be associated with MRI studies of semantic as well as sentence level processing².

Frontal lobe structures such as the IFG have been implicated in controlled semantic retrieval and selection (S. L. Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997; S.L. Thompson-Schill, D'Esposito, & Kan, 1999) and factor prominently in many fMRI studies of semantic processing (Vigneau et al., 2006). However, we do not observe stimulation of frontal structures leading to semantic naming error in our tasks. In this regard, several points are noteworthy: 1) In the confrontation naming task, the stimuli may be sufficiently rich and practiced such that there are few demands for controlled differentiation of potential lexical candidates; 2) Stimulation to frontal sites, and especially anterior locations are generally under-represented in the our data; and 3) Stimulation to inferior frontal sites (as well as the angular gyrus as described above), in our data often gives rise to no-response errors. We discuss the potential relationship between no-response errors and semantic paraphasia below.

²One must be cautious in interpreting the exact correspondences between CSM sites and those reported in fMRI studies as electrical stimulation used in CSM targets the crowns of the gyri, while BOLD signals are most easily detected within sulci.

What is perhaps most surprising in the present data is the observation of semantic errors following stimulation to parietal regions including aSMG, mPoG, and vPoG. A recent study has linked increased BOLD response during an explicit semantic judgment task to parietal region BA40, which has been interpreted as participants' attention to semantic associations (Kuperberg, Lakshmanan, Greve, & West, 2008). Moreover, in the Kuperberg et al. (2008) study, which examined the explicit versus implicit effects in lexical-semantic decision, regions in left post-central sulcus, post-central gyrus, and central sulcus were found to interact with task demands that contrasted lexical decision with semantic judgments, suggesting attentionally focused semantic decisions may recruit these regions. Our data are in accord with these findings and show that stimulation to the anterior SMG and post-central sulcus regions can result in semantic naming errors.

Taken together, these data suggest differential functional roles of temporal and parietal structures during semantic processing. We hypothesize that, in the context of this picture naming task, temporal regions may play a more important role in the automatic conceptual feature mapping required during picture identification leading to lexical-semantic activation. In contrast, anterior parietal regions (in concert with known connections to IFG regions) may contribute more to directed selection of lexical-semantic forms from the instantiated concepts (see discussion by Roelofs (1992) for stages in picture naming).

Finally, it is of further interest to note the relative lack of errors following stimulation to inferior ventral regions given the widespread evidence for the contribution of ventral temporal structures in semantic processing (Binder et al., 1997; Demonet, Price, Wise, & Frackowiak, 1994; Wise et al., 1991). This may in part be due the lack of sampling in this region.

4.2 Performance Errors

Performance errors were observed following stimulation to a number of cortical regions; however, as noted above, stimulation to pSMG ($\chi^2=5, 14/16, 4/10$) was prominent for performance errors compared to the other error types. Frequent performance errors were also observed in aSMG ($\chi^2=4, 6/12, 5/19$). The contributions of parietal and temporal-parietal regions in speech production have a long history in aphasiology. In a recent incarnation, Hickok and Poeppel (2004, 2007) propose a dual stream model of speech processing, with a dorsal stream which serves to map acoustic speech signals to frontal lobe articulatory networks. Some functions associated with this dorsal pathway are processes that occur at the level of segment sequences. This functionality may include the online guidance of speech sequences such as feed forward mechanisms (whereby sensory codes for a speech sequence are translated into a motor speech sequence), as well as feedback monitoring (Hickok & Poeppel, 2007). Not unrelated is the growing acceptance that inferior parietal regions including SMG function as a part of front-parietal network involved in storage during phonological working memory (Jonides, Smith, Marshuetz, Koeppe, & Reuter-Lorenz, 1998; Rypma, Prabhakaran, Desmond, Glover, & Gabrieli, 1999; for discussion see Vigneau et al., 2006). Models of naming such as those proposed by Kohn (1984) and Levelt (1989) suggest a multi-stage word production process. In Kohn's model, phonological representations are accessed from the lexicon and transmitted to working memory (i.e., phonological buffer), which retains a trace of the representation while they are programmed for production at a later stage. The representations are then converted into a sequence of phonological targets at the pre-articulatory programming stage. Finally, the output is converted to a sequence of motor commands. Paraphasic errors associated with conduction aphasia, for example, are considered to occur at the pre-articulatory stage. This involves the selection and sequencing of phonemic targets into a form necessary for articulatory realization.

Our data are broadly consistent with this characterization. Specifically, our data show a significantly high ratio of slurred and stuttered naming responses that were elicited following stimulation to pSMG and aSMG. The majority of stutters consisted of word-initial rather than word-final repetition. It has been argued that word-initial stuttering may indicate a deficit to the phonological output buffer (Nickels, 2001). In this view, wordfinal segments decay more quickly than they can be produced, resulting in repeated repair attempts. Note how working memory function is critical in the word production model of Kohn (1984) described above.

Hickok and Poeppel (2007) suggest that the juncture of the sylvian-parietal-temporal region (area Spt) serves as an sensorimotor interface that maintains parity between phonological representations and articulatory motor representations of speech. Derived from fMRI, they provide approximate Talairach coordinates for the region as $X = -50$, $Y = -38$, $Z = 20 \pm 3$ mm. The averaged coordinates derived from our cortical stimulation errors are proximal to this region: pSMG (-55, -41.28, 24.4) and aSMG (-54, -37.37, 32.9).

Our data shows that pSMG stimulation is more likely to lead to performance errors rather than phonological errors. Taken together these data suggest one main influence asserted by the SMG region is in the service of maintaining the integrity of the articulatory form, rather than in the sub-assembly of phonological information per se.

It is interesting to note that in these data aSMG factors prominently in both semantic errors and performance errors. Examination of individual patient records indicated that eight subjects elicited at least one semantic and/or performance error with aSMG stimulation. For two patients, both performance errors and semantic errors were elicited under repeat stimulation; in the other six subjects, repeated stimulation resulted in the same type of original error or a no-response error.

4.3 Phonological Paraphasias

Phonological errors were less common than performance errors (see above) and more restricted in anatomical location. Phonological paraphasias were evoked following stimulation to both temporal regions and parietal regions. However, stimulation to temporal regions produced relatively higher error ratios and a greater percentage of patients tested in these regions were observed to produce these errors. Particularly notable is region mSTG, where 20% of the patients tested produced phonological paraphasias. The most frequent phonological errors were deletions (48%) and substitutions (32%). This frequency distribution appears different from that reported for phonological paraphasias reported by Blumstein (1973) in which substitutions were moderately more frequent than deletions in their corpus (35.2% compared to 30.3%). Addressing phonological deletions, it should be noted that 77% of the deletions in our data involved omission of word final segments or syllables. In our data, stimulation to regions in the superior and middle temporal gyri, extending from anterior to posterior regions, gave rise to phonological errors. The electrically induced simplifications and substitutions have a broader distribution than areas classically associated with aphasias. The distribution of these errors supports anatomical models of language processing that hold that phonological representation and processing may involve an extension from pSTG to more anterior regions in STG (Scott, Blank, Rosen, & Wise, 2000). The CSM data further suggest these representational capacities are used in the service of naming. This view is additionally supported by other CSM studies that have shown considerable overlap in perisylvian cortex, where both the detection of speech sounds and motor speech gestures are altered during stimulation (G. Ojemann & Mateer, 1979; G. A. Ojemann, 1983).

4.4 Circumlocutions and Neologisms

Circumlocutions, though frequently observed in aphasia patients, were rather infrequent in the present brain mapping data. As opposed to semantic paraphasias, which suggest a disruption to the conceptual system resulting in subsequent lexical selection errors, circumlocutions may reflect a relatively undisrupted conceptual system. Evidence of this comes from the ability to describe the functional attributes of the target (BELT → ‘keep the-uh-pants on your hips’).

Neologisms, though also quite infrequent, occurred following stimulation to three temporal regions and two parietal regions. Notable regions included the mSTG and pMTG, where a greater percentage of patients tested in these regions produced neologisms. Wernicke’s aphasia, associated with lesions to temporal regions including pSTG, is characterized by fluent, paraphasic speech. A subset of these aphasics produce speech characterized by neologistic jargon, which has been argued to reflect deficits in lexical selection that map to lexical form (Blumstein, 2001; Christman, 1994; Hanlon & Edmondson, 1996). The majority of neologistic errors in our data were elicited by stimulation to middle and posterior temporal regions, a finding which is largely consistent with lesion studies.

Taking circumlocutions, phonological paraphasias, and neologisms together as phenomena reflecting failed or aberrant phonological retrieval, the superior temporal regions assume a more prominent role. Specifically, in our data, regions bounding the middle and posterior portion of the superior temporal sulcus appear to be preferentially sensitive (though not exclusive) to phonological disruption³. Boatman’s (2004) review of CSM studies of speech perception suggest phonological processing involves various STG regions that overlap a relatively circumscribed region in middle-posterior STG that is involved in acoustic-phonetic processing. Our data are broadly consistent with these findings and implicate regions bordering STS in phonological representation and selection. An important question, one which cannot be decided by these data alone, is the nature of the representations. Current accounts have emphasized the role of STS regions in the computation of acoustic-sensory properties of phonological form (Hickok & Poeppel, 2007; Obleser et al., 2006; Scott et al., 2000). However, our data indicate clear production errors with stimulation of these regions. This may imply, as noted above, that intact sensory representations are feeding word planning and execution processing. Another possibility is that these regions are not dichotomous, but rather have intermixed networks involved in both sensory mechanisms and production planning.

4.5 No-response

No-response errors were the most frequent and most widely distributed error resulting from electrocortical stimulation. However, prominent regions in our data included middle central sulcus regions and the posterior temporal-parietal-occipital region consisting of pMTG, and anG. Regions approaching prominence included inferior ventral frontal cortex and pSTG. These regions appear particularly prone to eliciting no-response errors as evidenced by large error ratios and the high proportion of subjects that produced these errors. The central sulcus and ventral premotor effects are perhaps not unexpected and consistent with the role of motor cortex and inferior ventral frontal in speech production and phonological processing (Poldrack et al., 1996; Bookheimer et al., 2000; Price, 2000; Wise, 2003; Hickok and Poeppel, 2004).

³Note: Collapsing these three categories and revising the denominator of equation (from 5 to 3) for determining “prominent” areas, pSTG is considered “prominent” ($\hat{c} = 3, 3/5, 3/20$) and mSTG approaches prominence ($\hat{c} = 20, 16/39, 13/29$)

The posterior regions at the temporal parietal occipital juncture, in which stimulation evoked no overt naming response, may correspond to regions associated with aphasic syndromes, such as anomic aphasia. Anomic aphasics exhibit word finding difficulties in the face of relatively intact auditory comprehension with minimal phonological and semantic paraphasias (Kirshner, 1995). Patients with anomic aphasia present a similar impaired ability to name objects (Damasio, 1991; Goodglass, 1980; Miceli, Silveri, Nocentini, & Caramazza, 1988). Goodglass and Kaplan (1983), however, note that the frequency of injury to temporal-parietal regions often extending into the angular gyrus is often associated with anomic aphasia. Other researchers have implicated posterior and inferior temporal regions (BA 37) with anomic aphasia (Antonucci, Beeson, & Rapcsak, 2004; Foundas, Daniels, & Vasterling, 1998; Raymer et al., 1997). In our data, stimulation to these temporal regions produced a relatively large percentage of no-response errors: pMTG (24/41, 12/20) with adjacent pSTG (13/18, 8/20) showing less prominence. Similarly, stimulation to the angular gyrus elicited numerous no-response errors, as well. More than 50% (5/9) of the patients tested in anG produced these errors, and 82% (9/11) of all the errors elicited by stimulation were no-response errors.

Comparing across error types, we observe higher correlations among regions producing semantic errors and no-response errors ($r = .77$) versus no-response errors and performance errors ($r = .51$) or phonological errors ($r = .66$). While obviously speculative, the common association between coterminous regions giving rise to a high percentage of semantic errors and no-response errors (for example, the mPOG and the pMTG) leads one to entertain whether disruption of semantic processing may lead to lack of overt naming.

Taken together, the stimulation results suggest two plausible sources for no-response errors, these may arise from blockage of speech-motor plans and/or from a disruption of semantic processing which is necessary component in object naming.

4.6 Non-Selectivity

Finally, one site, the mMTG, is notable for its relative *nonselectivity*. Despite being tested in 25 patients and eliciting an abundance of errors (15 naming errors, 9 no-response errors), we observe this site approaches prominence for both semantic and performance errors, but also contributes phonological errors and circumlocutions (but interestingly no neologisms). Whether this undifferentiated pattern of errors is attributable to an equipotentiality within a language network, whereby this site serves as a critical juncture for multiple component processes, or whether this reflects anatomical functional variation across subjects is unknown, but warrants further investigation.

5.0 Conclusion

In summary, several valuable confirmatory as well as novel findings emerge from this study. Current models of language processing acknowledge a wide distribution of cortical regions implicated in the language network. Our data demonstrate that errors in object naming may arise from widespread regions within perisylvian areas. However, our data also indicate that the network is functionally heterogeneous and honors distinctions between frontal, parietal, and posterior temporal dorsal implementation systems and ventral-temporal lexical semantic and phonological storage and assembly regions, the latter of which may participate in both language comprehension and production.

Specifically, our data showed that stimulation to pSMG, a region within the frontal-parietal dorsal stream, evokes significantly more performance related errors. We speculate that these performance errors may reflect disruption of an implementation process that mediates between phonological representations and articulatory motor representations of speech.

Given the greater prevalence of performance versus phonological errors exhibited in this area, we suggest the pSMG role may exert a greater articulatory role in these processes.

In contrast, semantic paraphasias were evoked following stimulation to several cortical structures. We observed that stimulation to the posterior middle temporal gyrus led to semantic paraphasias which accords with previous findings that implicate the temporal lobe in lexical semantics. We also reported semantic errors following stimulation to parietal regions, such as the post-central gyrus and the anterior aspect of the supramarginal gyrus a region which may contribute more to controlled selection of lexical-semantic forms. The lack of semantic errors arising from inferior frontal region and parietal regions such as angular gyrus, in these data may, in part, be explained by preponderance of no-response errors that occur when these regions are stimulated. Phonological paraphasias, neologisms, and circumlocutions were primarily confined to regions bordering the posterior STS. Taken together these patterns suggest that intact semantic representations may be feeding word planning and execution processes, which may be disrupted under cortical stimulation.

In conjunction with language perception studies, our data suggest that the STS is involved in both the acoustic perception of phonological form, as well as production. The most frequently observed form of naming disruption, the lack of an audible response from the patient, is a more difficult error from which to draw inferences. We did observe that the anatomical distribution of these errors includes a frontal region and a posterior temporal region. Our data suggest a close correspondence between regions prone to no-response errors and semantic errors, especially those affecting the posterior temporal region and angular gyrus.

Finally and equally compellingly, we observe cortical areas that appear resistant to naming errors during cortical stimulation. It is particularly interesting to note that these regions often border areas that lead to frequent naming errors, a condition which suggests that, rather than the entirety of the left hemisphere being involved in some sub-process of object naming, linguistic specializations above the word level are occurring.

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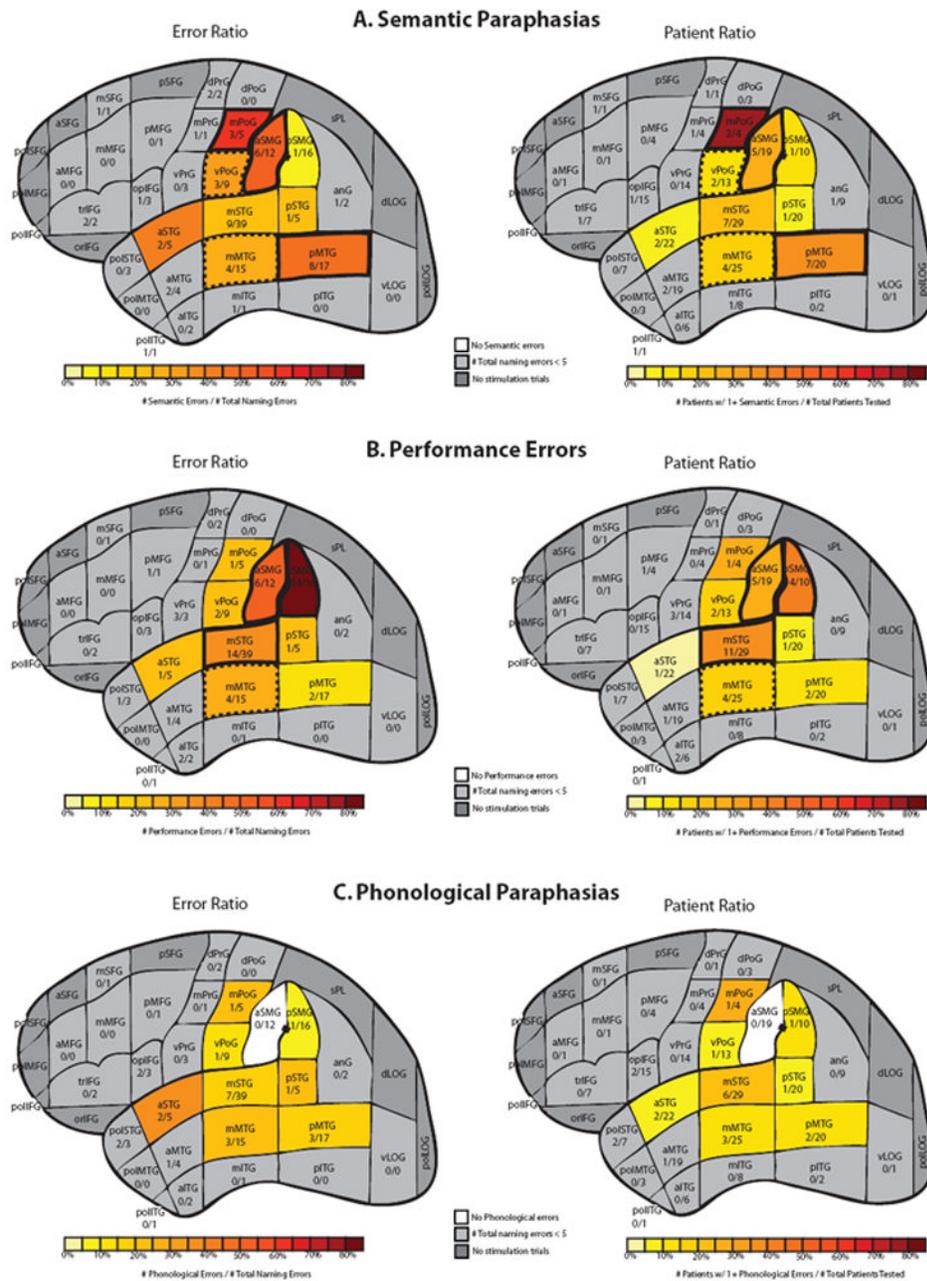


Figure 1. A. Cortical regions indicating error ratios (left) and patient ratios (right) for semantic paraphasias. Bolded borders demarcate prominent areas; stippled borders indicate regions approaching prominence (see text for explanation). B. Cortical regions indicating error ratios (left) and patient ratios (right) for performance errors. Bolded borders demarcate prominent areas; stippled borders indicate regions approaching prominence (see text for explanation). C. Cortical regions indicating error ratios (left) and patient ratios (right) for phonological paraphasias.

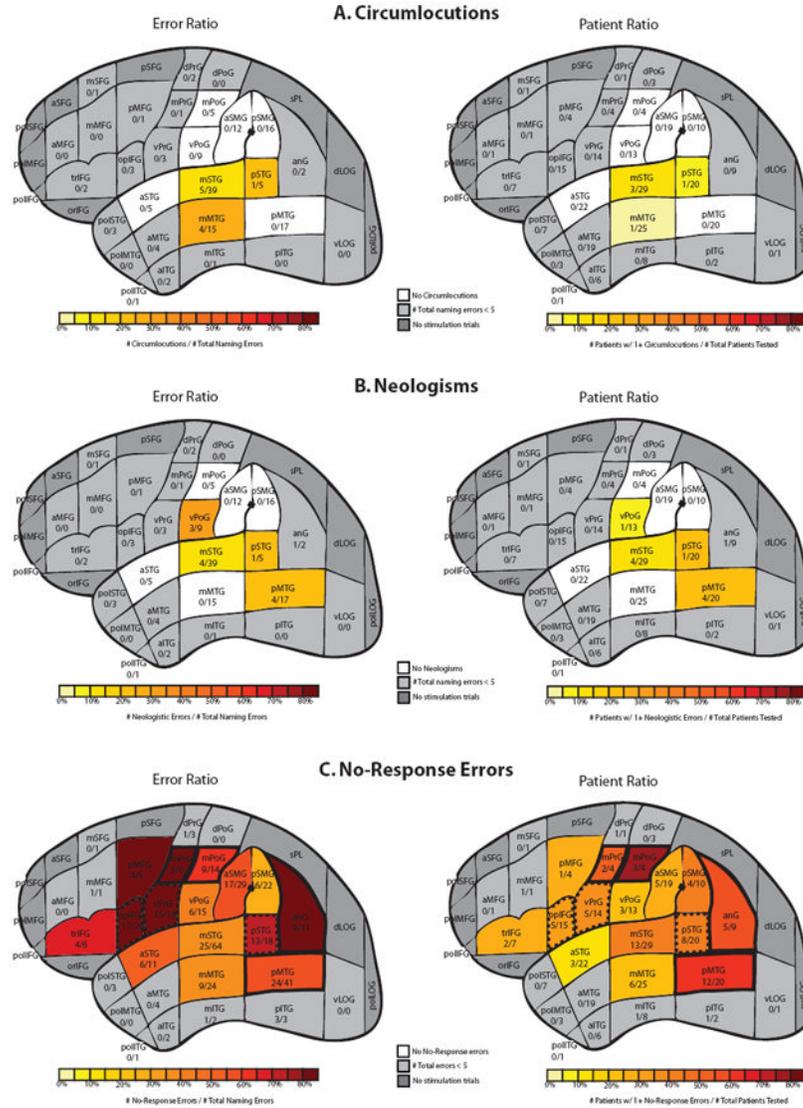


Figure 2.
 A. Cortical regions indicating error ratios (left) and patient ratios (right) for neologistic errors.
 B. Cortical regions indicating error ratios (left) and patient ratios (right) for circumlocution errors.
 C. Cortical regions indicating error ratios (left) and patient ratios (right) for no-response errors. Bolded borders demarcate prominent areas; stippled borders indicate regions approach prominence (see text for explanation).

Table 1

Patient characterization

Patient ID	Age	Sex	Side	Grid
40	38	F	L	N
50	39	M	L	Y
52	46	F	L	N
53	31	M	L	Y
54	25	M	L	Y
55	30	M	L	N
56	30	F	L	N
57	24	M	L	N
58	23	M	L	N
60	38	M	L	N
61	35	F	L	N
62	24	F	L	N
63	42	M	L	N
64	45	F	L	N
84	49	F	L	N
89	35	M	L	N
90	49	F	R	Y
91	18	M	L	N
94	48	M	L	N
122	41	M	L	N
124	51	F	L	Y
127	30	M	L	Y
129	58	F	L	N
130	35	F	L	N
132	27	M	L	N
136	55	F	R	N
137	40	F	L	Y
141	40	F	L	Y
144	23	M	L	Y
145	48	F	L	Y
147	37	F	L	Y
156	22	F	L	N
170	52	F	L	N
175	31	F	L	N
176	41	F	L	N
180	35	F	L	N

Table 2

Anatomical names and abbreviations

Abbrev	Anatomy	Abbrev	Anatomy
aITG	anterior inferior frontal gyrus	mSFG	middle superior frontal gyrus
aMFG	anterior middle frontal gyrus	mSTG	middle superior temporal gyrus
aMTG	anterior middle temporal gyrus	opIFG	opercular inferior frontal gyrus
anG	angular gyrus	pITG	posterior inferior temporal gyrus
aSMG	anterior supramarginal gyrus	pMFG	posterior middle frontal gyrus
aSTG	anterior superior temporal gyrus	pMTG	posterior middle temporal gyrus
dPoG	dorsal post-central gyrus	polITG	polar inferior temporal gyrus
dPrG	dorsal pre-central gyrus	polMTG	polar middle temporal gyrus
vLOG	ventral lateral occipital gyrus	polSTG	polar superior temporal gyrus
mITG	middle inferior temporal gyrus	pSMG	posterior supramarginal gyrus
mMFG	middle middle frontal gyrus	pSTG	posterior superior temporal gyrus
mMTG	middle middle temporal gyrus	trIFG	triangular inferior frontal gyrus
mPoG	middle post-central gyrus	vPoG	ventral post-central gyrus
mPrG	middle pre-central gyrus	vPrG	ventral pre-central gyrus

Table 3

Distribution of errors

	Semantic		Performance		Phonological		Neologism		Circumlocution		Totals	
	errors	patients	errors	patients	errors	patients	errors	patients	errors	patients	errors	patients tested
aITG	0	0	2	2	0	0	0	0	0	0	2	6
aMFG	0	0	0	0	0	0	0	0	0	0	0	1
aMTG	2	2	1	1	1	1	0	0	0	0	4	19
anG	1	1	0	0	0	0	1	1	0	0	2	9
aSMG	6	5	6	5	0	0	0	0	0	0	12	19
aSTG	2	2	1	1	2	2	0	0	0	0	5	22
dPoG	0	0	0	0	0	0	0	0	0	0	0	3
dPRG	2	1	0	0	0	0	0	0	0	0	2	1
vLOG	0	0	0	0	0	0	0	0	0	0	0	1
mITG	1	1	0	0	0	0	0	0	0	0	1	8
mMFG	0	0	0	0	0	0	0	0	0	0	0	1
mMTG	4	4	4	4	3	3	0	0	4	1	15	25
mPog	3	3	1	1	1	1	0	0	0	0	5	4
mPG	1	1	0	0	0	0	0	0	0	0	1	4
mSFG	1	1	0	0	0	0	0	0	0	0	1	1
mSTG	9	7	14	11	7	6	4	4	5	3	39	29
optFG	1	1	0	0	2	2	0	0	0	0	3	15
pITG	0	0	0	0	0	0	0	0	0	0	0	2
pMFG	0	0	1	1	0	0	0	0	0	0	1	4
pMTG	8	7	2	2	3	2	4	4	0	0	17	20
polITG	1	1	0	0	0	0	0	0	0	0	1	1
polMTG	0	0	0	0	0	0	0	0	0	0	0	3
polSTG	0	0	1	1	2	2	0	0	0	0	3	7
pSMG	1	1	14	4	1	1	0	0	0	0	16	10
pSTG	1	1	1	1	1	1	1	1	1	1	5	20
trIFG	2	1	0	0	0	0	0	0	0	0	2	7
vPoG	3	2	2	2	1	1	3	1	0	0	9	13

	Semantic		Performance		Phonological		Neologism		Circumlocution		Totals	
	errors	patients	errors	patients	errors	patients	errors	patients	errors	patients	errors	patients
vPrG	0	0	3	3	0	0	0	0	0	0	0	3
Total	49		53		24		13		10		149	