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Deficit-Lesion Correlations in Syntactic Comprehension in Aphasia

David Caplan, **Jennifer Michaud**, **Rebecca Hufford**, and **Nikos Makris**
[1]Neuropsychology Laboratory, Department of Neurology, Massachusetts General Hospital

Abstract

The effects of lesions on syntactic comprehension were studied in thirty one people with aphasia (PWA). Participants were tested for the ability to parse and interpret four types of syntactic structures and elements -- passives, object extracted relative clauses, reflexives and pronouns – in three tasks – object manipulation, sentence picture matching with full sentence presentation and sentence picture matching with self-paced listening presentation. Accuracy, end-of-sentence RT and self-paced listening times for each word were measured. MR scans were obtained and analyzed for total lesion volume and for lesion size in 48 cortical areas. Lesion size in several areas of the left hemisphere was related to accuracy in particular sentence types in particular tasks and to self-paced listening times for critical words in particular sentence types. The results support a model of brain organization that includes areas that are specialized for the combination of particular syntactic and interpretive operations and the use of the meanings produced by those operations to accomplish task-related operations.

This paper presents new data regarding deficit-lesion correlations in the area of syntactic comprehension in PWA. We begin with a brief introduction to syntactic comprehension, then review work relating lesions to disorders of syntactic comprehension, and then present our study.

The term “syntactic comprehension” refers to the processes of assigning syntactic structure to linguistic input (often called “parsing”) and using that structure to determine propositional meanings (sometimes called “interpretation”). Syntactic comprehension is an important human cognitive function because propositional meanings express relations between concepts that are not inherent in word meanings themselves, such as who is accomplishing and receiving an action (thematic roles of agent, theme, etc.), how mental states are related to one another (what a person believes, desires, intends, etc), and others, which are critical to the power of language to represent the world and to aid in thinking and communicating. The propositional meaning of a sentence is determined by its syntactic structure, not simply by associating words to one another, allowing sentences to express unlikely or even impossible

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Address Correspondence to: David Caplan, M.D., Ph.D., Neuropsychology Laboratory, 175 Cambridge Street, Suite 340, Fruit Street, Boston, MA, 02114, Tel: 617-726-3274, FAX: 617-724-7836, dcaplan@partners.org.

relations between items. For example, sentences such as “The man bit a dog” or “A dog was bitten by the man” mean that a particular man bit a dog, not the more likely event that a dog bit the man, because the syntactic structure of these sentences forces this interpretation. The ability to represent unlikely events allows humans to express ideas about what might happen under various possible circumstances; that is, to express counterfactual statements. This ability is critical for inter-individual communication that is used in planning of actions, scientific work, instruction, social organization, and other human activities that involve more than one person.

Although there is considerable disagreement about many details of syntactic structures and how they are constructed from auditory input, there is also widespread agreement about basic features of these representations and their processing. Virtually all contemporary linguistic theories maintain that syntactic representations are complex sets of syntactic categories (noun, verb, verb phrase, etc.) that are hierarchically organized, and that different structures – or different relations among categories in these hierarchical structures – determine different aspects of propositional meaning (thematic roles, the antecedents of pronouns and reflexives, etc.) (Chomsky, 1995; Culicover and Jackendoff, 2005). Virtually all models also agree that, although some aspects of syntactic representations – such as their hierarchical structure – are found in other domains such as mathematics, music and even action organization, and in some animal functions, the specific combination of nodes, organization, and semantic interpretation found in syntax is a unique biological entity (Caplan and Gould, 2008). Virtually all models of speech comprehension maintain that syntactic structures are built and interpreted incrementally (as each word is encountered) (Hale, 2001; Levy, 2008; Lewis and Vasishth, 2005). On-line behavioral measures of syntactic comprehension reflect the operation of parser/interpreter more directly than end-of-sentence measures, which are affected by memory for the content of a sentence, response selection, and other cognitive operations.

The areas of the brain that are involved in syntactic comprehension are of interest for many reasons. Clinically, knowing what brain areas support this function would be expected to help predict the effects of lesions. Scientifically, understanding the neural basis for syntactic comprehension would provide information about the way the human brain is organized to support a unique, and uniquely human, function. This could be a model for other human cognitive functions, or provide evidence that different human cognitive functions are supported in different ways by the brain.

The effects of lesions on syntactic comprehension provide information about the areas of the brain that are necessary for this function. The “deficit-lesion correlation” approach requires both an analysis of the deficits in normal functions that, along with compensatory mechanisms, produce the observed abnormal behaviors and an analysis of the brain areas that are lesioned. Lesions can be described in many ways (e.g., as areas of infarction, areas of hypoperfusion, areas of hypometabolism, patterns of disconnection, etc.); the focus of most work has been on areas of infraction and the implications of their associated deficits for functional specialization of areas of the brain (“localization of function”). We briefly review the criteria for demonstrating that a person with aphasia has a deficit in syntactic comprehension and methods for establishing the location and size of a lesion.

Criteria for diagnosing a syntactic comprehension emerged from the first paper on this subject, by Caramazza and Zurif (1976). These authors described PWA who could not match syntactically complex, semantically reversible ("experimental") sentences (1) to a picture but could match syntactically simple, semantically reversible ("baseline") sentences (2) and semantically constrained sentences (3) to pictures (the term "semantically reversible" indicates that any person or item in the sentence could either perform or receive the action depicted by the verb in the sentence).

1. Syntactically complex, semantically reversible sentence

   The boy who the girl chased was tall

2. Syntactically simple, semantically reversible sentence

   The boy chased the tall girl

3. Semantically irreversible sentence

   The apple the boy was eating was red

Caramazza and Zurif (1976) explained the selectivity of the abnormal comprehension performance in the following way. The good performance on semantically constrained (or "irreversible") sentences (3) indicated that their PWA were able to understand words and to combine the concepts that words evoked into propositions. The good performance on syntactically simple, semantically reversible sentences (2) further indicated that they could apply simple "heuristics," such as assigning the nouns in a sentence the thematic roles of agent and theme on the basis of their order of occurrence. The poor performance on syntactically complex, semantically reversible sentences (1) indicated that they could not assign the thematic roles in a sentence by applying syntactic rules to sequences of words.

Since 1976, the criteria for diagnosing a syntactic comprehension deficit have been refined, although the essentials of the criteria have remained the same. The intent and effect of the refinements have been to increase the likelihood that a person with aphasia who has an observed pattern of behavior has a deficit in syntactic comprehension and not in a related functional ability.

One widely adopted practice is to match the baseline and experimental sentences more closely. Thus, for instance, rather than use (2) as the baseline for (1), a baseline such as (4) might be used:

4. Syntactically simple, matched, semantically reversible sentence

   The boy who chased the girl was tall

(4) is semantically reversible and can be understood by using a heuristic based on the order of the nouns in the sentence (the sentence-initial NP is the agent of every verb) , and so qualifies as a baseline sentence. The fact that (4) is matched to (1) in terms of words, length, and number of thematic roles allows for the conclusion that selectively poor performance on (1) is due to an inability to apply the parsing and interpretive operations found in (1) and not in (4) more clearly than a difference in performance between (1) and (2) does.

A second change in approach has been to study syntactic comprehension in PWA using on-line measures rather than end-of-sentence accuracy. As noted, end-of-sentence performance involves memory for sentence meaning (and possibly form) and is distant from the incremental processing of syntactic structure. Studies using word monitoring (Tyler, 1985, 1995), on-line anomaly detection (Shankweiler et al, 1989), cross modal priming (Balogh et al, 1998; Love, et al, 2001, 2008; Burkhardt et al, 2003), self-paced listening (Caplan and Waters, 2003; Caplan et al, 2007a) and eye tracking in sentence picture matching (Hanne et al, 2011; Meyer et al, 2012) and in the visual world paradigm (Dickey and Thompson, 2009, Dickey et al, 2007; Thompson and Choy, 2009) have provided empirical data relevant to mechanisms that might underlie these disorders. Hypotheses regarding the mechanisms that produce syntactic comprehension disorders that have emerged from on-line studies include the ideas that the deficit consists of slowed lexical processing (Balogh et al, 1998; Love, et al, 2001, 2008), slowed processing of syntactic structure (Burkhardt et al, 2003), slowed integration of lexical and syntactic information (Meyer et al, 2012), and excessive sensitivity to meanings derived from sources other than parsing and interpretation (Caplan, in prep).

A third change, not widely adopted, is to gather information on the performance of PWA in more than one task. Caplan et al (2006, 2007a, 2013a) showed that performance in individual PWA differed for the same sentence type in different tasks, indicating that a performance in one task is not a reliable measure of parsing and interpretation. Caplan et al (2006, 2007a, 2013a) argued that abnormalities in syntactic comprehension that are seen only in one task are deficits in the ability to combine parsing and interpretation with the operations needed to perform a task, not deficits in parsing and interpretation themselves. Deficits in parsing and interpretation themselves should be task-independent.

On the neurological side, delineation of lesions on CT and MR scans is now standard in lesion-deficit correlation studies of syntactic comprehension deficits. The methods used to determine the location and size of lesions vary across studies and all face challenges in identifying some lesion boundaries (e.g., boundaries of lesions that abut the subarachnoid space or the ventricle). A few studies have included imaging of perfusion and metabolism, which usually identify larger areas of lesion than seen on CT or “structural” MR scans, and of white matter connectivity.

We know of six papers in the literature that that report deficit-lesion correlations for syntactic comprehension deficits in chronic stroke PWA that meet the criteria that deficits have been closely related to syntactic comprehension and that use modern, reliable imaging techniques — Caplan et al. (1996, 2007b), Warren et al. (2009), Thothathiri et al. (2012) and Tyler et al. (2010, 2011). [1]

Caplan et al. (1996) obtained CT scans in 18 PWA with left hemisphere strokes. The cortex and lesions were segmented and parcellated using computer-assisted algorithms. Five perisylvian regions of interest (ROI)s were defined following the Rademacher et al (1992) criteria: the pars triangularis and the pars opercularis of the inferior frontal gyrus, the supramarginal gyrus, the angular gyrus, and the first temporal gyrus excluding the temporal tip and Heschl’s gyrus. Normalized lesion volume was calculated within each ROI. Syntactic comprehension was assessed using an object manipulation task presenting 12 examples of each of 25 sentence types. The “experimental” and “baseline” sentence types were constructed to assess the ability to understand sentences containing overt referentially dependent noun phrases (pronouns or reflexives) and sentences containing what are referred to as phonologically empty noun phrases (PRO, NP-trace and wh-trace) in Chomsky’s mode, of syntax (Chomsky, 1986, 1995). The comparison of “experimental” and “baseline” sentence types resulted in nineteen separate measures of particular syntactic operations.

None of the correlations between these nineteen measures of particular syntactic operations with normalized lesion volume in the language zone, normalized lesion volume in each of the five ROIs, and normalized lesion volume in the anterior and posterior ROIs were significant. These correlations remained insignificant when the effect of overall lesion size was partialled out. The results all remained unchanged in ten PWA who were studied and scanned at the same time relative to their lesions. Detailed analyses of single cases with small lesions of comparable size, who were tested at about the same time after their strokes, indicated that the degree of variability found in quantitative and qualitative aspects of PWA’ performances was not related to lesion location or the size of lesions in the anterior or posterior portion of the perisylvian association cortex. Caplan et al (1996) concluded that these results were inconsistent with both localizationist and distributed models of the neural basis for syntactic comprehension, and that they suggested that different brain regions were required for syntactic comprehension in different individuals.

Caplan et al (2007b) studied 42 PWA secondary to left hemisphere strokes and 25 control subjects for the ability to assign and interpret three syntactic structures (passives, object extracted relative clauses, and reflexive pronouns) in enactment, sentence–picture matching and grammaticality judgment tasks. The sentence–picture matching and grammaticality judgment tasks were presented both with uninterrupted auditory presentation and in a self-paced listening fashion (as in Ferreira et al, 1996a, b, and Caplan and Waters, 2003). Differences in accuracy on experimental and baseline sentences were used as measures of the ability to construct and utilize specific syntactic structures to determine aspects of

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[1] Several papers that we are aware of have been said to provide data that are relevant to syntactic comprehension but fail to meet the criteria above. In several papers, the behavioral criteria for a syntactic comprehension deficit were not met. Karbe et al. (1989) related hypometabolism (based on FDG PET) to comprehension on the Western Aphasia Battery. The WAB does not distinguish between semantically reversible and irreversible sentences, or present pairs of reversible sentences that differ minimally from one another. Kempler et al (1991) also measured hypometabolism based on FDG PET and related it to performance on the Token Test. The Token Test requires the examinee to designate or manipulate different numbers of tokens, each of which is described by phrases with different numbers of adjectives. It therefore creates a strong confound between short term memory and syntactic comprehension. The final section of the Token Test presents a larger range of sentences but does not contain minimal baseline-experimental pairs; Kempler et al did not report correlations of PET measures with the final section of the Token Test. Two papers (Dronkers et al, 2004; Amici et al., 2007) used the Curtiss-Yamada Comprehensive Language Evaluation (CYCLE) to assess syntactic comprehension. The CYCLE is a sentence picture matching test with both syntactic and lexical foils for many items, and both papers that used the CYCLE did not separate errors in which lexical foils were selected from errors in which syntactic foil were selected, thereby including errors that reflect disorders of word comprehension in their measure of syntactic comprehension. Amici et al. (2007) divided the sentences in the CYVCLE into three sets and reported effects of lesions for each set, but each set contained some sentence types with lexical foils that were not removed from the analyses. In addition, the CYCLE does not allow comparison of performance on matched baseline and experimental reversible sentences. With respect to lesion measurement, in many early studies, lesion location was inferred on the basis of aphasic syndrome (e.g., individuals with Broca’s aphasia were assumed to have lesions in Broca’s area -- Caramazza & Zurif, 1976; Grodzinsky, 1990) or on the basis of a combination of behavioral and neurological data (Caplan et al, 1985). In others, CT and MR scans were analyzed by applying templates by eye (Dronkers et al, 2004; Dick et al., 2001), using a method that is known to have low inter-observer reliability (correlations of about 80% for analyses that assign the quartile involvement of large regions of interest by a lesion: Naeser & Hayward, 1978).) Dick et al. (2001) found no relation between lesion location in 56 PWA and performance on an actor identification test with 16 examples of each of four sentence types -- active, subject cleft, object cleft, and passive. Tramo et al (1988) showed unanalyzed CT scans in three PWA with Broca’s aphasia. The one PWA who had a posterior lesion was able to matched reversible passive sentences to pictures two years after her stroke; the 2 PWA who had anterior lesions were at chance.

sentence meaning, and a "combined syntactic complexity score" was obtained (accuracy on passive and object relatives *vs* actives and subject relatives). Self-paced listening times corrected for word duration and frequency were used as measures of local processing load. Differences in these times at words at which parsing and interpretive operations applied in experimental sentences and corresponding words in corresponding baseline sentences were used as measures of on-line parsing and interpretation.

Magnetic resonance scans and 5-deoxyglucose positron emission tomography data were obtained on 31 PWA and 12 controls. Six cortical regions of interest were determined using the same algorithms as in Caplan et al (1996). Four encompassed the perisylvian area: the inferior frontal region (consisting of the inferior frontal gyrus pars opercularis and triangularis and the adjacent portion of the frontal operculum), the posterior half of the superior temporal gyrus (corresponding to Wernicke's area), the inferior parietal lobe (consisting of the angular and supramarginal gyri), and the insula. Two were outside the perisylvian area -- the inferior anterior temporal lobe (consisting of the anterior inferior temporal gyrus and the temporal pole), and the superior parietal lobe (consisting of the region posterior to the postentral gyrus and the precuneus). These six ROIs included all the areas of the brain that had been related to syntactic comprehension in either deficit-lesion correlation or functional neuroimaging studies at the time of publication. The percent of these ROIs that was lesioned on MR and the mean PET counts per voxel in these ROIs (normalized to contralesional brain areas in the distribution of the anterior and posterior cerebral arteries, not affected by transneuronal degeneration via the corpus callosum from infarcted areas of the left hemisphere, and cerebellum) were calculated.

Regression analyses were used to relate lesion measures and performance. Percent lesion volume in Wernicke's area, the inferior parietal lobe and the anterior inferior temporal area were significant predictors of the combined syntactic complexity score in object manipulation, and total lesion volume and total subcortical lesion volume were significant predictors of the combined syntactic complexity score in sentence picture matching with uninterrupted presentation. FDG PET activity in the left inferior parietal lobe and in the entire perisylvian cortex were significant predictors of the combined syntactic complexity score in object manipulation, and FDG PET activity in the insula was a significant predictor of the combined syntactic complexity score in sentence picture matching with uninterrupted presentation. No neural measures were significant predictors of on-line processing. Examination of individual participants showed that PWA who performed at similar levels behaviorally had lesions of very different sizes, and that PWA with equivalent lesion sizes varied greatly in their level of performance. Caplan et al (2007b) concluded that these results were consistent with those of Caplan et al (1996) in not providing support for either localizationist or distributed models of the neural basis for syntactic comprehension, and in suggesting that different brain regions were required for syntactic comprehension in different individuals. A point that was not discussed by Caplan et al (2007b), but that we introduce here, is that the effects of lesions differed for object manipulation and sentence picture matching, suggesting the lesions in these brain areas support the interaction of syntactic comprehension and task performance, not syntactic comprehension itself.

Warren et al (2009) studied the effect of lesion location and size and the functional connectivity of the left anterolateral superior temporal cortex (LalSTC) in 24 PWA and 11 controls who were tested on spoken and written word and sentence comprehension using subtests of the Comprehensive Aphasia Test (Swinburn et al, 2004) and on syntactic comprehension with the Test for Reception of Grammar (TROG: Bishop, 1979). In the aphasic group, there was a significantly positive correlation between the connectivity strength between left and right alSTC and spoken word and sentence comprehension performances. No measures of functional connectivity were correlated with performance on the TROG. PWA who showed positive functional connectivity between left and right alSTC performed better on spoken word and sentence comprehension than PWA whose functional connectivity measures were negative, but did not differ on the TROG. The study therefore did not show effects of the neural parameters that were measured on syntactic comprehension.

Thothathiri et al (2012) studied 79 PWA using a sentence-picture matching task with five examples of each of six sentence types (actives, actives with prepositional phrases, passives, locatives, subject relative clauses, and object relative clauses). Imaging consisted of either CT or MR scans. For MR scans, lesions were drawn manually onto a structural image which was normalized to MNI space. For CT images, an experienced neurologist drew the lesion directly onto the normalized atlas. Voxel-based lesion symptom mapping revealed a significant association between damage in temporo-parietal cortex and overall sentence comprehension, which remained significant after a measure of phonological memory was used as a covariate. There was also a significant association between damage in temporo-parietal cortex and comprehension of both sentences with canonical thematic role order (using previous terminology, these are the “baseline” sentences -- active, subject relative) and sentences with non-canonical thematic role order (“experimental” sentences -- passive, object relative sentences). The VLSM analysis did not show any areas associated with the difference between noncanonical and canonical sentence scores, but the regional analysis found that the difference score was significantly correlated with damage in part of the inferior parietal lobe (BA 39).

Tyler et al (2010) studied 14 PWA and reported voxel-based lesion symptom mapping of effects of sentence type on word monitoring times. They presented three types of stimuli – normal sentences, grammatically correct but nonsensical sentences (anomalous prose), and random word strings – and measured participants’ reaction times to detect a word in each stimulus. Normal controls showed faster RTs for target words that appeared late in normal sentences and anomalous prose, which the authors said reflects the predictive value of the accruing syntactic and semantic representations, which is not available in random word strings. The authors argued that the purest measure of syntactic processing is the word position effect in syntactic prose, which reflects the predictive value of syntactic structure alone. PWA showed a position effect only in normal sentences. Voxel-based lesion symptom mapping showed a significant positive correlation between T_1 signal integrity in left pars orbitalis and triangularis and the size of the position effect in anomalous prose. The authors interpret this as “showing that increasing damage in left BA47/45 was associated with impaired syntactic processing (p. 3403).” [2] There are a number of issues that make this result hard to interpret. First, error rates were not reported, so speed-accuracy trade-offs cannot be assessed. Second, a larger difference score could be due to many combinations of slower and faster RTs for early and late targets. It would be useful to see the effect of tissue integrity on RTs for early and late targets separately. Third, the absence of a correlation between tissue integrity in left BA47/45 and the size of the position effect in normal sentences is puzzling, because PWA did show an position effect in normal sentences (and not in anomalous prose) and because the syntactic processing that produces the position effect in anomalous prose contributes to the effect in normal sentences.

Tyler et al (2011) studied the same 14 PWA as Tyler et al (2010) and reported voxel-based lesion symptom mapping for two additional measures of syntactic comprehension. The first was accuracy in matching semantically reversible active and passive sentences to pictures. Separate correlations of tissue integrity with syntactic errors in active and passive sentences showed that more damage in LIFG, LpMTG, LSTG and SMG was correlated with increasing syntactic errors in passive sentences, but not active sentences (their Supplementary Materials, Fig. 3). The second measure of syntactic comprehension was performance on an acceptability judgment task. Tyler et al used the difference in error rates in accepting correct ambiguous and matched unambiguous sentences as the measure of syntactic comprehension. They found that more tissue damage in left middle temporal gyrus and left inferior frontal gyrus (BA 45, extending into BA 44 and BA 47) was related to smaller differences in error rates in ambiguous compared to unambiguous sentences. Tyler et al based their interpretation of this result on the fact that error rates in controls were high (42.4%) for ambiguous sentences that were later disambiguated towards their less preferred interpretation. Tyler et al argued that these high error rates show that normal individuals were highly sensitive to the preferred interpretation of the ambiguous segment, and concluded that smaller differences between error rates in ambiguous and unambiguous sentences in PWA indicated less normal sensitivity to syntactic structure and its interpretation. However, PWA did better than controls on ambiguous sentences, which makes it hard to use their performance as evidence for a deficit in comprehension. A more straightforward measure of syntactic comprehension would simply be the error rates on each type of sentence.

Overall, the evidence regarding the effect of lesions in PWA with chronic stroke on syntactic comprehension is limited. Limitations arise with respect to the number of participants and/or the number of sentence types studied and/or the number of examples of each sentence type that was presented. Tyler et al (2010, 2011) reported only 14 PWA; Caplan et al (1996) reported 18. Thothathiri et al (2012) reported 79 subjects, but only presented five examples of each sentence type, which is likely to miss reliable but small differences in performance of different PWA. Caplan et al (2007b) is intermediate in both regards, presenting 10 examples of each sentence type to 42 PWA. With two exceptions (Tyler et al, 2010), one of which is hard to interpret, the results are based on accuracy in end-of-sentence tasks, not on-line observations. No previous study has reported reliability statistics.

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[2] Tyler et al (2010) also conducted an fMRI study in which BOLD signal activity associated with different conditions was reported. This aspect of their study is not related to deficit-lesion correlations.

The results of existing studies are inconsistent. Of the six studies that meet criteria for identifying syntactic comprehension deficits and use modern neuroimaging, two report null results (Caplan et al, 1996; Warren et al, 2009). With respect to positive findings, the effect of tissue damage in Tyler et al (2011) differed from that in Thothathiri et al. (2012), with Tyler et al (2011) reporting effects of lesion size in LIFG, LpMTG, LSTG and SMG on comprehension of passives and Thothathiri et al (2012) reporting an effect of lesion size only in the left inferior parietal lobe on comprehension of passive and object relative sentences. Caplan et al (2007b) found yet another pattern – there was no effect of lesion size in specific ROIs on syntactic complexity scores that were similar to the measure in Thothathiri et al (2012) in SPM, and FDG PET activity in the insula predicted these scores in SPM. Tasks affected results. In Caplan et al (2007b), lesion volume in Wernicke's area, the inferior parietal lobe and the anterior inferior temporal lobe and PET activity in the inferior parietal lobe predicted syntactic complexity scores in OM, but not in SPM. To our knowledge, there is no evidence for an equivalent effect of a focal lesion on syntactic comprehension performance in more than one task. Tyler et al (2010, 2011) reported correlations of lesion size in Broca's area with performance of PWA in three tasks, but results are hard to interpret in two of the three tasks. The limited available data thus suggest that focal lesions affect syntactic comprehension performance differently as a function of task.

Four studies report syntactic comprehension following acute stroke. Three measured both infarct size using diffusion weighted imaging (DWI) and the apparent diffusion coefficient (ADC) and perfusion using perfusion weighted imaging (PWI). One defined areas of infarction using DWI imaging.

Davis et al (2008) reported one PWA with hypoperfusion in 85% of BA 45 and 47% of BA44, which resolved within 36 hours. While these regions were hypoperfused, the PWA performed at chance on answering yes/no semantically reversible questions and matching semantically reversible active and passive sentences to videos. These deficits resolved completely after reperfusion.

Newhart et al (2012) studied 53 PWA with strokes on their first hospitalization day. They measured the size of infarction and hypoperfusion in Broca's area (BA 44 and 45) and 12 other BAs (6, 10, 11,18, 19, 20, 21, 22, 37, 38, 39, 40) on a three point scale: (1) part, (2) all, or (0) none. Comprehension was tested with both sentence-picture matching and object manipulation, presenting 10 reversible and 10 constrained sentences of each of four types of sentences (active, passive, subject-cleft, object-cleft). They defined a deficit in syntactic comprehension where three criteria were met: 1) performance was at or below chance level on passive reversible sentences on at least one test (SPM or object manipulation); 2) there was greater than 10 percentage points lower accuracy on passive compared to active sentences and object-cleft compared to subject-cleft sentences; and 3) there was greater than 10 percentage points lower accuracy on reversible compared to irreversible sentences. Lesions in the angular gyrus were associated with syntactic comprehension deficits by these criteria, and there was a trend for lesions in BA45 to be associated with these deficits as well. However, these criteria are questionable because the difference between performance on passive and active sentences that was needed to establish a dissociation in performance was chosen arbitrarily and is very low, and, when applied to passives and actives, was apparently calculated for all sentences (reversible and constrained). Newhart et al also compared performance of PWA with and without lesions in these ROIs. PWA with ischemia in left BA 45 and the supplementary motor area (SMA) and were significantly more impaired than those without ischemia in these regions in comprehension of reversible passive sentences in SPM. PWA with ischemia in left 39 were significantly more impaired than those without ischemia in these regions in comprehension of passive reversible sentences in SPM and OM, and in comprehension of cleft object reversible sentences in SPM.

Race et al (2013) studied 38 PWA within 24 hours of hospital admission for the ability to answer 6 yes/no constrained and 4 yes/no reversible questions. Lesion size (infarction and hypoperfusion) was measured in nine Brodmann areas (6, 21, 22, 37, 39, 40, 44, 45, 46). Their figure 2 shows better performance on reversible questions in PWA without ischemia than in PWA with ischemia in all areas; the difference was significant in BA6, 39 and 40. Lesions in BA 39 and 40 were also associated with word comprehension deficits.

Magnusdottir et al (2012) studied 50 pwa within 20 days of infarction (identified by DWI MRI) in a sentence-picture matching task using five examples of each of nine sentence types. All sentences were semantically reversible. Three had canonical thematic role order and three had non-canonical thematic role order. VLSM showed that overall performance was predicted by the presence of a lesion in a large area of the posterior left hemisphere encompassing the middle and superior temporal gyri, inferior parietal cortex, angular gyrus, superior to inferior occipital cortex, fusiform gyrus and middle temporal lobe. Lesions in the superior and posterior portions of this area were more predictive of performance on the canonical sentences, and lesions in the inferior and anterior portions of this area were more predictive of performance on the non-canonical sentences. Lesions in anterior superior and middle temporal gyri and the temporal pole predicted the difference between performance on canonical and non-canonical sentences.

These studies in acute stroke are also limited. All data consist of end-of-sentence accuracy measures and two studies used small numbers of sentences. The results are not consistent across studies. Davis et al (2008) reported effects of hypoperfusion in BA 44/45 on answering reversible questions, not seen in Race (2012); Magnusdottir et al (2012) found that lesions in STG and MTG were most predictive of disturbances of comprehension that required syntactic processing. Overall, the most consistent finding in both chronic and acute stroke is that posterior lesions and hypoperfusion, in inferior parietal and superior and middle temporal lobe, affect syntactic comprehension, but much remains to be learned about the effects of lesions on this function.

The study reported here adds additional information about these topics, based on MR scanning in 31 chronic PWA who were studied for the ability to understand eleven sentence types in three tasks, providing on-line as well as end-of-sentence measures of performance.

Methods

Participants[3]

Thirty-one aphasic PWA (12F, 19M; age: 60.9 years (s.d.: 13.1); education: years 15.3 (s.d.: 2.9)) were tested. PWA were required to be aphasic as determined by a physician or speech-language pathologist, right handed, have a single left hemisphere stroke, be able to perform the tests, and to have adequate single word comprehension to not fail because of lexical semantic disturbances. PWA were screened for disturbances of phoneme discrimination, auditory lexical decision and spoken word-picture matching, and were trained on the words in the sentences, if necessary. Forty-six age and education matched controls (mean age: 64.2 years, sd: 11.3, range: 38 – 87; mean education: 16.3 years, sd: 2.3, range: 8 – 28; M:F = 20:26) were also tested.

Materials and Procedures

Syntactic Comprehension

The ability to parse and interpret passives, object extracted clefts, object extracted relative clauses, and sentences with reflexives and pronouns was tested by having PWA respond to pairs of sentences in which the baseline sentence did not contain the construction/element in question or could be interpreted on the basis of a heuristic and the experimental sentence contained the structure/element and required the assignment of a complex syntactic structure to be understood. In addition, the ability to combine operations was tested by presenting sentences with relative clauses and either a reflexive or a pronoun. Twenty examples of each sentence type were presented. Table 1 lists the sentence types used.

For analysis of AMW data, in each sentence pair, a “critical word” in the experimental sentence was paired with a corresponding word in the corresponding baseline sentence. The critical words in the experimental sentences were ones at which an incremental parser performed an operations not needed in the baseline sentence, or where the demands of an operation were greater in the experimental than in the baseline sentence. In the experimental passive and corresponding baseline active sentences, the critical word was the main verb. In the experimental sentences with object extracted relative clauses and corresponding baseline sentences with subject relative extracted clauses, the critical word was the relative clause verb. In the experimental sentences with pronouns and reflexives, the critical word was the pronoun or reflexive, and in the corresponding baseline sentences with a third noun phrase in the position of the pronoun or reflexive, the critical word was the third noun phrase.

Subjects were tested in object manipulation (OM) and picture matching (SPM) tasks, the latter with both whole sentence (Full SPM) and self-paced listening (auditory moving windows – AMW-SPM) presentation conditions, using digitized computer-delivered auditory stimuli. Accuracy and end-of-sentence reaction time in Full SPM and AMW-SPM were measured. Procedures were as in previous studies (Caplan et al, 1985, 1996, 2006,

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[3] The participants in this study are a subset of those reported in Caplan et al (2013a, b) and at meetings of several scientific societies (Academy of Aphasia, Neurobiology of Language, CUNY sentence processing). The descriptions of PWA and behavioral methods are the same as in prior publications and are repeated here for the reader’s convenience.

2007, 2013a, b; Caplan and Hildebrandt, 1988; Caplan and Waters, 2003) and will be summarized briefly. All sentence stimuli were recorded by one of the authors (DC) at a normal, but slow, speaking rate, and digitized using SoundEdit software. Pictures were created as JPEG files. Auditory and visual stimuli were used to create experiments in Superlab, which were presented on Macintosh iBook computers, with auditory files presented over headphones. In all studies, sentences were presented in a pseudo-randomized order, so that three or more examples of the same sentence type never occurred in succession.

Enactment (Object Manipulation (OM))—In the enactment task, participants indicated thematic roles and co-indexation by manipulating paper dolls. PWA were told that the purpose of the experiment was to test their abilities to understand "who did what to whom" in the sentences. They were instructed to indicate "who did what to whom" by acting out the sentence using the items provided. The experimenter emphasized that the PWA did not need to show details of the action of the verb, but had to clearly demonstrate which item was accomplishing the action and which item was receiving it. The experimenter then proceeded with the digitized sentences and videotaped the participant's responses. See Caplan et al. (1985) and Caplan and Hildebrandt (1988) for a fuller description of the task.

Sentence-Picture Matching with uninterrupted auditory presentation (Full SPM)—In this test, each sentence was played auditorily with two black and white line drawings in full view of the participant, and the participant was required to choose the drawing that matched the sentence by pressing one of two keys on the computer keyboard using fingers on the non-paretic hand. Drawings depicted the thematic roles in the sentence and an alternate set of thematic roles that depicted either the reverse set of thematic roles or an incorrect antecedent of a pronoun or reflexive (Figure 1). Correct and incorrect pictures were displayed equally frequently on the right and left side of the computer screen; order of presentation on each side was randomized within sentence type. Responses were scored for accuracy and reaction time (RT).

Sentence-Picture Matching with auditory self paced (auditory moving window) presentation (AMW SPM)—The method was based on Ferreira et al. (1996a, b) and identical to that used in Caplan and Waters (2002) and Caplan et al (2007a). The files were edited by placing a “tag” in the waveform at each word boundary and saving segments (tag to tag portions of the waveform) as individual audio files. The participant's task was to pace his/her way through the sentence as quickly as possible, by pressing a computer key for the successive presentation of each segment, and choose the correct picture, as in Full SPM. If a participant pressed the button before the end of a segment, the segment was truncated at the point of the button press in order to discourage participants from pressing the button before they had heard and processed each segment. Inter-response times between successive button presses, as well as response time and accuracy on the SPM task, were recorded. Word duration was subtracted from button response time to yield “corrected self paced listening times” to adjusted for word length (for details, see Caplan et al, 2013b).

Short term working memory (ST-WM)

Ten tests of ST-WM were administered. Six were simple tests of immediate serial recall: Digit Span, Word Span; Span for Phonologically Similar Words; Span for Phonologically Dissimilar Words; Span for Long Words; Span for Short Words. The contrast between performance on Span for Phonologically Similar and Dissimilar Words is a measure of the Phonological Similarity Effect, an indication of the preservation of the Phonological Store in Baddeley's model. The contrast between performance on Span for Long and Short Words is a measure of the Word Length Effect, an indication of the preservation of the rehearsal mechanism in Baddeley's model. Four tests required both retention and manipulation of items: Alphabet Span, Backwards Digit Span, Subtract-2 Span, and Sentence Span. These tests were considered to assess the Central Executive component of ST-WM, which has been related to syntactic processing (Just and Carpenter, 1992, but see Caplan and Waters, 1999, 2012). We here report the results after performance on ST-WM was regressed from measures of syntactic comprehension (see below). Because Sentence Span requires sentence comprehension, which overlaps with the syntactic abilities being studied, it was dropped from the measure of ST-WM. Materials and methods for the remaining three tests are described here (see Caplan et al, 2013b, for discription of all tests).

Materials for Backwards Digit Span and Subtract-2 Span consisted of the digits 0 – 9. In Alphabet Span, they consisted of two syllable middle frequency words. Participants listened to lists of words or digits presented over headphones at a rate of one stimulus per second. In Backwards Span, they reported the digits in the list in the reverse order of presentation. In Subtract-2 Span, they reported the result of subtracting two from each digit, in the order in which the digits were presented. In Alphabet Span, they reported the words in the stimulus list in alphabetical order. In Sentence Span (Waters & Caplan, 1996), they listened to a series of sentences in a simple syntactic form (cleft subject) and indicated whether the sentence was acceptable or not. After seeing all sentences in a set they reported the final words of all of the sentences in the set in the order they had occurred. RT and accuracy on the sentence processing component of the task as well as word recall were measured.

Because of speech production disorders in some aphasic participants, participants made pointing responses in all tasks. In Subtract-2 Span and Backwards Span, the digits 0 through 9 were displayed on a computer screen. In Alphabet Span, the stimulus words and two additional words drawn from the same pool of words were displayed on a computer screen.

For both control participants and PWA, each task began with a practice session consisting of three trials at Span 2. Following the practice session, for controls, the task began at list length 2 and continued to list length 8, regardless of performance on lower spans. For PWA, the task began at list length 2 and continued to list length 5, regardless of performance on lower spans. The lower limit was selected because many PWA performed at very low levels at list lengths 4 or 5 on several tasks, leading to concerns about attrition due to frustration, with potentially significant loss of participants in all aspects of the study. For PWA who performed correctly on at least 3/5 trials at List Length 5, 6 or 7 correct, testing continued to the next list length.

Performance was scored for the number of items recalled in the correct serial position. Each participant's span score was determined to the highest list length at which s/he achieved at least 3/5 trials correct (regardless of performance on lower spans), plus 0.5 to the score if s/he achieved 2/5 trials on the next list length after the last one in which s/he achieved at least 3/5 correct. The total number of items each subject reported correctly in the correct order was also calculated. The number of correct responses in the last list length tested in PWA who were not tested to list length 8 was always less than 2, indicating that these measures of item and order recall did not significantly underestimate the performances of PWA who were not tested at longer list lengths.

Neuroimaging

Participants underwent a single MRI scanning session that included T1-weighted-MRI and DT-MRI. MRI scanning was performed on a Siemens 3.0T Tim Trio system (Siemens, Erlangen, Germany), equipped with 32-channel head coil. Head movement was restricted using expandable foam cushions. An automated scout image was acquired and shimming procedures conducted to optimize field homogeneity that was then utilized for subsequent slice positioning (van der Kouwe et al., 2005). Automatic alignment was done at acquisition time using "autoalign" (van der Kouwe et al., 2005). After scanning, each MR image data set was saved and transferred to CD and maintained in duplicate copy. A high resolution 3D Multi-Echo (ME) MPRAGE sagittal sequence, which minimizes signal from the dura in the pial surface (van der Kouwe et al., 2008), was collected with an isotropic resolution of 1 mm^3 (TR = 2.53 s, TI = 1.2 s, TE = 1.64/3.5/5.36/7.22 ms, bandwidth = 651 Hz/px, flip angle = 7°, FOV = 256 mm, 256×256 matrix, 176 slices, slice thickness = 1mm). Data was checked by visual inspection for artifacts such as ghosting and blurring principally due to motion.

Automated computational reconstruction of brain surface, cortical thickness maps, and segmentation of cortical and subcortical structures were undertaken using established protocols (Fischl et al., 2004; Salat et al., 2004) and followed previous work (Caplan et al 2007b). The T1-weighted ME-MPRAGE images from each subject were motion-corrected, averaged, and normalized for intensity using algorithms in the FreeSurfer software package (http://www.martinos.org/freesurfer) (Fischl et al., 1999, 2004; Fischl and Dale, 2000). Intensity variations due to magnetic field inhomogeneities were corrected, normalized intensity images created, and the skull removed from all normalized images using a skull-stripping algorithm (Segonne et al., 2004). Segmentation of cortex was done using algorithms described in prior publications (Dale et al., 1999; Fischl et al., 1999; Fischl and Dale, 2000). Minimal manual editing was performed as necessary, with standard, objective editing rules. High correlations between automated and manual methods have been demonstrated in a series of studies (Fischl and Dale, 2000, 2004; Fischl et al., 2002; Walhovd et al., 2005).

Cortical parcellation divided the cortex into 48 parcellation units ("PUs") (Rademacher et al, 1992; Fischl et al., 2002; Desikan et al., 2006). The first step in the parcellation process was the application of a standard coordinate system to each scan. Three user-specified points were identified the anterior commissure (AC), posterior commissure (PC) and interhemispheric plane (mid-sagittal point, MSP). The Y axis was determined by the anterior commissural - posterior commissural line, the Z axis was set by the intersection of the interhemispheric plane with the AC-PC line, and the X axis was orthogonal to the Y and Z axes. Second, sulci were identified and labeled by a neuroanatomically trained technician. The end-points of selected sulci served as limiting planes that were marked on multiplanar orthogonal views to permit them to be tracked three-dimensionally. Parcellation units were then created as the intersections of sulci and limiting planes. Volumes of parcellation units were derived by summing the voxels in each PU. The resulting volumes of PUs are individualized to each brain and are thus not subject to distortions associated with normalization to an atlas. [4]

In the lesioned hemisphere, segmentation was undertaken for the same set of gray and white matter structures as in the unlesioned hemisphere. The lesion was also segmented. Reconstruction of lesion-ablated structures was achieved by a combination of intensity borders, special image analysis techniques to permit visualization of the lesion borders, and use of correspondence between points of reference in the two hemispheres. Two types of lesion border may be obscured in these analyses, one between necrotic tissue and (apparently) intact gray or white matter, and the other between necrotic tissue and CSF-containing spaces. The first was addressed with intensity contours, as for segmentation in the intact brain. The second type of tissue border, which arises when the lesion extends to the cortical surface and has totally destroyed the cortex and underlying white matter, or extends to the ventricle, was first visualized by selective high contrast "windowing" and decreasing the brightness to near the threshold for visual detection of the image. A "veil" of surviving meningeal connective tissue that delineates approximately the cortical surface configuration becomes apparent under these conditions. The ependyma at the ventricular boundary of a lesion was established in similar fashion. The inner border of the destroyed cortical ribbon (that is, the destroyed cortical-white matter border) was estimated from the average cortical thickness in the opposite hemisphere and is generally about 2–3 mm in width.

The lesioned hemisphere was parcellated with the same procedure used in intact brains. Two classes of anatomical landmarks upon which the parcellation system is based were applied to lesion parcellation -- a set of points along the Y axis that specifies the location of X-Z co-ordinate planes, such as the tip of the genu and splenium of the corpus callosum, and points that specify locations defined by all three of the coordinate axes, such as the intersections of

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[4] The remainder of the segmented hemisphere, including central white matter, hippocampus and subcortical gray matter structures, was parcellated entirely computationally from the landmarks specified in the neocortical parcellation step plus four additional sub-cortical points specified by the user. The diencephalon was divided into two broad regions, the thalamus-epithalamus and hypothalamus-subthalamus, by an X-Y plane passing through the AC-PC line. The dorsal thalamus was subdivided into anterior, medial, lateral and posterior subdivisions; the caudate into head, body and tail; the putamen into anterior and posterior subdivisions; and the amygdala was separated from its apparent continuity with the hippocampal formation. The internal-external segments of the globus pallidus and the remainder of the diencephalon were not subdivided. The central white matter was divided into four concentric radial domains: (1) the corona radiata, subjacent to the neocortex; (2) the external sagittal stratum (which includes ipsilateral longitudinal fiber bundles); (3) the interhemispheric fibers of the corpus callosum; and (4) the internal capsule and the fornix-fimbria fibers. The corona radiata was parcellated by proximity into units corresponding to the overlying neocortical parcellation units. The external sagittal stratum was parcellated into callosal fibers, cingulate bundle, and superior, inferior, and temporal strata containing longitudinal intrahemispheric fibers. The callosal fibers, cingulate bundle, and inferior and superior longitudinal fibers were parcellated into six divisions along their antero-posterior course. The corpus callosum was subdivided into splenium, body (anterior and posterior segments) and genu. We did not analyze these PUs in this study.

precentral, central, or postcentral fissures with the interhemispheric or sylvian fissures. With few exceptions, the mean coordinate positions of these points for all planes (X, Y, and Z axes) are minimally variant (< 2–3 mm) between the two hemispheres, allowing their locations in the intact hemisphere of a lesioned brain to determine their approximate locations in the lesioned hemisphere. The application of segmentation and parcellation directly to images reduces mischaracterization of areas that are due to the effect of distortions of structures seen in images after stroke in normalization to templates.

The combined segmentation and parcellation procedures resulted in a total of 48 cortical parcellation units, associated white matter units (corona radiata), 27 deep white matter units, and 15 subcortical gray matter regions in each hemipshere. Each of these units was segmented in two dimensions, as described above, but involved three dimensions, due to MR slice thickness. For each brain, the volume of each parcellation unit was thus expressed as the number of voxels assigned to that structure. Lesion volume in each parcellation unit was expressed as the number of voxels in the lesion in that unit. The extent of damage to each parcellation unit was expressed as the percent of each reconstructed parcellation unit that was occupied by a lesion. The percent of left hemisphere cortex occupied by a lesion were also calculated. The resulting volumes of lesions are expressed as percentages of individual PWA’s PUs, and, like the volumes of PUs themselves, are not subject to distortions associated with normalization.

Results

Behavioral Results

Performance on the comprehension and short term/working memory tests is summarized for the 31 PWA reported here in Tables 2 – 4. The results are highly reliable, with Pearsons’ *r* and the Spearman Brown reliability co-efficients for each sentence type in each task for the PWA all significant (all *p*s < .001).

The sentences were grouped to reduce the number of analyses. Four sets of sentence types were considered, grouping together sentences with common linguistic elements:

1. Passive (P) vs Active (A).
2. Relative Clauses: Object extraction (CO, SO, SOREF and SOPRO) vs Subject extraction (CS, SS, SSREF and SSPRO)
3. Pronouns (PRO, SOPRO, SSPRO) vs sentences with referential NPs (3NP, SO, SS)
4. Reflexives (REF, SO REF, SS REF) vs sentences with referential NPs (3NP, SS)

We investigated whether age and time since stroke affected syntactic comprehension, by correlating the behavioral measures with age and time since stroke in the entire group of PWA and in the 31 PWA who were scanned. None of these correlations were significant and these factors were dropped from further analyses.

Neurological Results

We analyzed the effects of lesions on performance in parcellation units in which eight or more PWA had lesions. There were 21 such PUs, listed in Table 5. Lesions were more frequent in areas supplied by the middle cerebral artery. The four areas that were most frequently lesioned were the pre- and post- central gyri and their opercular cortex, and the insula. All areas in perisylvian cortex associated with language were ones in which eight or more PWA had lesions.

We used regression analyses to determine the effect of lesion size in parcellation units on syntactic comprehension. In all analyses, the dependent variable was a measure of performance for the experimental sentences in a sentence type group – accuracy, RT to respond in sentence picture matching, and corrected self-paced listening times for critical words. To measure lesion effects on syntactic comprehension independent of short-term/ working memory and the ability to assign propositional meaning through the use of heuristics, we used forward regression analyses in which we first entered measures of short term/working memory, and performance on baseline sentences. The measure of short term/ working memory was the total number of items reported in the correct serial positions in all STM/WM tasks. The measure of performance on the baseline sentences corresponded to the measure of syntactic comprehension -- accuracy, response RT, and corrected self paced listening times on words in baseline sentences that corresponded to critical words in experimental sentences. To reduce the possibility that a significant effect lesion size in a parcellation unit was due to effects in other parcellation units that were also infarcted, we also entered total lesion volume (percent of left hemisphere cortex) that was lesioned in the regressions. After these three variables were entered, we then entered percent lesion in each parcellation unit. The effect of percent lesion in each parcellation unit on performance on the experimental sentence measure after the effects of the other three variables are removed reflects the effect of lesion size in that parcellation unit on the ability to assign and interpret the syntactic structure while performing a comprehension task. We report all effects that reached the level of a trend. Bonferroni corrected *p* values can be obtained by multiplying the *p* values in Table 6 by 3.

There were no significant effects of lesion size in any parcellation units on RTs to respond in the two tasks that involved sentence picture matching.

There were three significant effects of lesion volume in particular parcellation units on corrected self paced listening times for critical words in experimental sentences. Greater percent lesion in the posterior portion of the supramarginal gyrus led to longer self paced listening times for critical words in sentences with reflexives. In two cases, greater percent lesion led to *shorter* self paced listening times for critical words. This was the case for lesions in the middle frontal gyrus and on-line processing in sentences with reflexives, and for lesions in the orbital frontal cortex and these measures of on-line processing in sentences with pronouns.

Effects of lesion volume in PUs on accuracy on a sentence type are listed in Table 6. There were eleven effects of lesion volume in parcellation units on accuracy for experimental sentences that were significant or at the level of a trend. Table 6 also lists the unique variance associated with lesion size on accuracy on the sentence type in difference tasks -- the squared semi-partial correlation (part correlation) of the percent lesion in each parcellation unit – and the difference in part correlations for the PU on that sentence type in different tasks. Cohen et al (2002) suggest that differences in unique variance of 2% should be considered weak, 9% moderate and 25% strong.

Larger lesions in the posterior superior temporal gyrus were associated with lower accuracy in sentences with passives in object manipulation. The difference between the unique variance in passives associated with lesion size in this PU in object manipulation and the unique variance in passives in sentence picture matching with either full or self paced presentation was large.

Larger lesions in the angular gyrus were associated with lower accuracy in sentences with object extracted relative clauses in sentence picture matching with full sentence presentation. The difference between the unique variance in object extracted relative clauses associated with lesion size in this PU in sentence picture matching with full presentation and the unique variance in object manipulation was moderate.

Larger lesions in the angular gyrus were also associated with lower accuracy in sentences with pronouns in sentence picture matching with auditory moving windows presentation. The differences between the unique variance in pronouns in sentence picture matching with auditory moving windows presentation associated with lesion size in this PU and the unique variance in pronouns in either sentence picture matching with full presentation or in object manipulation were moderate.

Larger lesions in the pars opercularis were associated with lower accuracy in sentences with pronouns in sentence picture matching with full sentence presentation. Larger lesions in the pars opercularis were also associated with lower accuracy in sentences with reflexives in sentence picture matching with full sentence presentation and in object manipulation.

Larger lesions in the pars triangularis were associated with lower accuracy in sentences with reflexives in object manipulation.

Larger lesions in the frontal pole were associated with lower accuracy in sentences with reflexives in object manipulation.

Larger lesions in the basal forebrain were associated with lower accuracy in sentences with reflexives in sentence picture matching with auditory moving windows presentation.

Larger lesions in the posterior portion of the supramarginal gyrus were associated with higher accuracy in sentences with reflexives in sentence picture matching with full sentence presentation and with auditory moving windows presentation. The difference between the unique variance sentences with reflexives associated with lesion size in this PU in sentence picture matching with full sentence presentation and the unique variance in sentences with reflexives in object manipulation was moderate.

Discussion

This study addresses some of the concerns regarding the database of deficit-lesion studies of syntactic comprehension raised in the introduction to this paper. The range of paring/ interpretive operations assessed is wide and is tested in depth -- the study presented four different types of syntactic operations, three of which using several sentence types containing the structure or requiring the operation, twenty sentences of each type, and two tasks, one of which had two presentation conditions. Accuracy, RT, and self-paced listening times were collected. The analyses focused on the ability to construct and interpret particular syntactic structures after taking into account PWA's ability to understand words, to understand matched baseline sentences that did not contain the experimental structures, STM/WM, and the effect of total lesion size.

A limitation of this study was that, although the number of PWA studied was larger than in many studies, it was relatively small. There is a trade-off between the extent to which an individual PWA can be tested and the number of PWA that can be tested in a study; this study increased depth and breadth of testing at the expense of greater sample size. Because of the relatively small sample size, we consider all results here to be suggestive, as is the case, in our view, for all studies of this subject in the literature. Our reporting of results that reach the statistical level of a trend is consistent with the view that results here are suggestive. We note that the most important results are reliable at conventional levels, including those with Bonferroni correction.

We begin by discussing two results that appear to be aberrant – the findings that larger lesions in two areas (middle frontal gyrus and orbital frontal cortex) were associated with shorter self paced listening times and that larger lesions in the supramarginal gyrus were associated with higher accuracy in sentences with reflexives in both sentence picture matching tasks.

The finding that larger lesions in some PUs were associated with faster self paced listening times seems paradoxical but can potentially be understood by considering the distribution of listening times in PWA and controls. Using the same regression as here without the neurological variables, Caplan et al. (under review) found that some PWA had residual self paced listening times for critical words in experimental sentences that were very short and outside the normal range. In most cases, these very short residual self paced listening times were associated with higher than normal rates of errors. This suggests that both very long and very short duration of on-line processing can be pathological. Very long duration of on-line processing is usually taken an indication that some incremental process is inefficient in a PWA (the same interpretation as is made in neurologically normal individuals). The inefficient process could be parsing, interpretation and/or performing a comprehension task. Very short duration of on-line processing that is associated with low comprehension performance has not been studied. Caplan et al (under review) suggested that it results from abnormal functioning of the control system, which must decide how much time to allow incremental processes to operate before requesting the next input. Longer times allocated to processing allow for more complete analysis but increase the time material must be maintained in memory. Very short durations of on-line processing that are associated with low comprehension performance could result from several abnormal functions of the executive control system. The control system might set abnormally low criteria for success in the task, leading to a speed-accuracy trade-off that increases speed of examination of the current word at the expense of final accuracy in comprehension. There may be limitations in the ability to maintain task goals – a limitation of “exective attention.” Other control abnormalities could be imagined. The finding that lesion size in middle frontal gyrus and orbital frontal cortex was associated with faster self paced listening times suggests that these regions are involved in these control processes. The fact that the negative relationship between lesion size and self paced listening times was only found for one sentence type suggests that control processes operate differently for different structures. Without obtaining data on incremental processing in a second task, it is impossible to know if they also operate differently in different tasks.

The second finding that is hard to explain is that larger lesions in the posterior supramarginal gyrus were associated with higher accuracy in sentences with reflexives. One possible explanation for this finding could be that this region is responsible for adding entities into the discourse representation, an operation that is required for the third NP in the baseline sentences but not in the experimental sentences (which contain reflexives). However, if this were the case one would expect lesion size in this area to be negatively correlated with accuracy on the baseline sentences, which was not found to be the case. We therefore cannot account for this finding. We can only offer the speculation that one effect of activity in this region is to inhibit activity in another that is involved in comprehension of these sentences.

Turning to results that comport with expectations, the finding that larger lesions in the posterior portion of the supramarginal gyrus were associated with longer self-paced listening times for reflexives is one of the few instances of an effect of lesion on a measure of on-line syntactic processing. It points to a role for this area in processing reflexives in this task. As reviewed above, documentation of relations between on-line measures of syntactic comprehension and lesions have been hard to document. This is likely partly due to the paucity of studies that have sought these relationships and the limited power of studies that have. This study also has limited power because of the relatively small number of PWA that were studied. Studies with greater power may reveal more such relations.

The finding that larger lesions in some areas resulted in lower accuracy on experimental sentences (relative to baseline sentences) was also expected. This study replicated previous findings that lesions in Broca’s area (pars opercularis and triangularis of the inferior frontal gyrus) and Wernicke’s area (the posterior half of the superior temporal gyrus) were associated with syntactic comprehension disorders. There were also effects of lesions outside the classic language areas – in the frontal pole and the basal forebrain – on syntactic comprehension.

The effect of lesion location differed for different syntactic structures. Larger lesions in pSTG were associated with lower accuracy on passives, larger lesions in the angular gyrus were associated with lower accuracy on object extracted relative clauses, and larger lesions in the supramarginal gyrus, pars opercularis and triangularis, the frontal pole, and the basal forebrain were associated with lower accuracy on sentences with pronouns or reflexives.

This suggests that these regions support the construction and/or interpretation of particular syntactic operations.

In no case was the effect of lesion size in a PU on accuracy for a sentence type found in all tasks. In two cases – the effect of lesions in the angular gyrus on object relatives (found in sentence picture matching with full sentence presentation) and on sentences with pronouns (found in sentence picture matching with auditory moving windows presentation) – the difference between the unique variance associated with the lesion in the task in which the lesion effect on the sentence type was significant and at least one task in which the lesion effect on the sentence type was not significant was moderate. In one case -- the effect of lesions in the posterior superior temporal lobe on passives (found in object manipulation) – the effect of the lesion was significant (not just a trend) and the difference between the unique variance associated with the lesion in the task in which the lesion effect on the sentence type was significant and a task in which the lesion effect on the sentence type was not significant was strong.

These results indicate that the effects of lesions on the ability to demonstrate that a PWA has assigned and interpreted particular syntactic structures differ in different tasks. The difference between tasks was not an artifact of properties of performance or the lesions. Table 2 shows that performance was well below ceiling and had large variance on all sentence types in all tasks. Similarly, the fact that there were significant effects of lesion size in these areas and the comprehension of a structure in one task indicates that the lack of effects of lesion size in these areas and comprehension of a structure in another task is not due to limited variance in lesion size in those areas. The function that becomes increasingly deficient as lesions in these areas become larger is also not simply the ability to evaluate the congruence between the thematic roles depicted in pictures and those in a spoken sentence, or to enact thematic roles, because those abilities are required in all the sentences presented in the SPM and OM tasks.

The selective relation of lesions in different areas to sentences with different syntactic elements and structures in different tasks thus indicates that the effect of a lesion in those areas is not to affect parsing and/or interpretive operations themselves. Rather, the effect of a lesion in these areas is on the combination of the parsing and interpretive operations in that sentence type and the use of the information derived from those operations to perform a task. If the effect of a lesion in an area was on parsing and/or interpretive operations themselves, lesion size in that area would correlate negatively with accuracy in the affected sentences in all tasks.

The finding that larger lesions in these areas led to lower accuracy but not to longer self paced listening times for critical words in these sentences delineates a temporal window within which the operations that are affected by lesions in these areas occur. They must occur after a PWA presses the response key to hear the next word in a sentence and before s/he selects a response for the task. The fact that this window follows initial incremental processing is consistent with the view that lesions in these areas affect operations that select responses on the basis of both the meaning of a sentence and its syntactic elements and structure.

The view that brain areas support the combination of comprehension and task-related operations is consistent with a "situated" model of cognitive and language, that maintains that knowledge is attained through activity associated with social, cultural and physical contexts and is represented in relation to such activity. In the area of syntactic comprehension, situated language processing has received support from results such as finding that the nature of items in an array affects the on-line interpretation of syntactically ambiguous sentences (Tanenhaus et al, 1995; Farmer et al, 2007). Most theories assume that situated processing results from the integration of multiple brain areas. However, it could also be supported by functional specialization for particular combinations of cognitive and task-related operations, which could arise as a result of the development of a skill. The repeated combination of parsing and interpretive operations with task-related operations could lead to the development of skilled operations in different domains, such as extracting the meaning of sentences from sound and mapping them onto the visual world, which could be supported by particular brain areas, at least in part. A potentially interesting finding is that the regions in which there is the strongest evidence for task-specific, structure-specific effects of lesions (significant effects of lesion size on one structure in one task and moderate to large differences in unique variance in that structure accounted for by lesion size in different tasks) are all posterior, involving the posterior half of STG and the adjacent AG. This requires further study.

Regional specialization for combinations of operations does not preclude the brain supporting skilled integrated performance in other ways, such as through the interaction of many brain regions or novel sets of brain regions being activated in novel ways "on the fly" under some circumstances (e.g., to accomplish new tasks). It only maintains that one aspect of brain organization is that operations that are frequently performed together can come to utilize and eventually to require particular brain areas.

To summarize, the major result of this study is the finding that the size of lesions in small areas of the left hemisphere were negatively related to accuracy in particular operations required for syntactic comprehension in particular tasks. This suggests that these areas are specialized for these operations in these tasks. The view of cortical specialization suggested here has not been proposed in other areas of cognition, to our knowledge. If it receives additional support from other studies in the area of syntactic comprehension, consideration of task effects on neural correlates of other cognitive functions would become an interesting topic to explore. The view of cortical specialization suggested here raises the question of what combinations of operations can be co-localized this way, and what the conditions are that produce such co-localization.

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Highlights

This paper reports effects of lesions on syntactic comprehension 31 in PWA

It tests 11 sentences types, reflecting 4 structures, and uses two tasks, one with two presentations

Performance on baseline sentences, WM and percent LH lesion are regressed out

Lesion in small areas had different effects on a structure in different tasks

The results suggest a situated model of regional specialization

Fig. 1.
Sample stimulus

Table 1

Sentence Types.

Sentence Type	**Example**
Active (A)	The girl **hugged** the boy.
Passive (P)	The boy was **hugged** by the girl.
Three Noun Phrases (3NP)	The niece said that the girl hugged the ***boy***.
Pronoun (PRO)	The niece said that the girl hugged ***her***.
Reflexive (REF)	The niece said that the girl hugged ***herself***.
Cleft Subject (CS)	It was the girl who **hugged** the boy.
Cleft Object (CO)	It was the boy who the girl **hugged**.
Subject Object (SO)	The boy who the girl **hugged** washed the ***woman***.
Subject Subject (SS)	The girl who **hugged** the boy washed the ***woman***.
Subject Subject and Pronoun (SSPRO)	The woman who **hugged** the girl washed ***her***.
Subject Object and Pronoun (SOPRO)	The woman who the girl **hugged** touched ***her***.
Subject Subject and Reflexive (SSREF)	The woman who **hugged** the girl washed ***herself***.
Subject Object and Reflexive (SOREF)	The woman who the girl **hugged** touched ***herself***.

Verbs in bold underline and pronouns and NPs in bold italics served as measures of on-line performance (see text). Experimental-Baseline contrasts used to examine effects of structures were as follows:

Passive: P-A

Object Extraction: CO-CS, SO-SS, SOPRO-SSPRO, SOREF-SSREF

Pronouns: PRO-3NP, SSPRO-SS, SOPRO-SO

Reflexives: REF-3NP, SOREF-SO, SSREF-SS

Table 2

Performance (accuracy) of people with aphasia on sentence comprehension tests.

	Sentence Picture Matching with Auditory Moving Window Presentation												
	A	**P**	**3NP**	**PRO**	**REF**	**CS**	**CO**	**SS**	**SO**	**SSPRO**	**SOPRO**	**SSREF**	**SOREF**
PWA Mean	82.1	79.9	84.6	74.5*	86.3	83.4	74.3*	75.7	63.1*	75.2	63.7*	71.9	63.5*
PWA std	18.4	20.2	16.0	21.0	21.0	18.4	23.0	20.1	22.4	21.0	20.6	22.5	19.9
EC Mean	94.8	94.1	97.9	93.1	98.7	95.7	94.4	93.4	91	96.6	88.4	95.8	83.7
EC std	6.1	8.3	5.8	4.4	3.7	6.7	6.2	9.7	8.9	6.9	14.8	7.9	13.1
	Sentence Picture Matching with Full Sentence Presentation												
	A	P	3NP	PRO	REF	CS	CO	SS	SO	SSPRO	SOPRO	SSREF	SOREF
PWA Mean	83.8	77.5*	81.7	74.5*	80.4	81.2	72.6*	70.0	66.5$^+$	71.1	60.1$^{*,+}$	69.3	61.0$^{*,+}$
PWA std	15.3	18.4	17.3	21.9	23.8	18.6	20.4	17.8	14.8	19.8	20.5	20.5	17.7
EC Mean	95.1	93.6	97	96.3	97.2	95	92.6	92.1	82.3	95.1	82.4	94.2	83
EC std	3.6	6.5	5.5	5.7	4.8	4.5	6.6	8	13.4	6.1	14.1	8.9	12.7
	Object Manipulation												
	A	P	3NP	PRO	REF	CS	CO	SS	SO	SSPRO	SOPRO	SSREF	SOREF
PWA Mean	88.1	77.6*	66.3	68.8	67.0	88.2	71.8*	56.2	33.5*	53.3	36.8*	60.4	37.1*
PWA std	16.9	27.0	35.6	32.9	39.9	18.3	28.8	41.5	37.8	42.6	33.3	39.5	37.7
EC Mean	100	99	97.2	97.4	95.4	100	98.8	99	84.2	91.8	83.4	96.4	87.9
EC std	0	6.7	14.9	13.4	17.8	0	6	2.7	21.2	25.6	24.2	15.1	22.9

Sentence type labels as in Table 1 * indicates a significant difference between the experimental sentence annotated and its baseline (e.g., PRO and 3NP in sentence picture matching with auditory moving window presentation.

$^+$indicates a significant difference between SOPRO and SO and between SOREF and SO sentences.

Table 3

Performance (RT) of people with aphasia on sentence comprehension tests. Sentence type labels as in Table 1.

	Sentence Picture Matching with Auditory Moving Window Presentation												
	A	**P**	**3NP**	**PRO**	**REF**	**CS**	**CO**	**SS**	**SO**	**SSPRO**	**SOPRO**	**SSREF**	**SOREF**
PWA Mean	1178	1242	1016	1115	940	932	1038	1180	1472	1343	1522	1145	1383
PWA std	823	885	692	822	615	652	695	848	970	922	940	766	817
EC Mean	527	599	529	559	522	501	534	584	778	650	836	600	775
EC std	236	272	270	285	277	258	278	329	393	328	402	346	414
	Sentence Picture Matching with Full Sentence Presentation												
	A	P	3NP	PRO	REF	CS	CO	SS	SO	SSPRO	SOPRO	SSREF	SOREF
PWA Mean	4944	5402	6480	6212	5486*	5762	6447*	7298	7927	7543	7996	7157	7789
PWA std	1674	1874	1911	1792	1430	1722	1868	2034	2215	2156	1940	1893	2204
EC Mean	3284	3591	4502	4465	4154	3990	4482	4831	4986	4795	5243	4565	4864
EC std	801	779	834	827	733	698	753	863	737	875	720	881	781

Table 4

Performance on ST-WM tests

CONTROLS					
Task	**Mean**	**SD**	**Minimum**	**Maximum**	**Maximum**
Word	85.13	23.85	41	158	158
Digits F	131.48	35.44	64	175	175
WORD DIS	79.45	29.22	38	161	161
WORD SIM	51.23	22.96	22	118	118
WORD SHORT	74.88	17.62	41	121	121
WORD LONG	71.55	22.23	38	124	124
Digits B	85.43	39.54	25	167	167
Sent	35.33	20.69	8	96	96
Alpha	88.78	35.98	39	159	159
Sub2	74.43	36.09	25	168	168
PWA					
Task	Mean	SD	Minimum	Maximum	Maximum
Word	52.23	30.22	0	125	125
Digits F	55.46	47.54	0	173	173
WORD DIS	44.52	35.16	0	131	131
WORD SIM	27.65	32.31	0	136	136
WORD SHORT	40.06	31.25	0	126	126
WORD LONG	43.52	34.39	0	160	160
Digits B	30.77	37.53	0	166	166
Sent	10.69	16.61	0	68	68
Alpha	38.31	30.52	0	123	123
Sub2	40.65	37.24	0	171	171

Table 5

Distribution of lesions

Parcellation Unit		Numer of pwa with lesion	Mean lesion percent	SD	Minimum	Maximum
OLs	occipital lateral gyri, superior division	8	8.5575	10.43732	0.23	27.5
PHa	parahippocampal gyrus, anterior division	8	2.935	3.0357	0.04	8.73
AG	angular gyrus	10	34.927	21.5499	4.34	76.95
FP	frontal pole	10	5.979	6.4945	0.05	20.77
T1p	superior temporal gyrus, posterior division	10	46.428	41.15907	1.23	100
BFsbcmp	basal forebrain	12	13.45917	12.17854	0.03	43.56
F3t	inferior frontal gyrus, pars triangularis	12	43.3125	35.91228	0.2	100
H1	Heschl’s gyrus	12	75.41583	35.05663	4.53	100
PP	planum polare	12	68.08833	36.26746	2.67	100
SGa	supramarginal gyrus, anterior division	12	59.42333	42.43712	1.03	100
F2	middle frontal gyrus	13	20.14	26.14542	0.02	88.95
FOC	fronto-orbital cortex	13	23.85308	24.68038	0.02	74.47
PO	parietal operculum	13	75.29615	37.6085	3.15	100
PT	planum temporale	13	68.01538	33.55446	2	100
SGp	supramarginal gyrus, posterior division	15	31.03267	28.48812	0.22	84.51
F3o	inferior frontal gyrus, pars opercularis	16	41.76813	39.29025	3.51	100

Parcellation Unit		Numer of pwa with lesion	Mean lesion percent	SD	Minimum	Maximum
FO	frontal operculum	16	66.06813	34.60829	0.16	100
POG	postcentral gyrus	17	15.19176	16.56305	0.24	48.38
CO operculum	central	21	57.03619	39.20564	0.05	100
INS	insula	21	51.64381	41.17554	0.02	100
PRG	precentral gyrus	23	8.9113	16.65685	0.01	69.6

Parcellation Unit	Number of pwa with lesion
OLs	occipital lateral gyri, superior division
PHa	parahippocampal gyrus, anterior division
AG	angular gyrus
FP	frontal pole
T1p	superior temporal gyrus, posterior division
BFsbcmp	basal forebrain subcomponent (sublnticulate extended amygdala, hypothalamus, subthalamic nucleus, red nucleus, substantia nigra)
F3t	inferior frontal gyrus, pars triangularis
H1	Heschl's gyrus
PP	planum polare
SGa	supramarginal gyrus, anterior division
F2	middle frontal gyrus
FOC	fronto-orbital cortex
PO	parietal operculum
PT	planum temporale
SGp	supramarginal gyrus, posterior division
F3o	inferior frontal gyrus, pars opercularis
FO	frontal operculum

Parcellation Unit	Number of pwa with lesion
POG	postcentral gyrus
CO	central operculum
INS	insula
PRG	precentral gyrus

Table 6

Significant effects of percent lesion in parcellation units on accuracy on experimental sentences. The table shows the results of forwards regressions in which the dependent variable is accuracy on experimental sentence and the in dependent variables are total WM span, accuracy on baseline sentence, percent lesion in the LH cortex, and percent lesion in each parcellation unit (entered last).

			Unstandardized Coeff				**Std Coeff**				**Differences in part correlations**		
PU	**sentgrp**	**task**	**Estimate (B)**	**StdErr**	**tValue**	**p**	**Beta**	**R-square**	**Part Correlation**	**%Unique**	**AMW-Full**	**AMW -OM**	**Full-OM**
Posterior perisylvian areas													
T1p	PvA	AMW	−0.255	0.147	−1.740	0.143	−0.553	0.532	0.283	0.531	0.022	0.347	0.368
T1p	PvA	Full	−0.245	0.135	−1.820	0.129	−0.560	0.544	0.301	0.553			
T1p	PvA	OM	−0.295	0.068	−4.320	0.013	−0.604	0.962	0.178	0.185			
AG	ObjSubj	AMW	−0.384	0.331	−1.160	0.299	−0.531	0.578	0.114	0.196	0.018	0.195	0.177
AG	ObjSubj	Full	−0.173	0.078	−2.210	0.078	−0.408	0.846	0.151	0.178			
AG	ObjSubj	OM	0.021	0.189	0.110	0.916	0.036	0.658	0.001	0.002			
AG	Pro	AMW	−0.282	0.115	−2.440	0.059	−0.387	0.905	0.113	0.125	0.122	0.093	0.029
AG	Pro	Full	−0.034	0.165	−0.210	0.844	−0.051	0.754	0.002	0.003			
AG	Pro	OM	−0.097	0.244	-0.400	0.710	-0.144	0.555	0.018	0.032			
SGp	Ref	AMW	0.130	0.051	2.520	0.033	0.217	0.953	0.033	0.035	0.162	0.007	0.170
SGp	Ref	Full	0.309	0.091	3.400	0.008	0.492	0.867	0.171	0.197			
SGp	Ref	OM	0.190	0.175	1.090	0.304	0.194	0.827	0.023	0.028			
Anterior perisylvian areas													
F3o	Pro	AMW	−0.058	0.039	−1.470	0.169	−0.148	0.912	0.017	0.019	0.063	0.018	0.081
F3o	Pro	Full	−0.127	0.067	−1.880	0.086	−0.293	0.798	0.065	0.082			
F3o	Pro	OM	−0.026	0.101	−0.260	0.803	−0.036	0.844	0.001	0.001			
F3o	Ref	AMW	0.002	0.045	0.060	0.957	0.006	0.885	0.000	0.000	0.065	0.032	0.033
F3o	Ref	Full	−0.116	0.062	−1.890	0.086	−0.267	0.832	0.054	0.065			
F3o	Ref	OM	−0.166	0.076	−2.190	0.051	−0.207	0.931	0.030	0.032			

			Unstandardized Coeff				Std Coeff				Differences in part correlations		
PU	**sentgrp**	**task**	**Estimate (B)**	**StdErr**	**tValue**	**p**	**Beta**	**R-square**	**Part Correlation**	**%Unique**	**AMW-Full**	**AMW -OM**	**Full-OM**
F3t	Ref	AMW	−0.072	0.062	−1.160	0.283	−0.158	0.895	0.020	0.023	0.082	0.048	0.035
F3t	Ref	Full	−0.168	0.093	−1.800	0.115	−0.337	0.816	0.085	0.105			
F3t	Ref	OM	−0.241	0.096	−2.530	0.039	−0.285	0.929	0.065	0.070			
Non-perisylvian areas													
BF	Ref	AMW	−0.537	0.108	−4.960	0.002	−0.412	0.979	0.073	0.075	0.011	0.061	0.071
BF	Ref	Full	−0.605	0.358	−1.690	0.135	−0.406	0.826	0.071	0.086			
BF	Ref	OM	0.382	0.406	0.940	0.378	0.153	0.899	0.013	0.014			
FP	Ref	AMW	−0.007	0.531	−0.010	0.991	−0.003	0.859	0.000	0.000	0.018	0.071	0.052
FP	Ref	Full	−0.425	0.686	−0.620	0.562	−0.141	0.807	0.015	0.018			
FP	Ref	OM	−1.453	0.360	−4.030	0.010	−0.303	0.979	0.069	0.071			