

Mapping syntax using imaging: problems and prospects for the study of neurolinguistic computation

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The study of language in the brain is the study of the computations responsible for the structure and processing of language. Hemodynamic imaging techniques can make a contribution to this area, but only if paired with a theory of the underlying formal processes. Statements like 'syntax is mediated by Broca's area' are too coarse (cognitively and cytoarchitecturally) to constitute insights into neurolinguistic computation. Numerous studies of syntactic processing report activation in Broca's area. However, other studies implicate Broca's area in non-syntactic/non-linguistic tasks, ruling out a restrictive linguistic interpretation of this region. This problem results from the failure to recognize that 'syntax' is not a monolithic task, nor is 'Broca's area' a monolithic area. Further progress in this area requires linking neuroimaging studies with detailed theories of the linguistic and non-linguistic computations.

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Non-invasive imaging techniques fall into two classes: **hemodynamic** (PET, fMRI) and **electromagnetic** (EEG, MEG). A primary thread in imaging research has been directed at identifying brain areas associated with subcomponents of linguistic competence, such as **phonology** (Poeppel 1996), **syntax** (Stowe et al. 2004), and **semantics** (Bookheimer 2002). Research in this area makes extensive use of hemodynamic imaging because the impressive spatial resolution offered by such techniques (millimeter scale) lends itself naturally to functional mapping. Here we examine a set of findings that implicate Broca's area - the canonical language area - in syntactic processing, and review the extent to which recent results converge in a way that is interpretable from the perspective of the language sciences. Our focus is on the experimental and conceptual issues that render results from imaging difficult to interpret. We put aside discussion of the more technical problems that confront functional imaging studies, including issues associated with the experimental design (e.g. subtraction methodology), analysis (complexity and potential arbitrariness of criteria in data analysis), and implicit assumptions about the relationship between loci of activation and cognitive systems.

The activation of Broca's area has been reported in many studies of both syntactic comprehension and production (Caplan et al. 1998, Dapretto and Bookheimer 1999, Embick et al. 2000, Friederici et al. 2000, Friederici 2002, Homae et al. 2002, Indefrey et al. 2001, Kaan and Swaab 2002, Kang et al. 1999, Moro et al. 2001,

Musso et al. 2003, Newman et al. 2003, Ni et al. 2000), from which it has been concluded that this area has a privileged status with respect to this aspect of grammar. One complicating factor is the use of different terminologies in identifying the relevant cortical regions. In particular, there are reports in terms of both Brodmann areas (i.e. BA 44/45) and in terms of gyral and sulcal anatomy (pars opercularis, pars triangularis; also F3op, F3t). Because these definitions are not coextensive, there is potential for terminology-induced confusion. This situation is in principle capable of being remedied by making reference to standardized coordinate systems, such as the atlas of Talairach and Tournoux (1988), although this process itself is not unproblematic because of the anatomical transformations that are required for such a standardization. The identification of 'Broca's area' in such terms ranges in Talairach coordinates from x -28 to -55, y -8 to +34, and z 0 to 28 (without even including studies that take BA 47 to be part of Broca's area). It seems, then, that the great range of variability found in the discussion of this area precludes any straightforward biological interpretation.

Specific studies that associate Broca's area with syntax employ a number of different design types. Dapretto and Bookheimer (1999), used fMRI in a **block design**, and presented sentences **auditorily** to subjects who performed one of two tasks. In the 'syntactic' condition, the task was to judge whether two sentences -- one active (*The policeman arrested the thief*), and one passive (*The thief was arrested by the policeman*) -- were the same or different. In a 'semantic' condition, subjects judged 'same' or 'different' for two sentences that differed by a single word (*The lawyer/attorney questioned the witness*) or different (*The lawyer/driver questioned the witness*). Activation in BA 44 was reported for the comparison *syntax* minus *semantics* (as well as *syntax* minus *rest*), and activation in BA 47 for *semantics* minus *syntax*. **Auditory** presentation was also used in the **event-related fMRI** study performed by Ni et al. (2000). Subjects performed syntactic and semantic oddball tasks, in which a sequence of grammatical sentences contained an occasional deviant oddball (syntactic: **Trees can grew*; semantic: *#Trees can eat*). Activation in BA 44/45 was reported for the subtraction of *semantics* from *syntax*. The PET study of Moro et al. (2001) used a **block design** with **visual** presentation was employed in the PET study of Moro et al. (2001); the task involved silent reading and acceptability judgments on four types of Italian sentences. In addition to a baseline of Jabberwocky (*Il gulco gianigevale brale*), there were three types of violation: word-order (**Gulco il gianigevale brale*); morphosyntactic (**Il gulco ha gianigiataquesto brale*); and phonotactic (**Il gulco gianigzlevale brale*). Activation for the syntactic and morphosyntactic conditions minus the phonotactic condition was found in left BA 45, and Right BA 44/45. Kang et al. (1999) used an **event-related** design with fMRI in which subjects were presented **visually** with phrasal stimuli containing syntactic and semantic violations. The stimuli were verb phrases like *drove cars* (the normal condition), in addition to which there were two deviant conditions: syntactically deviant **forgot made*; and semantically deviant **wrote beers*. Relative to the normal condition, activation was found for both the syntactically and semantically deviant stimuli in BA 44/45; the activation in left BA 44 was greater for syntax than for semantics.

In addition to the studies using anomaly detection/judgment outlined above, activation in Broca's area has also been reported in studies of the syntax of artificial language learning (Musso et al. 2003), as well as in studies of syntactic complexity (Caplan et al. 1998). Musso et al. taught subjects artificial 'grammars' with two distinct types of rules. One type was a rule found in natural languages, but not in the language of the subjects. A second type of rule involved a string manipulation of a type that is not attested in the world's languages. Subjects were asked to perform an acceptability task on visually presented sentences. Results showed increased

activation in BA 45 for the first type of rule (real) in comparison with the second type of rule (unreal). Musso et al. conclude from these results that Broca's area is specialized for the learning of syntactically possible rules, independently of the age of the learner. Caplan et al. (1998) show that syntactic complexity effects (measured in terms of processing time differences) are reflected in an increase in signal in Broca's area. They conclude from this that this region is specialized for the processing of certain aspects of syntactic structure.

The activation of Broca's area (defined as BA 44/45) in a number of 'syntax' studies employing distinct tasks and designs seems at first glance to be confirmation of the claim that this area is specialized for syntax. There are two further considerations, however, that suggest that this conclusion is at best an oversimplification.

First, Broca's area has been reported to be active in a number of linguistic tasks that are not syntactic; tasks ranging from lexical tasks, for instance auditory lexical decision (Zatorre et al. 1992, Poeppel et al. 2004) and studies of minimal pairs in tone languages (Gandour et al. 2000), to phonological/phonetic tasks such as the discrimination of rapid phonetic transitions (Fiez et al. 1995), or the processing of phoneme sequences as opposed to hummed notes (Gelfand and Bookheimer 2003). The role of Broca's area in phonetics/phonology is reviewed in Burton (2001). The claim that Broca's area is exclusively devoted to syntax is thus incorrect, although the possibility that Broca's area might be specialized for language in some broader sense is left open.

The second consideration that complicates the view of a syntactic Broca's area is the fact that Broca's area is active in a number of entirely non-linguistic tasks. The tasks include motor activation (Iacoboni et al. 1999), motor imagery (Binkofski et al. 2000, Hamzei et al. 2003), and rhythmic perception (Halpern and Zatorre 1999, Platel et al. 1997). These findings constitute a challenge to the weaker position that Broca's area is specialized for language in the broad sense.

The interpretation that identifies Broca's area as responsible for syntax is informed by sources of evidence other than imaging studies: deficit-lesion studies, electrophysiological studies, and clinical findings, and so on. From the imaging studies, it is clear that a simple association between 'Broca's area' and 'syntax' cannot be maintained. At the same time, the apparent set of contradictions generated by imaging studies cannot be surprising given a realistic view of how cognitive functions -- including syntax -- are computed. In linguistic domains other than syntax, for instance, a complex internal structure is clearly required for processes such as phonetic and phonological analysis, lexical analysis, and so on. Therefore the expectation that syntax should be a simplex, unstructured computation associated with a single undifferentiated cortical region is unrealistic. While it is clear that some of the computational subroutines that are essential for syntactic processing/production are computed in the inferior frontal gyrus (IFG), these are not 'syntax' per se -- they are subcomponents of syntax. What is required is a theory of these computations at the correct level of abstraction or granularity, and theory that seeks to associate these computations with different subparts of 'Broca's area'. For example, two components essential to syntax are the creation of hierarchical structures and a process that linearizes these hierarchical structures. Computations of this type may be factored out of 'syntax' in the broad sense, and are perhaps associated with different subparts of the IFG. The natural assumption is that differently structured cortical areas are specialized for performing different types of computations, some of which are necessary for language but also for other cognitive functions. For instance, the activation of 'mirror neurons' in the IFG has a role in motor action/imitation; but this activation also is relevant to the linguistic domain in

the context of 'forward' models of speech perception (Halle and Stevens 1962). Some preliminary proposals making distinctions among subregions of BA 44/45 are found in Horwitz et al. (2003).

In conjunction with an appropriately granular theory of the computations performed in the brain, the spatial information provided by imaging has the potential to illuminate aspects of the biological foundation of language by providing the critical link between specialized cortical areas and cognitively relevant types of computations.

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