

## Twenty-First Century Psycholinguistics: Four Cornerstones

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## Broca's Complex as the Unification Space for Language

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The 1990s saw an enormous increase in studies investigating the brain correlates of language processing. With the advent of techniques for in-vivo scanning of the human brain in action (e.g., PET, fMRI, MEG), we no longer need to rely on the experiments of nature in the form of a brain lesion, to study the relation between brain and language. One could thus argue that a solid bridge between psycholinguistics and neurobiology has been established. In addition to the classical behavioral measures such as reaction times, speech errors, acceptability ratings, etc., we are nowadays able to measure the neuronal responses that underlie specific language tasks. Psycholinguistics and neurobiology are on common ground, so one could think.

However, there is also another perspective on the relation between psycholinguistics and neurobiology. Many in the field of psycholinguistics feel a deep dissatisfaction about the psycholinguistic quality of most neuroimaging studies on language. The sophistication in psycholinguistics in carefully controlling for numerous potential confounds in the materials (frequency, familiarity, morphological structure, phonological structure, etc., etc.) and in addressing issues based on explicit models of speaking, listening, reading or writing, is very often not present in neuroimaging studies on language. I had the privilege to review the language abstracts for the annual meeting of the Organization for Human Brain Mapping for a number of years. Overall, the psycholinguistic quality of the majority of these submissions is disappointing. In short,

although the bridge between psycholinguistics and neurobiology is there, more traffic back and forth is needed to shape an integrated cognitive neuroscience of language.

In order to define the criteria that an adequate neurobiology of language has to meet, we first need to clarify what we take our *explanandum* to be. If, like myself, one is interested not only in the cognitive architecture of language, but also in the only machinery that so far has been able to instantiate natural language (i.e., the human brain), it is obvious that the bridge between psycholinguistics and neurobiology has to be crossed. However, it is a perfectly valid position to restrict one's explanandum to the *cognitive* architecture of language functions. For a psycholinguist of that kind the brain facts will only be relevant in so far as they can be used to develop, select or constrain a cognitive architecture model for the language function of interest. The cognitive architecture then specifies the levels of representation needed and the processing steps required for accessing representational structures, and for performing the necessary computational operations on them, such that unification of all the relevant bits and pieces results. Even in this case, I believe that brain facts are relevant. Let me give two examples. Recently, Kempen (2003) has proposed an explicit computational model of syntactic processing that deals with both syntactic encoding and grammatical decoding (parsing). For a number of reasons (such as speaker-hearer alignment during dialog (Garrod & Pickering, 2004; Pickering & Garrod, this volume) a common mechanism for grammatical encoding and decoding is attractive. Nevertheless, the common mechanism view goes against the standard view that assumes separate mechanisms for encoding and parsing. To decide empirically between the one vs. two mechanisms architecture, brain facts might be relevant. For instance, a common mechanism view would be hard to reconcile with neuroimaging data that show a clear segregation of areas activated by encoding and areas activated by decoding. Under the reasonable assumption that a common mechanism view and a separate mechanism view have consequences for the hypothesized neural organization of grammatical encoding/decoding, brain facts do contribute to the body of empirical data that might guide the choice for one cognitive architecture option over the other.

A second example relates to the nature of the information flow. For instance, strictly feedforward models of language processing (e.g., Cutler & Clifton, 1999) predict a fixed spatio-temporal pattern of brain activity that is not seriously modulated by attention or output related factors (e.g., task parameters). It is compatible with a serial model of perception and action, in which a perceptual stage is followed by central cognition

(e.g., executive function), which is then followed by appropriate action (cf Fodor, 1983). Recent findings in cognitive neuroscience (e.g., Rizzolatti, Fogassi, & Gallese, 2002) raise serious doubts about the general tenability of the serial model. Whoever's model may finally turn out to be the right one for language perception, it seems that a strictly feedforward model of language perception predicts another spatio-temporal profile of brain activity under various task conditions than an interactive model. Again evidence from MEG/EEG and/or fMRI studies could provide relevant empirical evidence to select among alternative architectural options.

In summary, an adequate neurobiology of language can provide data that are of relevance for specifications in terms of the cognitive architecture of language functions. At the same time, the relevant brain facts can only be obtained in neuroscience research that is strongly guided by state of the art psycholinguistics in terms of theoretical models and experimental materials. Finally, explicit computational models are helpful in achieving the necessary precision in specifying the consequences of particular principles of both cognitive and neural architectures. This is what I refer to as the triangle of cognitive neuroscience, with mutual constraints operating at the levels of the computational models, the cognitive architectures and the neural architectures. The criteria for an integrated neurobiology of language are thus specifications of the neural principles of language functions that are adequate in relation to behavioral data and the cognitive architectures derived from these data (*upward adequacy*), and specifications of the cognitive architectures that are adequate in the light of our understanding of the principles of brain function (*downward adequacy*). The underlying assumption is of course that there is a systematic relation between cognitive states and brain states. Despite claims made in the past that these two levels of description and explanation might not be related in a lawful or transparent way (e.g., Fodor, 1975; Mehler, Morton, & Jusczyk, 1984), the recent success of cognitive neuroscience is seen as an indication that this assumption is valid.

In the remainder of this chapter I outline how in a neurobiological account of language one can specify the contribution of the classical language area, Broca's area, in a way that does justice to both psycholinguistic models of language and our general understanding of this part of the brain.

### BROCA'S COMPLEX

Despite some disagreement in the literature, most authors agree that Broca's area comprises Brodmann Areas 44 and 45 of the left hemisphere.

In the classical textbooks these areas coincide at the macroscopic level with the pars opercularis (BA 44) and the pars triangularis (BA 45) of the third frontal convolution. However, since there is much anatomical variability, in many brains these areas are not easy to identify (Uylings, Malofeeva, Bogolepova, Amunts, & Zilles, 1999). Furthermore, cytoarchitectonic analysis (Amunts, Schleicher, & Zilles, 1997) shows that the borders of areas 44 and 45 do not neatly coincide with the sulci that were assumed to form their boundaries in gross anatomical terms. More fundamentally, one has to ask what the justification is to subsume these two cytoarchitectonic areas under the overarching heading of Broca, rather than, say, areas 45 and 47. Areas 44 and 45 show a number of clear cytoarchitectonic differences, one of which is that 45 has a granular layer IV, whereas 44 is dysgranular. In contrast, like area 45, area 47 is part of the heteromodal component of the frontal lobe, known as the granular cortex (Mesulam, 2002). In addition, areas 44 and 45 have clearly distinct postnatal developmental trajectories and show a difference in their patterns of lateral asymmetry. Using an observer-independent method for delineating cortical areas, Amunts and colleagues (1999) analyzed histological sections of 10 human brains. They found a significant left-over-right asymmetry in cell density for area 44, whereas no significant left-right differences were observed for area 45.

From a neuroanatomical perspective, there thus seems to be no strong motivation to treat Broca's area as a natural kind. There is not (yet) convincing neuroanatomical evidence that necessitates the marriage of BA 44 and BA 45 into one unified area that is motivated from a cytoarchitectonic, histological, and receptor-architectonic point of view. On the basis of imaging studies, it is not unlikely that the pars orbitalis of the third frontal convolution (roughly corresponding to BA47) is part of the frontal language network as well (Devlin, Matthews, & Rushworth, 2003; Hagoort, Hald, Bastiaansen, & Petersson, 2004). From a functional anatomical perspective it thus makes sense to use the term *Broca's complex* for this set of areas. Most of Broca's complex (especially BA 45 and 47) is part of prefrontal cortex, the remainder (especially BA 44) is classically seen as belonging to premotor cortex, just as ventral BA6, which might be involved in language processing as well.

The account that I propose hereafter is based on an embedding of Broca's complex in the overall functional architecture of prefrontal cortex, and a general distinction between memory retrieval of linguistic information and combinatorial operations on information retrieved from the mental lexicon. These operations are referred to as unification or binding.

### Broca's complex as part of prefrontal cortex

Integration is an important part of prefrontal cortex function. This holds especially for integration of information in the time domain (Fuster, 1995). To fulfill this role, prefrontal cortex needs to be able to hold information online (Mesulam, 2002), and to select among competing alternatives (Thompson-Schill, D'Esposito, & Kan, 1999; Thompson-Schill, this volume). Electrophysiological recordings in the macaque monkey have shown that this area is important for sustaining information triggered by a transient event for many seconds (Miller, 2000). This allows prefrontal cortex to select among and to establish unifications between pieces of information that are perceived or retrieved from memory at different moments in time. Recent neuroimaging studies indicate that Broca's complex contribute to the unification operations required for binding single word information into larger structures. In psycholinguistics, integration and unification refer to what is usually called post-lexical processing. These are the operations on information that is retrieved from the mental lexicon. It seems that prefrontal cortex is especially well suited to contribute to post-lexical processing. In the context of language processing, integration includes selection among competing unification possibilities, so that one unified representation spanning the whole utterance remains.

In this chapter I do not review the rapidly increasing number of neuroimaging studies on different aspects of language processing, and on the role of the left inferior frontal cortex in this context. However, what I do is highlight a few points of what I take to be lessons to be learnt from this recent body of evidence.

A first important lesson is that it would be a serious mistake to assume that Broca's area is a language-specific area, and that within the language domain it only subserves one very specific function. As Mesulam has argued in a series of classical papers (Mesulam, 1998, 1990), "many cortical nodes are likely to participate in the function of more than one network. Conceivably, top-down connections from transmodal areas could differentially recruit such a cortical node into the service of one network or another." (1998: 1040). In this conception, a particular cognitive function is most likely served by a distributed network of areas, rather than by one local area alone. In addition, the local area participates in more than one function. For instance, Broca's area has also been found activated when subjects had to search for a target hidden within a complex geometric pattern (Fink et al., in press), or during mental imagery of grasping movements (Decety et al., 1994). A one-to-one mapping between Broca's area and a specific functional component of the language system would thus be a highly unlikely outcome. Nevertheless,

many neurolinguistic accounts of the role of Broca's area still presuppose such a one-to-one mapping (e.g., Grodzinsky, 2000). Data from neuroscience argue against such a kind of organization. Even for the visual system, it is claimed that the representations of, for example, objects and faces in ventral temporal cortex are widely distributed and overlapping (Flaxby et al., 2001). It would indeed be highly surprising if the different representational domains in the language network would behave according to more localist principles than the visual system.

The second lesson to be learnt is that within Broca's complex, there might be functionally defined subregions. By now, there is some indication that this complex shows a ventral to dorsal gradient (Bookheimer, 2002). Roughly speaking, BA 47 and BA 45 are involved in semantic processing, BA 45, 44, and 46 contribute to syntactic processing (see Figure 10.1). Finally BA 44 and BA 6 have a role in phonological processing. Broca's complex is thus involved in at least three different domains of language processing (semantic, syntactic, phonological), with, presumably, a certain level of relative specialization within different subregions of Broca's complex. However, the overlap of activations between these three different types of information is substantial. Subregional specificity within Broca's complex for any of these information types can thus not be concluded.

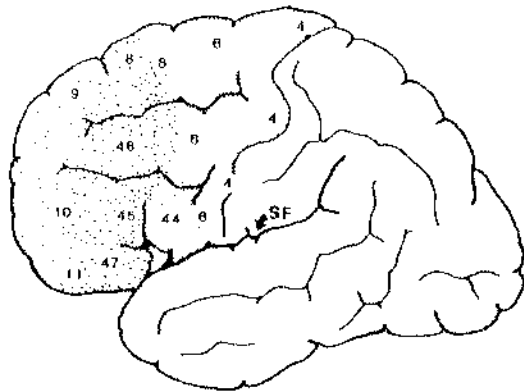


FIG. 10.1. Lateral view of the left hemisphere. Brodmann areas (BA) are marked by number. Classically, Broca's area comprises BA 44 and BA 45. (after Mesulam, 2002). SF: Sylvian Fissure. Sparsely dotted areas: Heteromodal association cortex, including BA 45 and BA 47. Densely dotted area: Motor-premotor cortex, including BA 44 and BA 6.

From a cognitive neuroscience perspective, the conclusion must be that neither at the level of brain structure nor at the level of cognitive function is Broca's area a natural kind. Instead, within the left inferior frontal cortex, it refers to a conglomerate of related but cytoarchitectonically distinct areas with a responsivity to distinct information types within the domains of language comprehension and production. Almost certainly, the conglomerate contributes to other cognitive functions as well. In what follows I propose a role of Broca's complex in what I refer to as binding or unification of information retrieved from the mental lexicon.

### Broca's complex as the unification space for language

Recent accounts of the human language system (Jackendoff, 1999, 2002; Levelt, 1999) assume a cognitive architecture, which consists of separate processing levels for conceptual/semantic information, orthographic/phonological information, and syntactic information. Based on this architecture, most current models of language processing agree that, in on-line sentence processing, different types of constraints are very quickly taken into consideration during speaking and listening/reading. Constraints on how words can be structurally combined operate alongside qualitatively distinct constraints on the combination of word meanings, on the grouping of words into phonological phrases, and on their referential binding into a discourse model.

Moreover, in recent linguistic theories, the distinction between lexical items and traditional rules of grammar is vanishing. For instance, Jackendoff (2002) proposes that the only remaining rule of grammar is UNIFY PIECES, "and all the pieces are stored in a common format that permits unification." (p. 180). The unification operation clips together lexicalized patterns with one or more variables in it. The operation MERGE in Chomsky's Minimalist Program (Chomsky, 1995) has a similar flavour. Thus, phonological, syntactic, and semantic/pragmatic constraints determine how lexically available structures are glued together. In Jackendoff's recent account (2002), for all three levels of representation (phonological, syntactic, semantic/conceptual) information that is retrieved from the mental lexicon has to be unified into larger structures. In addition, interface operations link these three levels of analysis. The contribution of Broca's complex can be specified in terms of the unification operations at these three levels. In short, the left inferior frontal cortex recruits lexical information, mainly stored in temporal lobe structures, and unifies them into overall representations that span multiword utterances. Hereafter, I show in more detail how this could work for the syntactic level of analysis (for more details, see Hagoort, 2003).

According to the Unification Model for parsing (see Vosse & Kempen, 2000) each word form in the lexicon is associated with a structural frame. This structural frame consists of a three-tiered unordered tree, specifying the possible structural environment of the particular lexical item (see Figure 10.2).

The top layer of the frame consists of a single phrasal node (e.g., NP). This so-called root node is connected to one or more functional nodes (e.g., Subject, Head, Direct Object) in the second layer of the frame. The third layer contains again phrasal nodes to which lexical items or other frames can be attached.

This parsing account is 'lexicalist' in the sense that all syntactic nodes (e.g., S, NP, VP, N, V, etc.) are retrieved from the mental lexicon. In other words, chunks of syntactic structure are stored in memory. There are no syntactic rules that introduce additional nodes. In the on-line comprehension process, structural frames associated with the individual word forms

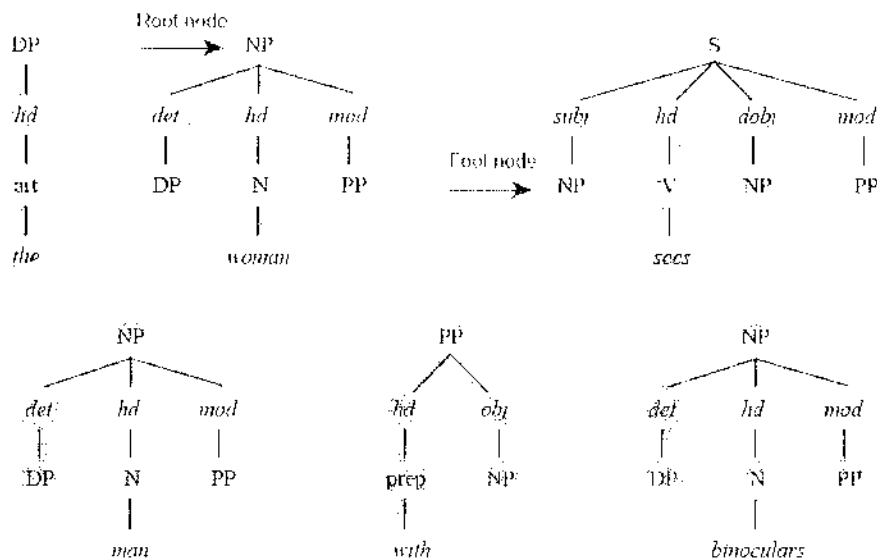


FIG. 10.2. Syntactic frames in memory (the mental lexicon), retrieved on the basis of the word form input for the sentence "The woman sees the man with the binoculars." DP: Determiner Phrase; NP: Noun Phrase; S: Sentence; PP: Prepositional Phrase; art: article; hd: head; det: determiner; mod: modifier; subj: subject; dobj: direct object.

incrementally enter the unification workspace. In this workspace constituent structures spanning the whole utterance are formed by a unification operation. This operation consists of linking up lexical frames with identical root and foot nodes, and checking agreement features (number, gender, person, etc.).

The resulting unification links between lexical frames are formed dynamically, which implies that the strength of the unification links varies over time until a state of equilibrium is reached. Due to the inherent ambiguity in natural language, alternative binding candidates will usually be available at any point in the parsing process. That is, a particular root node (e.g., PP) often finds more than one matching foot node (i.e. PP) with which it can form a unification link (for examples see Hagoort, 2003).

Ultimately, one phrasal configuration results. This requires that among the alternative binding candidates only one remains active. The required state of equilibrium is reached through a process of lateral inhibition between two or more alternative unification links. The outcome of the unification process is thus achieved via a selection mechanism (i.e. lateral inhibition) that 'chooses' between different unification options (cf. Thompson-Schill, this volume). In general, due to gradual decay of activation more recent foot nodes will have a higher level of activation than the ones that entered the unification space earlier. In addition, strength levels of the unification links can vary in function of plausibility (semantic) effects. For instance, if instrumental modifiers under S-nodes have a slightly higher default activation than instrumental modifiers under an NP-node, lateral inhibition can result in overriding the recency effect.

The Unification Model accounts for sentence complexity effects known from behavioral measures, such as reading times. In general, sentences are harder to analyze syntactically when more potential unification links of similar strength enter into competition with each other. Sentences are easy when the number of U-links is small and of unequal strength.

The advantage of the Unification Model is that it is computationally explicit, it accounts for a large series of empirical findings in the parsing literature and in the neuropsychological literature on aphasia, and it belongs to the class of lexicalist parsing models that have found increasing support in recent years (Bresnan, 2001; Jackendoff, 2002; Joshi & Schabes, 1997; MacDonald, Pearlmutter, & Seidenberg, 1994).

This model also nicely accounts for the two classes of syntax-related ERP-effects that are consistently reported over recent years in ERP studies on language. One type of ERP effect related to syntactic

processing is the P600/SPS (Hagoort, Brown, & Grootjens, 1993). The P600/SPS is reported in relation to syntactic violations, syntactic ambiguities, and syntactic complexity. Another syntax-related ERP is a left anterior negativity, referred to as LAN or, if earlier in latency than 400 ms as ELAN (Friederici, Hahne, & Mecklinger, 1996). In contrast to the P600/SPS, the (E)LAN has so far only been observed to syntactic violations. In the Unification Model, binding (unification) is prevented in two cases. One case is when the root node of a syntactic building block (e.g., NP) does not find another syntactic building block with an identical foot node (i.e. NP) to bind to. The other case is when the agreement check finds a serious mismatch in the grammatical feature specifications of the root and foot nodes. The claim is that the (E)LAN results from a failure to bind, as a result of a negative outcome of the agreement check or a failure to find a matching category node. For instance, the sentence "The woman sees the man because with the binoculars" does not result in a completed parse, since the syntactic frame associated with "because" does not find unoccupied (embedded) S-root nodes that it can bind to. As a result, unification fails.

In the context of the Unification Model, I have proposed that the P600/SPS is related to the time it takes to establish unification links of sufficient strength (Hagoort, 2003). The time it takes to build up the unification links until the required strength is reached is affected by ongoing competition between alternative unification options (syntactic ambiguity), by syntactic complexity, and by semantic influences. The amplitude of the P600/SPS is modulated by the amount of competition. Competition is reduced when the number of alternative binding options is smaller, or when lexical, semantic or discourse context modifies the strengths of the unification links in a particular direction, thereby shortening the duration of the competition. Violations result in a P600/SPS because unification attempts are still made. For instance, a mismatch in gender or agreement features might still result in weaker binding in the absence of alternative options. However, in such cases the strength and build-up of U-links will be affected by the partial mismatch in syntactic feature specification. Compared to less complex or syntactically unambiguous sentences, in more complex and syntactically ambiguous sentences it takes longer to build up U-links of sufficient strength. The latter sentences, therefore, result in a P600/SPS in comparison to the former ones.

In summary, it seems that the Unification Model provides an acceptable account for the collective body of ERP data on syntactic processing. It is the most explicit computational model account of these data that is currently around.

The Unification Model also seems to be compatible with PET/fMRI studies on syntactic processing. In a recent meta-analysis of 28 neuroimaging studies, Indefrey (2003) found two areas that were critical for syntactic processing, independent of the input modality (visual in reading, auditory in speech). These two supramodal areas for syntactic processing were the left posterior superior temporal gyrus and the left posterior inferior frontal cortex, substantially overlapping with left prefrontal cortex. The left posterior temporal cortex is known to be involved in lexical processing (Indefrey & Cutler, 2004). In connection to the Unification Model, this part of the brain might be important for the retrieval of the syntactic frames that are stored in the lexicon. The Unification Space where individual frames are connected into a phrasal configuration for the whole utterance might be localized in the left frontal part of the syntax-relevant network of brain areas.

However, unification operations take place not only at the syntactic processing level. Combinatoricity is a hallmark of language across representational domains. That is, it holds equally for syntactic, semantic and phonological levels of analyses. In all these cases lexical bits and pieces have to be combined and integrated into larger structures. The need for combining independent bits and pieces into a single coherent percept is not unique for language comprehension. It also holds for the visual system. In visual neuroscience this is referred to as the *binding problem*. However, the tricks that the brain might use for solving the binding problem in vision most likely don't work for language. The central question in vision is how the different attributes of an object, that are known to be processed in different cortical areas within visual cortex, are brought together so that they result in a unified visual percept. One solution that has gained popularity in recent years, although it is still controversial, is that the mechanism of visual binding is related to the synchronicity of firing in the cell assemblies that code for the individual visual features (Varela, Lachaux, Rodriguez, & Martinerie, 2001).

The major difference between visual perception and language comprehension is that visual binding is more or less instantaneous, whereas language comprehension is extended in time. The relevant areas in visual cortex deliver their specific outputs (e.g., color information, motion information, etc.) within a very narrow time window. On the basis of the available experimental evidence, it is assumed that synchronous networks emerge and disappear at time scales between 100 ms and 300 ms (Varela et al., 2001). In contrast, one of the hallmarks of language processing is that information is spread out over relatively extended time periods. For instance, in parsing the auditory sentence "Noam thought of a couple of nice example sentences for his linguistics

class but by accident wrote them down in his political diary," the information of Noam as the subject of the sentence still has to be available some second or so later when the acoustic information encoding the finite verb form "wrote" has reached auditory cortex.

Crucially, the binding problem for language is how information that is not only processed in different parts of cortex, but also at different time scales and at relatively widely spaced parts of the time axis, can be unified into a coherent representation of a multiword utterance.

One requirement for solving the binding problem for language is, therefore, the availability of cortical tissue that is particularly suited for maintaining information on-line, while binding operations take place. As we have seen, prefrontal cortex seems to be especially well-suited for doing exactly this. It has reciprocal connections to almost all cortical and subcortical structures, which puts it in a unique neuroanatomical position for binding operations across time, both within and across different domains of cognition.

The unification operations at semantic and phonological levels share the extended time characteristics with syntactic processing. Therefore, Broca's complex is also suited for these types of unification operations. Figure 10.3 shows how semantic/conceptual unification and phonological unification could be worked out along similar lines, with BA 47 and 45 involved in semantic binding, BA 45 and 44 in syntactic binding, and BA 44 and 6 in phonological binding. However, one has to realize that the overlap of activations for these different information types is substantial, and the ventral-to-dorsal gradient cannot be taken as solid evidence for a subregional specificity within Broca's complex.

### BROCA'S AREA REVISITED

As I have tried to make clear, despite the large appeal of Broca's area, it is not a very well defined concept. Instead of Broca's area I have therefore proposed the use of the term Broca's complex, to refer to a series of related but distinct areas in the left inferior frontal cortex, at least encompassing BA 47, 45, 44, and ventral BA6. This set of areas subserves more than one function in the language domain, and presumably other non-language functions as well. In the context of language processing the common denominator of Broca's complex is its role in selection and unification operations by which individual pieces of lexical information are bound together into representational structures spanning multiword utterances. One can thus conclude that Broca's complex plays a pivotal role in solving the binding problem for language.

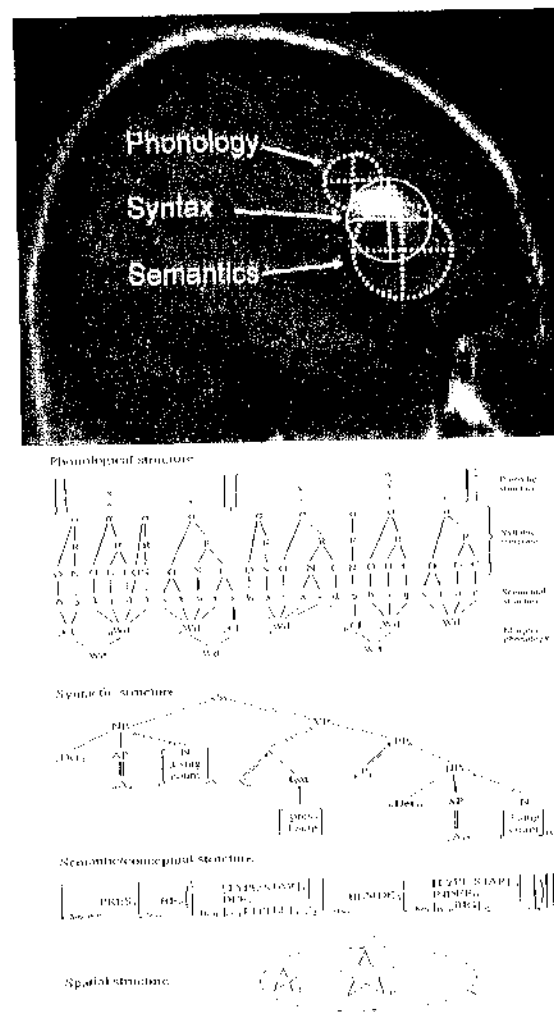


FIG. 10.3. The gradient in left inferior frontal cortex for activations and their distribution, related to semantic, syntactic and phonological processing, based on the meta-analysis in Bookheimer (2002). The centers represent the mean coordinates of the local maxima, the radii represent the standard deviations of the distance between the local maxima and their means (courtesy of Karl Magnus Petersson). The activation shown is from artificial grammar violations in Petersson, Forkstam, and Ingvar (2004). Below, the phonological, syntactic, and semantic/ conceptual structures for the sentence "The little star's beside the big star" (Jackendoff, 2002). The unification operations involved are suggested to require the contribution of Broca's complex.

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