

On Broca, Brain, and Binding

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Not all brain areas are equal. Some have triggered the attention and fascination of mankind more than others. Few have even seen books devoted to them or entered the domain of general awareness. Broca's area is one of these areas. No doubt, one of the main reasons is that this area is often seen as distinctly human. After all, isn't it Broca's area that is connected to the faculty that makes us uniquely human, the faculty of language? However, sometimes fascination breeds confusion. In this case, our fascination makes us believe that "Broca's area" is a coherent notion. Closer inspection reveals that it stands for a family of concepts that are loosely connected at best. We thus need to begin by deconstructing the concept of Broca's area. Only then we can see it more clearly.

Broca's area has different interpretations across different domains of research. We should at least distinguish between Broca's area in neuroanatomical, neuropsychological, and functional terms. At all these levels one can ask the question: *Is Broca's area a natural kind?* That is, does it carve brain and mind at its

joints? We discuss these issues in the first part of this chapter. The second part presents a proposal about the role of the left inferior frontal cortex, which contains Broca's area as classically defined.

DECONSTRUCTING BROCA'S AREA

The Neuroanatomical Perspective

Despite some disagreement in the literature (see Uylings et al., 1999), most authors agree that Broca's area comprises Brodmann's areas 44 and 45 of the left hemisphere. In the classic 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, given anatomical variability, in many brains these two parts are not easy to identify (Uylings et al., 1999), and clear microanatomical differences (see Amunts and Zilles, this volume, Chapter 2) have been missed when macro-

anatomical landmarks are used (Tomaiuolo et al., 1999). Furthermore, cytoarchitectonic analysis (Amunts et al., 2003) shows that areas 44 and 45 do not neatly coincide with the sulci that have been assumed to form their boundaries in gross anatomical terms. More fundamentally, one has to question the justification for subsuming 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 (see Fig. 15-1) (Mesulam, 2002). In addition, areas 44 and 45 have clearly distinct postnatal developmental trajectories and show a difference in their patterns of lateral asymmetry (Uylings et al., 1999). Using an observer-independent method for delineating cortical areas, Amunts et al. (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. However, areas 44 and 45 are cytoarchitectonically more similar to each other than 44 and 6 or than 45 and 6 (Amunts and Zilles, 2001).

Studies on corresponding regions in the macaque brain (Petrides and Pandya, 2002) have shown that area 44 receives projections from mainly somatosensory and motor-related regions like SII, the rostral inferior parietal lobule, supplementary, and cingulate motor areas. There is input from portions of the ven-

tral prefrontal cortex but only sparse projections from inferotemporal cortex (Pandya and Yeterian, 1996). Conversely, area 45 receives massive projections from most parts of prefrontal cortex, from auditory areas of the superotemporal gyrus, and visually related areas in the posterior superior temporal sulcus. In other words, the connectivity patterns of macaque BA 44 and 45 suggest clear functional differences between these areas.

Finally, studies on the receptorarchitecture of left inferofrontal areas indicate that functionally relevant subdivisions within BA 44 and 45 might be necessary (for more details, see Amunts and Zilles, this volume, Chapter 2). For instance, there is a difference within BA 44 of the receptor densities, for example, of the 5-HT₂ receptor for serotonin, with relatively low density in dorsal BA 44 and relatively high density in ventral BA 44.

In short, from a cytoarchitectonic and receptor-architectonic point of view, Broca's area, comprising BA 44 and BA 45, is a heterogeneous patch of cortex and not a uniform cortical entity. However, the degree of uniformity required for an inference of functional unity is not known.

With respect to language areas in prefrontal cortex, it has become clear that, in addition to BA 44 and 45, at least BA 47 and the ventral part of BA 6 should be included in the left frontal language network. Recent neuroimaging studies indicate that the pars orbitalis of the third frontal convolution (roughly corresponding to BA47) is involved in language processing (e.g., Devlin et al., 2003; Hagoort et al., 2004).

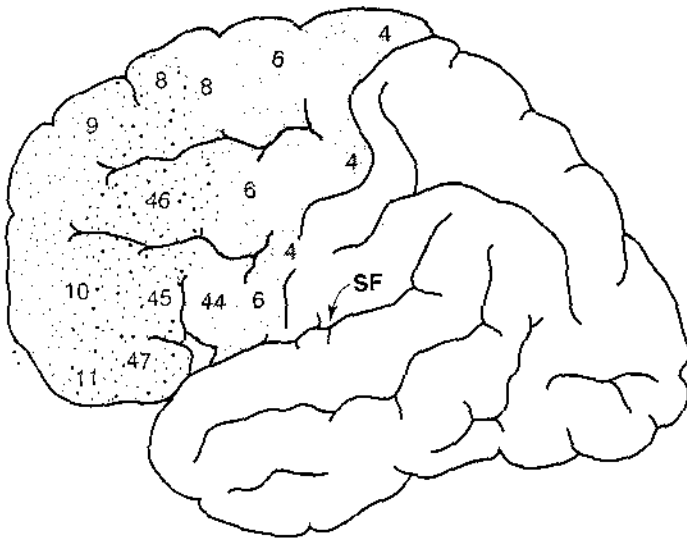


FIGURE 15-1. Lateral view of the frontal lobes. The numbers refer to Brodmann areas. *Dark grey markings*, motor-premotor cortex; *dotted markings*, heteromodal association cortex. SF, Sylvian fissure. (After Mesulam, 2002. Used by permission of Oxford University Press.)

From a functional anatomical perspective, it thus makes sense to use the term *Broca's complex* for this set of areas. Broca's complex is used here to distinguish it from *Broca's area* as classically defined. The latter definition of Broca's area is both too broad, because it comprises anatomically and functionally distinct areas, and too narrow, because it leaves out adjacent areas that are shown to be crucial for language processing. Broca's complex as here defined is the set of anatomical areas in left inferior frontal cortex that are known to play a crucial, but by no means exclusive, role in language processing.

The Neuropsychological Perspective

The name and fame of Broca's area can be traced back to 1861, when Paul Broca presented a detailed case history of a patient with a restricted brain lesion and a language disorder, which he referred to as *aphemia* (see Schiller, 1992). In fact, the autopsy of this patient (Leborgne, better known as Tan, since the syllable "tan" was the only utterance the patient could produce) demonstrated an extensive lesion in the left hemisphere encompassing the frontal, parietal, and temporal cortex. Broca's conclusion that the third inferior frontal part of the lesion caused the aphemia was inferred from the degree of necrosis and an analysis of the patient's medical history (Whitaker, 1998). What Broca referred to as aphemia is now known as aphasia, a term introduced by Trousdale in 1864 to refer to brain-related language disorders (Ryalls, 1984). In the decades following Broca's influential papers, other types of aphasia were described as well, pointing out that disorders might involve not only speech production but also comprehension. The publication by Carl Wernicke of "Der Aphasische Symptomencomplex" (1874) was a further hallmark in this initial era of aphasia research.

The history of neuropsychological research since Broca has resulted in the description of a series of aphasic syndromes, including Broca's aphasia and Wernicke's aphasia. Although these aphasias were described in terms of their symptoms, they were also associated with particular lesions, with their focus in what we now refer to as Broca's area and Wernicke's area, respectively. Although it is certainly true that the field of aphasiology has contributed enormously to our current understanding of the relation between brain and language, certainly the implicit link between

functional symptom complexes of Broca's and Wernicke's aphasia and particular brain areas has also resulted in some confusion. I focus here particularly on the problematic relationship between Broca's aphasia and Broca's area. To do so, I first have to clarify what is commonly referred to as Broca's aphasia (e.g., Caplan, 1992).

Despite substantial individual variation in severity, characteristic features of Broca's aphasia are the non-fluent speech and the reduced syntactic complexity of the utterances, sometimes resulting in telegraphic speech in which function words and grammatical morphemes are omitted (agrammatism). In contrast to what is often used as a defining characteristic of Broca's aphasia, this type of aphasia is not restricted to language production but also comprises syntactic and other deficits in comprehension (Caramazza and Zurif, 1976; Kolk and Friederici, 1985; Zurif et al., 1972). Only in very rare cases does one find an impairment of language production with an intact language comprehension (Kolk and Friederici, 1985; Miceli et al., 1983; Nespoulous et al., 1988). On the basis of the neurolinguistic studies in the 1970s, Broca's area came to be seen as crucially involved in both grammatical encoding and parsing operations. Modality-independent grammatical knowledge was also thought to be represented in this area (Zurif, 1998). However, since then the pivotal role of Broca's area in syntactic processing has faced a number of serious challenges. Studies that correlated aphasic syndromes with site of lesion led to the conclusion that the relation between Broca's area and Broca's aphasia is not as straightforward as once believed, for a number of reasons.

First, lesions restricted to Broca's area often do not seem to result in lasting aphasia (including agrammatic) symptoms (Mohr et al., 1978). In other words, a lesion in Broca's area is not a sufficient condition for a Broca's aphasia.

Second, large-scale correlational studies have found a substantial number of exceptions to the general rule that left frontal lesions go together with Broca's aphasia (Basso et al., 1985; Willmes and Poeck, 1993). Basso et al. (1985) correlated cortical lesions as revealed by computed tomography scans with aphasiological symptomatology for a group of 207 patients. They reported a substantial number of exceptions (17%) to the classic associations between lesion site and aphasia syndromes. Among these ex-

ceptions were patients with lesions restricted to left anterior areas, but with a fluent aphasia of the Wernicke type (seven cases), as well as nonfluent Broca's aphasics with posterior lesions and sparing of Broca's area (six cases). Willmes and Poeck (1993) investigated the computed tomography lesion localization for a group of 221 aphasic patients with a vascular lesion in the territory of the middle cerebral artery. Their results were even more dramatic. The conditional probability of an anterior lesion given a Broca's aphasia was no higher than 59%, whereas the probability that an anterior lesion resulted in a Broca's aphasia was only 35%.

In addition, later studies indicate that the syntactic deficit in Broca's aphasics is probably more limited than was believed in the 1970s. Many agrammatic patients with Broca's aphasia show a relatively high sensitivity to syntactic structure in tasks such as judging the grammaticality of sentences (Linebarger et al., 1983). With respect to language output, other analyses indicate that the telegraphic style of agrammatic aphasics follows the syntactic regularities of elliptic utterances, and therefore these patients show syntactic competence at least to some degree (Kolk and Heeschen, 1992).

In summary, the view that a central syntactic deficit is the distinguishing feature of Broca's aphasia, and therefore that Broca's area is crucial for grammatical encoding and parsing, is difficult to maintain in the light of more recent neurolinguistic studies and lesion studies correlating Broca's aphasia with the concomitant lesion sites.

However, there are good reasons to consider all this evidence as not really decisive with respect to the role of Broca's area in syntactic processing. One major reason is that the characterization of the language disorder in lesion studies usually is based on clinical impressions (Mohr et al., 1978) or clinical aphasia test batteries (Basso et al., 1985; Willmes and Poeck, 1993), which are often insufficient to determine the degree and specificity of the syntactic impairment. The classification of aphasic patients in terms of a limited set of syndromes does not guarantee that core language operations are singled out according to articulated cognitive architectures for speaking, listening, or reading (cf. Shallice, 1988). Willmes and Poeck (1993) therefore rightly conclude that "localization studies along the traditional lines will not yield results that lend themselves to a meaningful interpretation of

impaired psychological processes such as aphasia. Small-scale in-depth studies lend themselves better to characterizing the functional impairment in an information-processing model" (pp. 1538–1539).

In one of these in-depth studies, Caplan et al. (1996) tested patients on a series of sentence types that required them to process a range of syntactic structures. These studies showed that the task performance for the different sentence types did not differ between patients with anterior (Broca's area) lesions and those with posterior lesions. The size of the lesion within the peri-Sylvian area also did not correlate with the syntactic task performance. Caplan et al. (1996) gave two possible explanations for these results. One is that syntactic processing is fairly strictly localized, but the exact site can vary quite substantially between individuals within the borders of the left peri-Sylvian area including the insula (Caplan, 1987; Vanier and Caplan, 1990). The other possibility is that the syntactic machinery is organized as a distributed neural network in which several regions of the left peri-Sylvian cortex are critically involved.

Grodzinsky (2000) acknowledges the problems of the classic view of the relation between the syntactic deficit in Broca's aphasia and the role of Broca's area. He proposes a much more restricted role of Broca's area. In his view, "Broca's area and its vicinity (operculum, insula, and adjacent white matter) support receptive language mechanisms that implement some, but not all aspects of syntax, namely those pertaining to syntactic movement rules in comprehension (as well as limited aspects of tree building in speech production)" (Grodzinsky, 2000, p. 7). However, one has to realize that BA 44 and 45, operculum, and insula together constitute a substantial amount of cortex. It would be surprising if no further functional subdivisions were to be found within this large area.

Finally, a more general problem of the lesion approach is that for some cognitive functions, alternative brain systems might be available. This is referred to as degeneracy (Price and Friston, 2002). In addition, one area within association cortex might be a node in different functional networks (Mesulam, 1998). This implies, on the one hand, that the absence of a cognitive deficit after a lesion to a specific site does not necessarily imply that the lesioned area is not involved in the spared function and, on the other hand, that a lesion to one particular area will often not result in a deficit that conforms to the idea

that deficits can be easily parcellated into different cognitive domains.

In conclusion, our view on Broca's area from a neuropsychological perspective has suffered from the assumption that the symptoms of a Broca's aphasia are related in a straightforward way to a lesion of Broca's area. In fact, the contribution of Broca's area cannot be easily inferred from the symptoms of patients with a Broca's aphasia. The functional lesion of patients with Broca's aphasia thus cannot be directly mapped onto Broca's area.

Broca's Area From a Cognitive Neuroscience Perspective

In this chapter, I will not be able to 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 will do is highlight several lessons to be learnt from this recent body of evidence that cognitive neuroscience has provided.

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 classic papers (1990, 1998), "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 each cortical node into the service of one network or another" (1998, p. 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, a local area participates in more than one function. 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. 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 (Haxby et al., 2001). It would indeed be highly surprising if the different representational domains in the language network would behave according to a principle of localization that is less distributed than for the visual system. Moreover, Broca's area has been found activated in imaging studies on nonlanguage functions. For instance, Fink et al. (Chapter 16) found activation in Broca's area when subjects had to search for

a target hidden within a complex geometric pattern. Broca's area is also activated in action recognition (Decety et al., 1997; Hamzei et al., 2003) and movement preparation (Thoenissen et al., 2002). Of course, all of this does not mean that cognitive functions are not localized and that the brain shows equipotentiality. It only means that the one-area-one-function principle is in many cases not an adequate account of how cognitive functions are neurally instantiated.

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 an anterior-to-posterior gradient (Bookheimer, 2002). Roughly speaking, BA 47 and BA 45 are involved in semantic processing, while BA 45, 44, and 46 contribute to syntactic processing. 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 a certain level of relative specialization within different subregions of Broca's complex. However, the overlap of activations for these three different types of processing is substantial. For this reason, subregional specificity within Broca's complex cannot (yet) be concluded.

Based on the neuroanatomical, neuropsychological, and cognitive neuroscience perspectives, it is evident that Broca's area is not a natural kind at the level of either brain structure or cognitive function. Instead, within the left inferior prefrontal cortex, it refers to a grouping of related but cytoarchitecturally distinct areas with a responsibility to distinct information types within the domains of language comprehension and production. Most likely, the conglomerate contributes to other cognitive functions as well. In the remainder of this chapter, I propose a role for Broca's complex in what I refer to as binding or unification of information retrieved from the mental lexicon.

BROCA'S COMPLEX AS PART OF THE UNIFICATION SPACE

The proposed role for Broca's complex is based on (1) an embedding of this complex in the overall functional architecture of prefrontal cortex and (2) a general distinction between memory retrieval of linguistic information and combinatorial operations on information retrieved from the mental lexicon. These

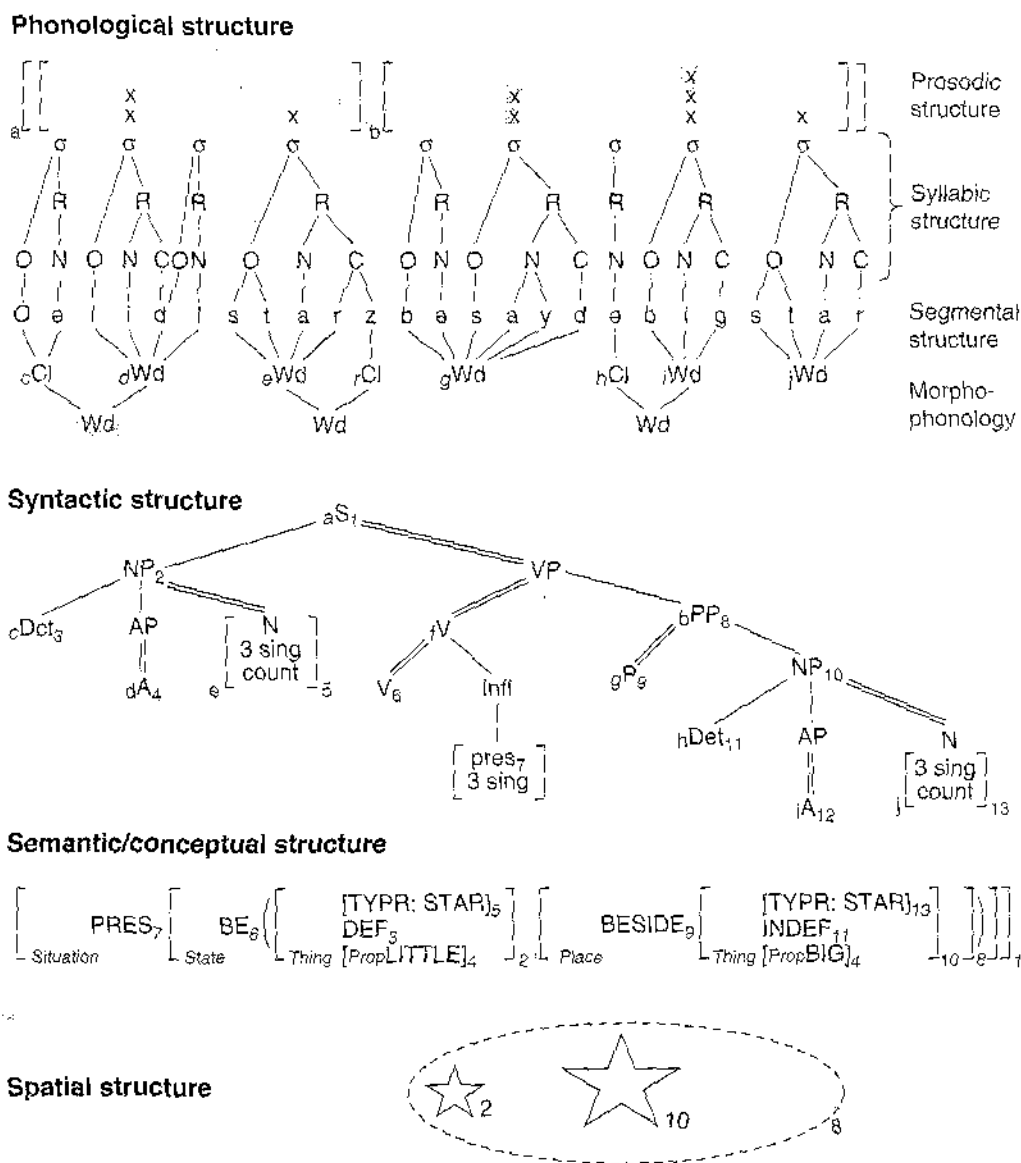


FIGURE 15-2. The phonological, syntactic, and semantic/conceptual structures for the sentence "The little star's beside the big star." (Jackendoff, 2002.

Used by permission of Oxford University Press.) The unification operations involved are suggested to require the contribution of Broca's complex.

operations are referred to as unification or binding. The notion of binding is inspired by the visual neurosciences, where one of the fundamental questions is: How do we get from the processing of different visual features (color, form, motion) by neurons that are far apart in brain space to a unified visual percept? This is known as the *binding problem*. In the context of the language system, the binding problem refers to an analogous situation but now transferred to the time domain: How is information that is incrementally retrieved from the mental lexicon unified into a coherent overall interpretation of a multiword utterance?

Most likely, unification needs to take place at the conceptual, syntactic, and phonological levels, as well as between these levels (see Fig. 15-2) (Jackendoff, 2002). Binding in this context refers to a problem that the brain has to solve, not to a concept from a particular linguistic theory.

Broca's Complex as Part of Prefrontal Cortex

Integration is an important part of the function of the prefrontal cortex. 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 on-line (Mesulam, 2002) and to select among competing alternatives (Thompson-Schill et al., 1999). 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 establish unifications between pieces of information that are perceived or retrieved from memory at different moments in time (Fuster, 1995).

Recent neuroimaging studies indicate that Broca's complex contributes to the unification operations required for binding single-word information into larger structures. In psycholinguistics, integration and unification refer to what is usually called postlexical 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 postlexical processing, because this includes selection among competing unification possibilities, so that one unified representation spanning the whole utterance remains.

In short, the properties of neurons in the prefrontal cortex of macaques suggest that this part of the brain is suitable for integrating pieces of information that are made available sequentially, that is spread out over time, regardless of the nature of the material to be handled (Owen et al., 1998). Clearly, there are interspecies differences in terms of the complexity of the information binding operations (Fitch and Hauser, 2004), possibly supported by a corresponding increase in the amount of frontal neural tissue from monkey to humans (Passingham, 2002). With respect to language processing in humans, different complex binding operations take place. Hereafter, I will propose that subregions in the Broca complex contribute to the different unification operations that are required for binding single-word information into larger structures.

Broca's Complex as the Unification Space for Language

Accounts of the human language system (Jackendoff, 1999, 2002; Levelt, 1999) generally 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 (see Fig. 15-2).

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 flavor. Thus, phonological, syntactic, and semantic/pragmatic constraints determine how lexically available structures are glued together. In Jackendoff's (2002) recent account, for all three levels of representation (phonological, syntactic, semantic/conceptual), information retrieved from the mental lexicon has to be unified into larger structures. In addition, interface operation link these three levels of analysis. The gradient observed in 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 will show in more detail how this could work for the syntactic level of analysis (see Hagoort, 2003). The challenge for the future is to specify computational models with similar detail for the unification of conceptual and phonological information.

According to the Unification Model for parsing (see Vosse and Kempen, 2000), each word form in the mental 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 Fig. 15-3).

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

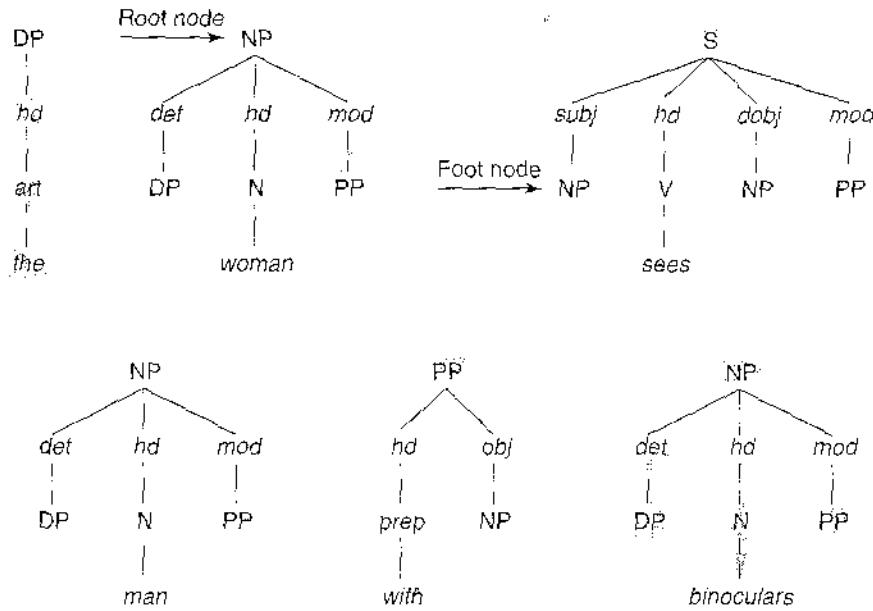


FIGURE 15-3. Syntactic frames in memory. These frames are retrieved on the basis of incoming word form information. DP, determiner phrase; NP, noun phrase; S, sentence; PP, prepositional phrase; art, article; hd, head; det, determiner; mod, modifier; subj, subject; dobj, direct object.

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 incrementally enter the unification workspace. In this workspace, constituent structures spanning the whole utterance are formed by a unification operation (see Fig. 15-4). This operation consists of linking up lexical frames with identical root and foot nodes, and checking agreement features (number, gender, person, etc.). It specifies what Jackendoff (2002) refers to as the only remaining “grammatical rule”: UNIFY PIECES.

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

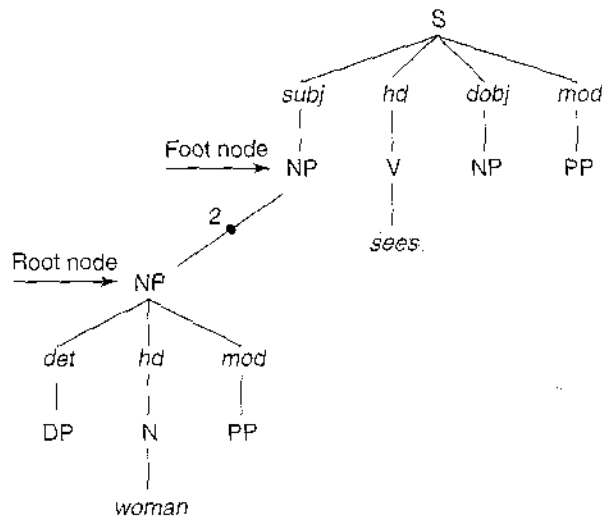


FIGURE 15-4. The unification operation of two lexically specified syntactic frames. The unification takes place by linking the root node NP to an available foot node of the same category. The number 2 indicates that this is the second link that is formed during on-line processing of the sentence “The woman sees the man with the binoculars.” (See Fig. 15-3 legend for abbreviations.)

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. 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 as a 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 a 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. In addition, the model accounts for a number of other experimental findings in psycholinguistic research on sentence processing, including syntactic ambiguity (attachment preferences; frequency differences between attachment alternatives), and lexical ambiguity effects. Moreover, it accounts for breakdown patterns in agrammatic sentence analysis (see, for details, Vosse and Kempen, 2000).

The advantage of the unification model is that it (1) is computationally explicit, (2) accounts for a large series of empirical findings in the parsing literature and in the neuropsychological literature on aphasia, and (3) belongs to the class of lexicalist parsing models that have found increasing support in recent years (Bresnan, 2001; Jackendoff, 2002; Joshi and Schabes, 1997; MacDonald et al., 1994).

This model also nicely accounts for the two classes of syntax-related ERP effects that have been consistently reported over recent years. One type of ERP effect related to syntactic processing is the P600/SPS (Hagoort et al., 1993; Osterhout and Holcomb, 1992). 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 et al., 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, because 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 propose that the P600/SPS is related to the time it takes to establish unification links of sufficient strength. 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 biases the strengths of the unification links in a particular direction, thereby shortening the duration of the competition. Violations result in a P600/SPS as long as unification attempts are 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 with 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 computationally most explicit account of the (E)LAN and P600/SPS effects that is currently available (Fig. 15-5).

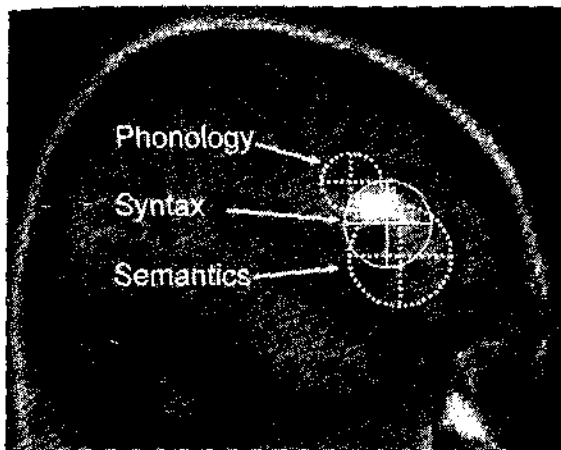


FIGURE 15-5. The gradient in left inferior frontal cortex for activations and their distribution, related to semantic, syntactic, and phonological processing, based on the meta-analysis in Bookheimer (2002). The centers represent the mean coordinates of the local maxima, and the radii represent the standard 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 et al. (2004).

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 prefrontal cortex. The left posterior temporal cortex is known to be involved in lexical processing (Indefrey and 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 Broca's complex. Presumably, this holds for both language comprehension and language production (Indefrey et al., 2001).

However, unification operations take place not only at the level of syntactic processing. Combinatorality is a hallmark of language across representational domains. That is, it holds equally for syntactic, semantic, and phonological levels of analyses. In all of 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 sin-

gle coherent percept is not unique for syntax. Models for semantic/conceptual unification and phonological unification could be worked out along similar lines as the unification model for syntax, with BA 47 and 45 involved in semantic binding, BA 45 and 44 in syntactic binding, and BA 44 and 6 in phonological binding (see Fig. 15-5).

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 to use the term "Broca's complex," to refer to a series of related but distinct areas in the left prefrontal cortex, at least encompassing BAs 47, 45, and 44 and ventral BA 6. This set of areas subserves more than one function in the language domain and almost certainly other nonlanguage 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 has a pivotal role in solving the binding problem for language.

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