Automaticity and Control in Language Processing

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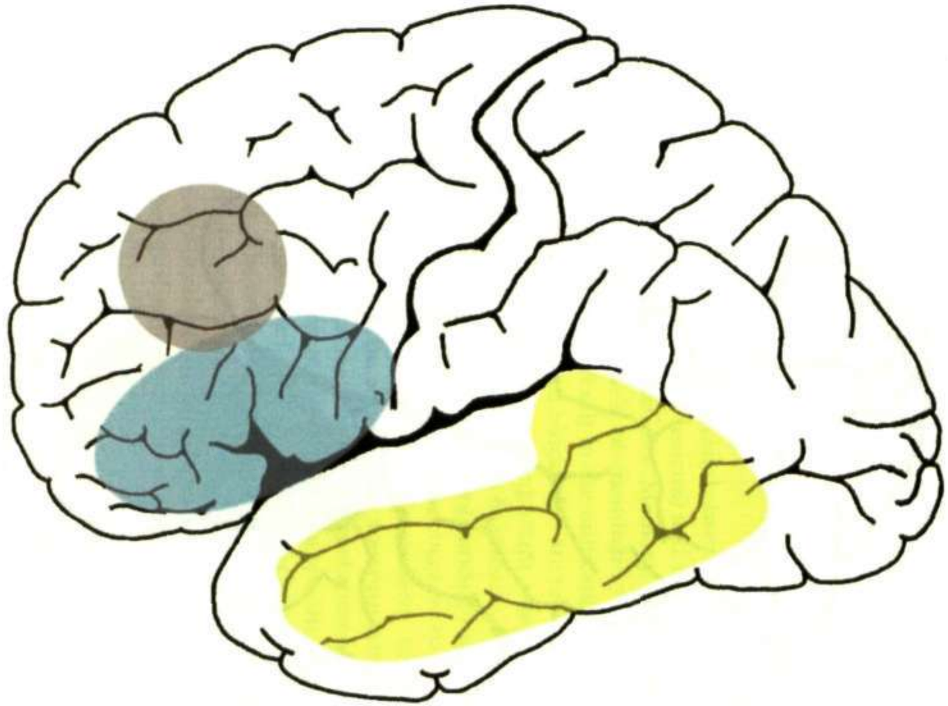

Figure 11.1 The three components of the MUC model projected onto a lateral surface of the left hemisphere: memory (yellow) in the left temporal cortex, unification (blue) in Broca's complex, and control (grey) in the dorsolateral prefrontal cortex. The ACC (part of the control component) is not shown.

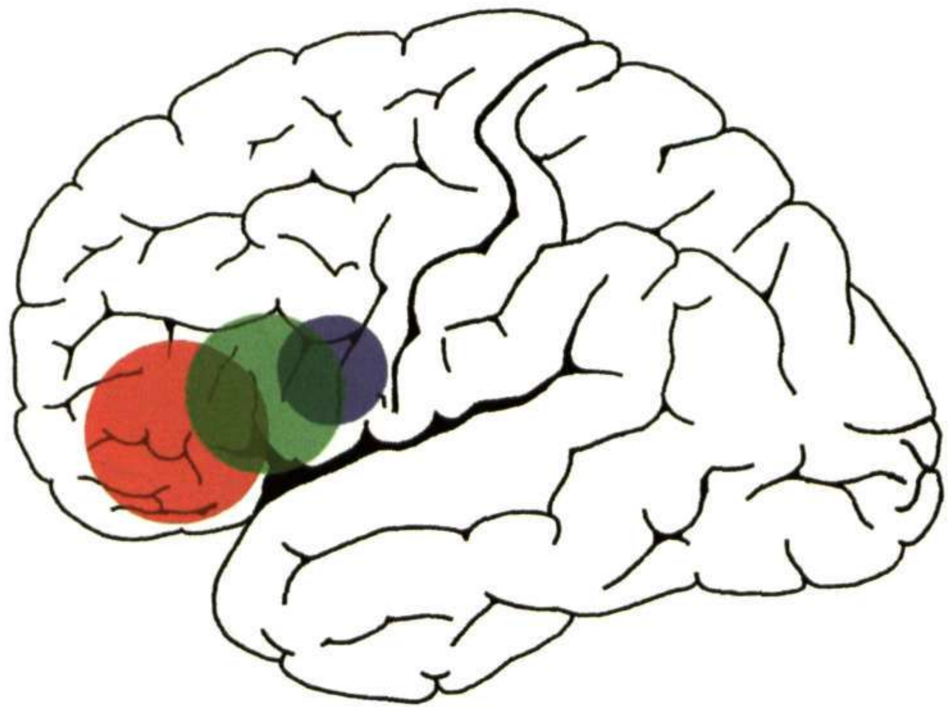

Figure 11.10 The unification gradient in the left inferior frontal cortex. Activations and their distribution are shown, related to semantic (red), syntactic (green), and phonological (blue) processing. Areas are based on the meta-analysis in Bookheimer (2002).

11 The memory, unification, and control (MUC) model of language

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Models of language processing distinguish between retrieval of information from long-term memory (the mental lexicon) and operations that combine lexical information into larger structures. Memory retrieval and combinatorial operations occur at the levels of meaning, syntax, and phonology. These combinatorial operations result in the unification of the conceptual, syntactic, and phonological building blocks that are retrieved from memory. While the left temporal cortex plays an important role in lexical retrieval, Broca's area and the adjacent cortex seem to be relevant to unification.

The MUC (memory, unification, and control) model provides a framework for a neurobiologically plausible account of language processing. It connects psycholinguistically motivated processing components to their neuronal substrate, guided by knowledge about brain function across domains of cognition. The model distinguishes three functional components of language processing. The memory component comprises a specification of the different types of language information stored in long-term memory, and of their retrieval operations. The unification component refers to the integration of lexically retrieved information into a representation of multiword utterances. The control component relates language to action.

According to the MUC model, the left temporal cortex plays a critical role in storage and retrieval of linguistic information that language acquisition has laid down in memory. This refers to the phonological/phonetic properties of words; their syntactic features such as grammatical gender and word class (verb, noun, etc.), including the syntactic frames; and finally the conceptual specifications of the 60,000 or so words that a native speaker of a language such as English has stored in memory. Activations related to phonological/phonetic properties are reported for the central to posterior superior temporal gyrus (STG) extending into the superior temporal sulcus (STS) (Aleman, Formisano, Koppenhagen, Hagoort, De Haan, & Kahn, 2005; Indefrey & Cutler, 2004; Scott & Johnsrude, 2003).

Semantic information is presumably distributed over a number of brain areas, but most likely different parts of the left middle and inferior temporal gyri may be crucially involved in lexical-semantic processing (Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996; Indefrey & Cutler, 2004; Indefrey & Levelt, 2000; Saffran & Sholl, 1999).

Hardly anything is known about the brain areas involved in the lexical retrieval of a word's syntactic specifications. On the basis of the meta-analysis of a large series of imaging studies on syntactic processing (Indefrey, 2004), the hypothesis is that the left posterior superior temporal cortex (Wernicke's area) is involved in the retrieval of lexical-syntactic information.

The memory component thus seems to be distributed mainly over the left temporal cortex. The control component of the model accounts for the fact that the language system operates in the context of communicative goals and actions. For example, attentional control allows individuals to speak while seeing irrelevant objects or hearing interlocutors; to take turns in conversational settings; or, in case of bilingualism, to select the correct language in a particular communicative setting. The issue of verbal control has so far mostly been studied in the context of a Stroop task (Botvinick, Cohen, & Carter, 2004; Bush, Luu, & Posner, 2000; MacLeod & MacDonald, 2000; Roelofs & Hagoort, 2002). These studies suggest that a network of areas consisting of the anterior cingulate cortex (ACC) and the dorsolateral prefrontal cortex (DLPC, BA 46/9) is involved in verbal action planning and attentional control.

Figure 11.1 (see colour plate section) summarizes the network of areas subserving the three central components (memory, unification, and control) of human language in action. The precise effective connectivity between these areas is a topic for further research.

Hereafter I will mainly focus on the processing principles behind unification. First, I will discuss syntactic unification and then semantic unification. In addition, the neural architecture of unification will be discussed.

Syntactic unification

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 online 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 models of language processing, there exists a fairly wide agreement on the types of constraints that are effective during the formulation and the interpretation of sentences and beyond. However, disagreement prevails with respect to exactly how these are implemented in the overall sentence-processing architecture. One of the key issues is when and how the assignment of a syntactic structure to an incoming string of words and the semantic integration of single-word meanings interact during listening/reading. The by now classical view is that, in sentence comprehension, the syntactic analysis is autonomous and initially not influenced by semantic variables (Frazier, 1987). Semantic integration can be influenced by syntactic analysis, but it does not contribute to the initial computation of syntactic structure. An alternative view maintains that lexical-semantic and discourse information can guide or contribute to the syntactic analysis of the utterance. This view is mainly supported by studies showing that the reading of syntactically ambiguous sentences is immediately influenced by lexical or more global semantic information (e.g., Altmann & Steedman, 1988; Trueswell, Tanenhaus, & Garnsey, 1994; Trueswell, Tanenhaus, & Kello, 1993; Tyler & Marslen-Wilson, 1977).

Some of the discrepancies between the different views on this topic are due to the fact that no clear distinction is made between cases where the syntactic constraints are, at least temporarily, indeterminate with respect to the structural assignment (syntactic ambiguity), and cases where these constraints are sufficient to determine the syntactic analysis. In the former case, there is a substantial body of evidence for an immediate influence of non-syntactic context information on the structure that is assigned (Tanenhaus & Trueswell, 1995; Van Berkum, Brown, & Hagoort, 1999a). However, for the latter case, although it has not been studied as intensely, the available evidence seems to provide some support for a certain level of syntactic autonomy (Hagoort, 2003; O'Seaghdha, 1997; but see Ferreira, 2003).

A more recent version of the autonomous syntax view is proposed by Friederici (2002). Based on the time course of different language-relevant event-related brain potentials (ERP) effects, she proposes a three-phase model of sentence comprehension. The first phase is purely syntactic in nature. An initial syntactic structure is formed on the basis of information about the word category (noun, verb, etc.). During phase two, lexical-semantic and morphosyntactic processes take place, which result in thematic role assignments. In the third phase, integration of the different types of information takes place, and the final interpretation results. This proposal is mainly based on findings in ERP studies on language processing. The last decade has seen an increasing number of ERP studies on syntactic processing, triggered by the discovery some 10 years ago of an ERP effect on syntactic violations that was clearly different from the well-known N400 effect on semantic violations (Hagoort, Brown, & Groothusen, 1993; Osterhout & Holcomb, 1992).

These studies have been followed up by a large number of ERP studies on syntactic processing that have provided a wealth of data. Here I will connect the known syntax-related ERP effects to a computational model of parsing (Vosse & Kempen, 2000). This model was developed to account for a large portion of behavioural findings in the parsing literature and for deficit patterns in aphasic patients. In the context of considerations based on brain organization, it makes the right distinction between lexicalized patterns and a unification component. However, before discussing the model, I will first discuss the relevant ERP results, and then present some data that are more compatible with an immediacy model than a syntax-first model. Later in this chapter, I will indicate how the model connects to relevant brain areas for syntactic processing, and to data from lesion studies.

Language-relevant ERP effects

The electrophysiology of language as a domain of study started with the discovery by Kutas and Hillyard (1980) of an ERP component that seemed especially sensitive to semantic manipulations. Kutas and Hillyard observed a negative-going potential with an onset at about 250 ms and a peak around 400 ms (hence the N400), whose amplitude was increased when the semantics of the eliciting word (i.e., *socks*) mismatched with the semantics of the sentence context, as in *He spread his warm bread with socks*. Since 1980, much has been learned about the processing nature of the N400 (for extensive overviews, see Kutas & Van Petten, 1994; Osterhout & Holcomb, 1995). As Hagoort and Brown (1994) and many others have observed, the N400 effect does not depend on a semantic violation. Subtle differences in semantic expectancy, as between *mouth* and *pocket* in the sentence context, "Jenny put the sweet in her *mouth/pocket* after the lesson", can modulate the N400 amplitude (Figure 11.2) (Hagoort & Brown, 1994).

The amplitude of the N400 is most sensitive to the semantic relations between individual words, or between words and their sentence and discourse context. The better the semantic fit between a word and its context, the more reduced the amplitude of the N400. Modulations of the N400 amplitude are generally viewed as directly or indirectly related to the processing costs of integrating the meaning of a word into the overall meaning representation that is built up on the basis of the preceding language input (Brown & Hagoort, 1993; Osterhout & Holcomb, 1992). This holds equally when the preceding language input consists of a single word, a sentence, or a discourse, indicating that semantic unification operations might be similar in word, sentence, and discourse contexts (Van Berkum, Brown, & Hagoort, 1999b). In addition, recent evidence indicates that sentence verification against world

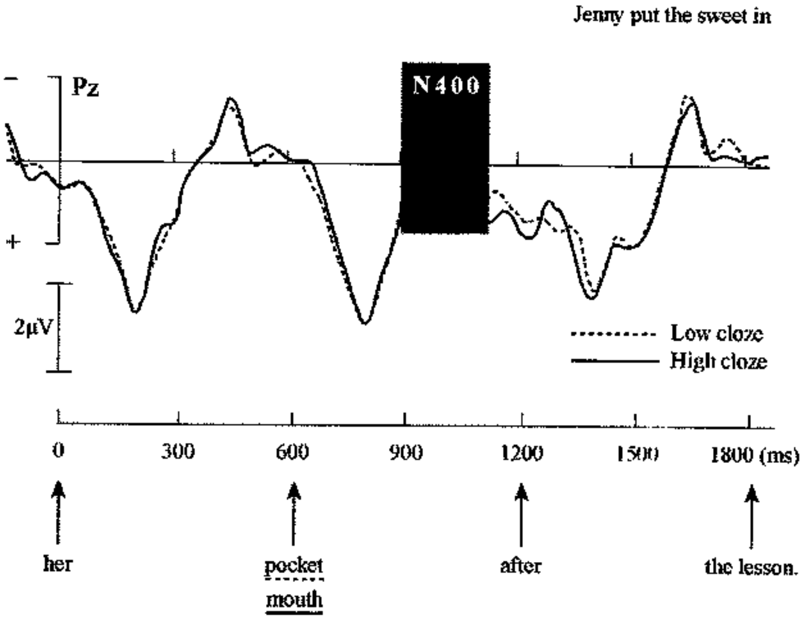

Figure 11.2 Modulation of the N400 amplitude as a result of a manipulation of the semantic fit between a lexical item and its sentence context. The grand-average waveform is shown for electrode site Pz (parietal midline), for the best-fitting word (high cloze; solid line), and for a word that is less expected in the given sentence context (low cloze; dashed line). The sentences were visually presented word by word, every 600 ms. In the figure, the critical words are preceded and followed by one word. The critical word is presented at 600 ms on the time axis. Negativity is up. (Adapted from Hagoort and Brown (1994). Copyright © 1994 Erlbaum, reprinted by permission).

knowledge in long-term memory modulates the N400 in the same way (Hagoort, Hald, Bastiaansen, & Petersson, 2004).

In recent years, a number of ERP studies have been devoted to establishing ERP effects that can be related to the processing of syntactic information. These studies have found ERP effects to syntactic processing that are qualitatively different from the N400. Even though the generators of these effects are not yet well determined and not necessarily language-specific (Osterhout & Hagoort, 1999), the existence of qualitatively distinct ERP effects to semantic and syntactic processing indicates that the brain honours the distinction between semantic and syntactic unification operations. Thus, the finding of qualitatively distinct ERP effects for semantic and syntactic processing operations supports the claim that these two levels of language processing are domain specific. However, domain specificity should not be confused with modularity (Fodor, 1983). The modularity thesis makes the much stronger claim that domain-specific levels of processing operate autonomously without interaction (informational encapsulation). Although domain specificity is widely assumed in models of language processing, there is much less agreement about the organization of the cross-talk between different levels of sentence processing (cf. Boland & Cutler, 1996).

ERP studies on syntactic processing have reported a number of ERP effects related to syntax (for an overview, see Hagoort, Brown, & Osterhout, 1999). The two most salient syntax-related effects are an anterior negativity, also referred to as LAN, and a more posterior positivity, here referred to as P600/SPS.

LAN

A number of studies have reported negativities that are different from the N400, in that they usually show a more frontal maximum (but see Münte, Matzke, & Johannes, 1997), and are sometimes larger over the left than the right hemisphere, although in many cases the distribution is bilateral (Hagoort, Wassenaar, & Brown, 2003). Moreover, the conditions that elicit these frontal negative shifts seem to be more strongly related to syntactic processing than to semantic integration. Usually, LAN effects occur within the same latency range as the N400, that is, at 300–500 ms after a stimulus (Friederici, Hahne, & Mecklinger, 1996; Kluender & Kutas, 1993; Münte, Heinze, & Mangun, 1993; Osterhout & Holcomb, 1992; Rösler, Friederici, Pütz, & Hahne, 1993). But in some cases the latency of a left-frontal negative effect is reported to be much earlier, approximately 100–300 ms (Friederici, 2002; Friederici, Pfeifer, & Hahne, 1993; Neville, Nicol, Barss, Forster, & Garrett, 1991).

In some studies, LAN effects have been reported to violations of word-category constraints (Friederici et al., 1996; Hagoort et al., 2003; Münte et al., 1993). That is, if the syntactic context requires a word of a certain syntactic class (e.g., a noun in the context of a preceding article and adjective), but, in fact, a word of a different syntactic class is presented (e.g., a verb), early negativities are observed. Friederici and colleagues (e.g., Friederici, 1995; Friederici et al., 1996) have tied the early negativities specifically to the processing of word-category information. However, in other studies, similar early negativities are observed with number, case, gender, and tense mismatches (Münte & Heinze, 1994; Münte et al., 1993). In these violations, the word category is correct but the morphosyntactic features are wrong. Friederici (2002) has recently attributed the very early negativities that occur approximately between 100 and 300 ms (ELAN) to violations of word category, and the negativities at 300–500 ms to morphosyntactic processing.

LAN effects have also been related to verbal working memory in connection to filler-gap assignment (Kluender & Kutas, 1993). This working memory account of the LAN is compatible with the finding that lexical, syntactic, and referential ambiguities seem to elicit very similar frontal negativities (Hagoort & Brown, 1994; Van Berkum et al., 1999a; Kaan & Swaab, 2003b; King & Kutas, 1995). Lexical and referential ambiguities are clearly not syntactic in nature, but can be argued to tax verbal working memory more heavily than sentences in which lexical and referential ambiguities are absent. Syntactic ambiguities might also tax working memory stronger than their unambiguous counterparts. Future research should indicate whether or not these two functionally distinct classes of LAN effects can be dissociated at a more fine-grained level of electrophysiological analysis.

P600/SPS

A second ERP effect that has been related to syntactic processing is a later positivity, nowadays referred to as P600/SPS (Coulson, King, & Kutas, 1998; Hagoort et al., 1999; Osterhout, Bersick, & McKinnon, 1997). One of the antecedent conditions of P600/SPS effects is a violation of a syntactic constraint. If, for instance, the syntactic requirement of number agreement between the grammatical subject of a sentence and its finite verb is violated (see item (1) below, with the critical verb form in italics; the asterisk indicates the ungrammaticality of the sentence), a positive-going shift is elicited by the word that renders the sentence ungrammatical (Hagoort et al., 1993). This positive shift starts at about 500 ms after the onset of the violation and usually lasts for at least 500 ms. Given the polarity and the latency of its maximal amplitude, this effect was originally referred to as the P600 (Osterhout & Holcomb, 1993) or, on the basis of its functional characteristics, as the syntactic positive shift (SPS) (Hagoort et al., 1993).

(1) *The spoilt child *throw* the toy on the ground.

An argument for the independence of this effect from possibly confounding semantic factors is that it also occurs in sentences where the usual semantic/pragmatic constraints have been removed (Hagoort & Brown, 1994). This results in sentences like (2a) and (2b) in which one is semantically odd but grammatically correct, whereas the other contains the same agreement violation as in (1):

(2) a. The boiled watering can *smokes* the telephone in the cat.
b. *The boiled watering can *smoke* the telephone in the cat.

If one compares the ERPs to the italicized verbs in (2a) and (2b), a P600/SPS effect is visible with the ungrammatical verb form (Figure 11.3). Despite the fact that these sentences do not convey any conventional meaning, the ERP effect of the violation demonstrates that the language system is nevertheless able to parse the sentence into its constituent parts.

Similar P600/SPS effects have been reported for a broad range of syntactic

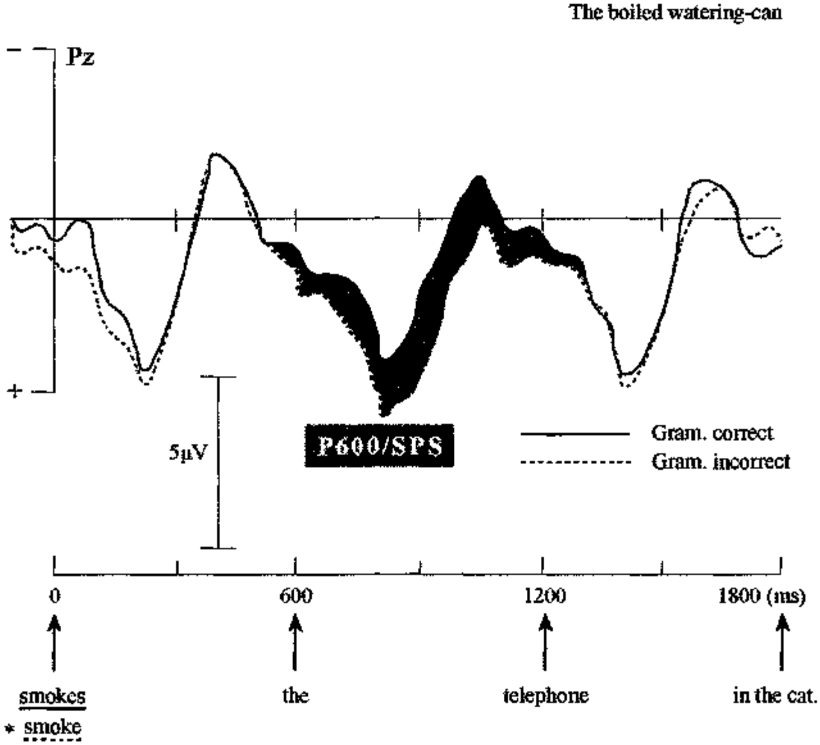

Figure 11.3 ERPs to visually presented syntactic prose sentences. These are sentences without a coherent semantic interpretation. A P600/SPS is elicited by a violation of the required number agreement between the subject-noun phrase and the finite verb of the sentence. The averaged waveforms for the grammatically correct (solid line) and the grammatically incorrect (dashed line) words are shown for electrode site *Pz* (parietal midline). The word that renders the sentence ungrammatical is presented at 0 ms on the time axis. The waveforms show the ERPs to this and the following two words. Words were presented word by word, with an interval stimulus onset asynchrony (SOA) of 600 ms. Negativity is plotted upward (adapted from Hagoort & Brown (1994). Copyright © 1994 Erlbaum, reprinted by permission.)

violations in different languages (English, Dutch, and German), including phrase-structure violations (Hagoort et al., 1993; Neville et al., 1991; Osterhout & Holcomb, 1992); subcategorization violations (Ainsworth-Darnell, Shulman, & Boland, 1998; Osterhout, Holcomb, & Swinney, 1994); violations in the agreement of number, gender, and case (Coulson et al., 1998; Hagoort et al., 1993; Münte et al., 1997; Osterhout & Mobley, 1995); and violations of subjacency (McKinnon & Osterhout, 1996; Neville et al., 1991) and of the empty-category principle (McKinnon & Osterhout, 1996).

Recently, a P600/SPS is also reported in relation to thematic role animacy violations (Kuperberg, Sitnikova, Caplan, & Holcomb, 2003). Moreover, a P600/SPS can be found with both written and spoken input (Friederici et al., 1993; Hagoort & Brown, 2000; Osterhout & Holcomb, 1993).

Recently, a P600/SPS is also reported in relation to thematic role assignment (Kim & Osterhout, 2005; Kuperberg et al., 2003; Van Herten, Kolk, & Chwilla, 2005; Wassenaar & Hagoort, accepted). In this case, a P600/SPS is elicited to verbs when constraints for grammatical role assignment conflict with thematic role biases.

In summary, two classes of syntax-related ERP effects have been consistently reported. These two classes differ in their polarity and topographic distribution, and in their latency characteristics. In terms of latency, the first class of effects is an anterior negativity. Apart from LANs related to working memory, anterior negativities are mainly seen with syntactic violations. In a later latency range, positive shifts occur which are elicited not only by syntactic violations, but also in grammatically well-formed sentences that vary in complexity (Kaan, Harris, Gibson, & Holcomb, 2000), as a function of the number of alternative syntactic structures that are compatible with the input at a particular position in the sentence (syntactic ambiguity) (Osterhout et al., 1994; Van Berkum et al., 1999a), or when constraints for grammatical role assignment are overwritten by thematic role biases (Kim & Osterhout, 2005).

Since these two classes of effects are now well established in the context of language processing, and are clearly different from the N400 effect, the need arises to account for these effects in terms of a well-defined model of language processing.

Broadly speaking, models of sentence processing can be divided into two types. One type of model assumes a precedence of syntactic information. That is, an initial syntactic structure is constructed before other information (e.g., lexical-semantic, discourse information) is taken into account (Frazier, 1987). I will refer to this type of model as a *syntax-first model*. The alternative broad set of models claims that the different information types (lexical, syntactic, phonological, and pragmatic) are processed in parallel and influence the interpretation process incrementally, that is, as soon as the relevant pieces of information are available (Jackendoff, 2002; Marslen-Wilson, 1989; Zwitserlood, 1989). I will refer to this type of model as the *immediacy model*. Overall, the behavioural data, although not decisive, are more in favour of the second type of model than the first. I will first present some recent ERP data that support the immediacy model.

Evidence against the syntax-first principle

The strong version of a syntax-first model of sentence processing assumes that the computation of an initial syntactic structure precedes semantic unification operations, because structural information is necessary as input for thematic role assignment. In other words, if no syntactic structure can be built up, semantic unification will be impaired. Recent electrophysiological evidence has been taken as evidence for this syntax-first principle (Friederici, 2002). Alternative models (MacDonald, Pearlmutter, & Seidenberg, 1994; Marslen-Wilson & Tyler, 1980) claim that semantic and syntactic information is immediately used as it becomes available without priority for syntactic information over other information types.

ERP evidence for an autonomous syntax-first model in sentence processing is derived from a series of studies in which Friederici and colleagues found an ELAN to auditorily presented words whose prefix is indicative of a word category violation. For instance, Hahne and Jescheniak (2001) and Friederici et al. (1993) had their subjects listen to sentences such as "Die Birne wurde im *gepflückt*" ("The pear was being in-the *plucked*") or "Die Freund wurde im *besucht*" ("The friend was being in-the *visited*"), where the prefixes "ge-" and "be-", in combination with the preceding auxiliary "wurde", are indicating a past participle where the preposition "im" requires a noun. In this case, a very early (100–300 ms) left anterior negativity is observed that precedes the N400 effect.

Although this evidence is compatible with a syntax-first model, it is not necessarily incompatible with an immediacy model of sentence processing. As long as word-category information can be derived earlier from the acoustic input than semantic information, as was the case in the above-mentioned studies, the immediacy model predicts that it will be used as it comes in. The syntax-first model, however, predicts that even in cases where word-category information comes in later than semantic information, this syntactic information will nevertheless be used earlier than semantic information in sentence processing, or semantic integration will not succeed. In line with their version of this model, Hahne and Friederici (2002) claim that their data "suggest that semantic integration processes are not initiated automatically in the case of a phrase structure violation" (p. 352), and "thus, the comprehension system does not seem to attempt at integrating the element eliciting a phrase structure violation on a semantic level" (p. 353). As they conclude, "the processing of phrase structure information has priority over that of lexical-semantic information", and "the syntactic feature of an incorrect word category may block the semantic integration of that particular word" (p. 353).

Van den Brink and Hagoort (2004) designed a strong test of the syntax-first model, in which semantic information precedes word-category information. In many languages, information about the word category is often encapsulated in the suffix rather than the prefix of a word. In contrast to an immediacy model, a syntax-first model would in such a case predict that semantic processing (particularly semantic unification) is postponed until after the information about the word category has become available, or it will not take place at all.

In their study, Van den Brink and Hagoort (2004) compared correct Dutch sentences (see item 3a below) with their anomalous counterparts (see 3b) in which the critical word (italicized in 3a/b) both was a semantic violation in the context and had the incorrect word category. However, in contrast to the experiments by Friederici and colleagues, word-category information was encoded in the suffix "-de".

(3) a. Het vrouwtje veegde de vloer met een oude *bezem* gemaakt van twijgen. ("The woman wiped the floor with an old *broom* made of twigs.")

b. *Het vrouwtje veegde de vloer met een oude *kliederde* gemaakt van twijgen.
("The woman wiped the floor with an old *messed* made of twigs.")

Figure 11.4 shows the waveform of the spoken verb form "kliederde" (messed). This verb form has a duration of approximately 450 ms. The stem already contains part of the semantic information. However, the onset of the suffix "-de" is at about 300 ms into the word. Only at this point will it be clear that the word category is a verb, and not a noun as required by the context. We define this moment of deviation from the correct word category as the category violation point (CVP), because only at this time is information provided on the basis of which it can be recognized as a verb, which is the incorrect word category in the syntactic context. Although in this case semantic information can be extracted from the spoken signal before word category information, the syntax-first model predicts that this semantic information can not be used for semantic unification until after the assignment of word category.

Figure 11.5 shows the averaged waveforms that are time-locked to the CVP

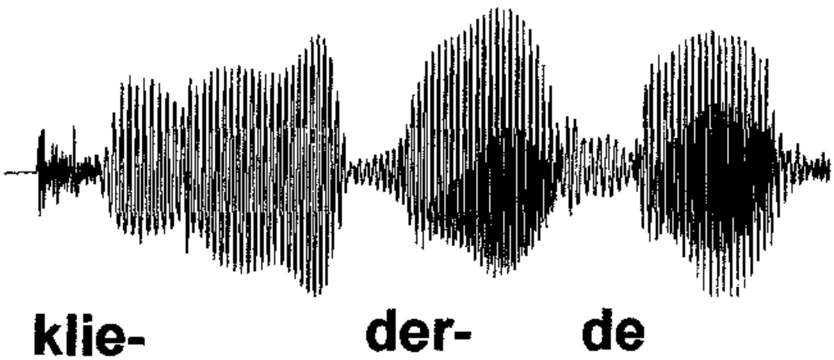

Figure 11.4 A waveform of an acoustic token of the Dutch verb form "kliederde" (messed). The suffix "-de" indicates past tense. The total duration of the acoustic token is approximately 450 ms. The onset of the suffix "-de" is at approximately 300 ms. Only after 300 ms of signal can the acoustic token be classified as a verb. Thus, for a context that does not allow a verb in that position, the category violation point (CVP) is at 300 ms into the verb (see text).

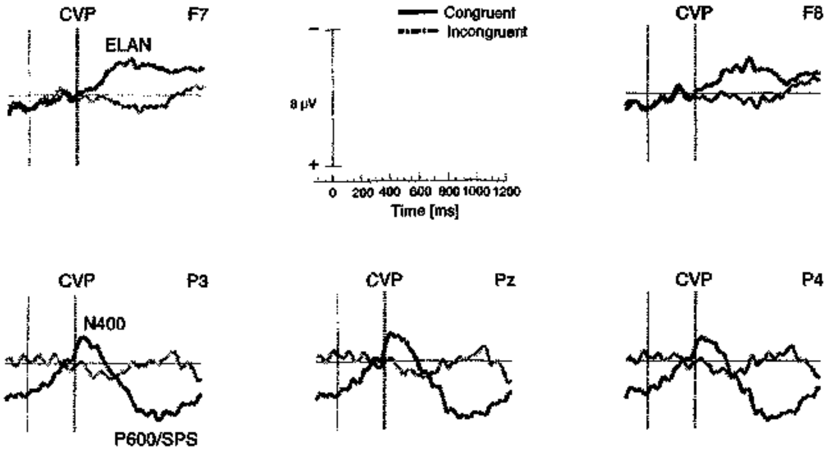

Figure 11.5 Connected speech. Grand-average ERPs from two frontal electrode sites (F7, F8) and three posterior electrode sites (Pz, P3, P4) to critical words that were semantically and syntactically congruent with the sentence context (congruent: solid line), or semantically and syntactically incongruent (incongruent: alternating dashed/dotted line). Grand-average waveforms were computed after time locking on a trial-by-trial basis to the moment of word-category violation (CVP: category violation point). The baseline was determined by averaging in the 180–330-ms interval, corresponding to a 150-ms interval preceding the CVP in the incongruent condition. The time axis is in milliseconds, and negativity is upward. The ELAN is visible over the two frontal sites; the N400 and the P600/SPS over the three posterior sites. The onset of the ELAN is at 100 ms after the CVP; the onset of the N400 effect precedes the CVP by approximately 10 ms (after Van den Brink & Hagoort, 2004).

for two frontal sites where usually the ELAN is observed, and two posterior sites that are representative of N400 effects. As can be seen, the N400 effect clearly precedes the ELAN in time. Whereas the ELAN started at approximately 100 ms after the CVP, the N400 effect was already significant before the CVP. To my knowledge, this is the clearest evidence so far for the claim that semantic unification can start before word-category information is provided. This is strong evidence for the immediacy assumption: information available in the signal is immediately used for further processing. In contrast to what a strong version of the syntax-first model predicts, semantic unification does not need to wait until an initial structure is built on the basis of word-category information. Only when a syntax-first model allows prediction of word category could it be claimed that this prediction was falsified only at the CVP, and thus initially semantic unification could be started up. However, this weaker version of a syntax-first model has given up the characteristic of bottom-up priority and assumes an interaction between syntactic context and lexical processing. One can then ask which feature of the processing architecture guarantees that interaction between context and lexical processing is restricted to syntax.

In summary, the evidence so far indicates that distinct ERP effects are observed for semantic integration (N400) and syntactic analysis ((E)LAN, P600/SPS). The ERP data presented argue against a syntax-first model of sentence processing. Rather, as soon as semantic or syntactic information is available, it is used for the purpose of interpretation. This is in line with the assumptions of the immediacy model. The triggering conditions of the syntax-related ERP effects are becoming more clear. Apart from the LAN effects related to working memory, so far (E)LAN effects have mainly been seen in response to syntactic *violations*. These violations can be word-category violations that are sometimes seen early (ELAN), but they can also be morphosyntactic violations that are usually observed within the same time frame as the N400 effects (300–500 ms). The anterior negativities are normally followed by a P600/SPS. In contrast to the (E)LAN, the P600/SPS is seen not only in syntactic violations but also in syntactically less preferred structures (i.e., in the case of syntactic ambiguity; Van Berkum et al., 1999a; Osterhout et al., 1994), and in syntactically more complex sentences (Kaan et al., 2000). In many cases, the P600/SPS occurs without a concomitant early negativity. For straightforward syntactic violations, the distribution of the P600/SPS seems to be more posterior than the P600/SPS reported in relation to syntactic ambiguity resolution and syntactic complexity (Hagoort et al., 1999; Kaan & Swaab, 2003a, 2003b).

The unification model

The increasing numbers of ERP studies on syntactic processing in the last decade have resulted in a substantial number of data that are in need of a coherent, overall account. I will propose an explicit account of syntax-related ERP effects based on a computational model of parsing developed by Vosse and Kempen (2000), here referred to as the unification model. This proposal is certainly not the end stage, but only a beginning. The model needs to be adapted and the account of the ERP data needs to be refined. Nevertheless, I believe that progress will be made only if we attempt to connect not only the behavioural data but also data from electrophysiology and neuroimaging to explicit computational accounts. I will first describe the general architecture of this model.

According to the unification model, 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 (Figure 11.6). (For details concerning the computation of word order, see Harbusch & Kempen, 2002.)

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.

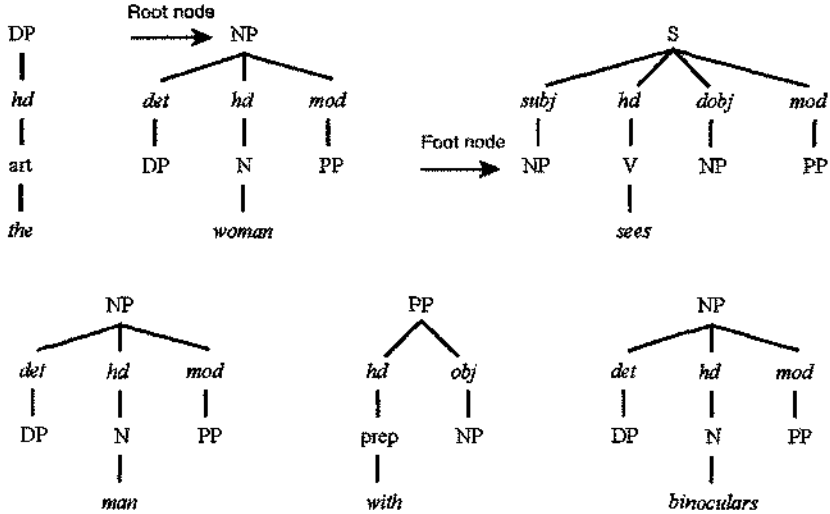

Figure 11.6 Syntactic frames in memory (the mental lexicon). Frames are retrieved on the basis of the word form input for the sentence, *The woman sees the man with the binoculars*. DP: Determiner Phrase; NP: Noun Phrase; S: Sentence; PP: Prepositional Phrase; art: article; hd: head; det: determiner; mod: modifier; subj: subject; dobj: direct object.

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 online 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. This operation consists of linking up lexical frames with identical root and foot nodes (Figure 11.7), 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, implying 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 unification 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 (Figure 11.8).

Ultimately, one phrasal configuration results. This requires that among the alternative unification 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 acti-

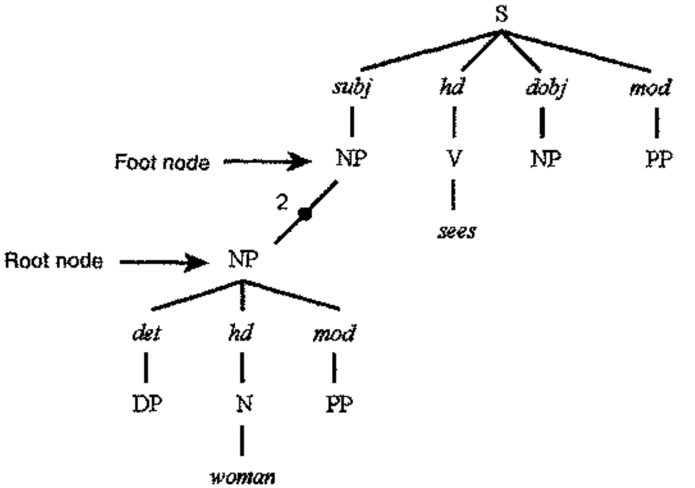

Figure 11.7 The unification operation of two lexically specified syntactic frames. The unification takes place by linking the root node NP to an available foot node of the same category. The number 2 indicates that this is the second link that is formed during online processing of the sentence, *The woman sees the man with the binoculars*.

vation, more recent root nodes will have a higher level of activation than the ones that entered the unification space earlier. This is why the likelihood of an attachment of the PP into the syntactic frame of the verb "sees" is higher than into the syntactic frame for "woman" (see Figure 11.7). 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 override the recency effect. For our example sentence (see Figure 11.8), it means that the outcome of lateral inhibition is that the PP may be linked to the S-frame (unification link 7) rather than to the more recent NP-node of "man" (U-link 8) (for details, see Vosse & Kempen, 2000).

The unification model accounts for sentence complexity effects known from behavioural measures, such as reading times. In general, sentences are harder to analyse syntactically when more potential unification links of similar strength compete 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 (1) it is computationally explicit, (2) it accounts for a large series of empirical findings in the parsing literature (but presumably not for all the locality phenomena in Gibson, 1998) and in the neuropsychological literature on aphasia, and (3) 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 et al., 1994).

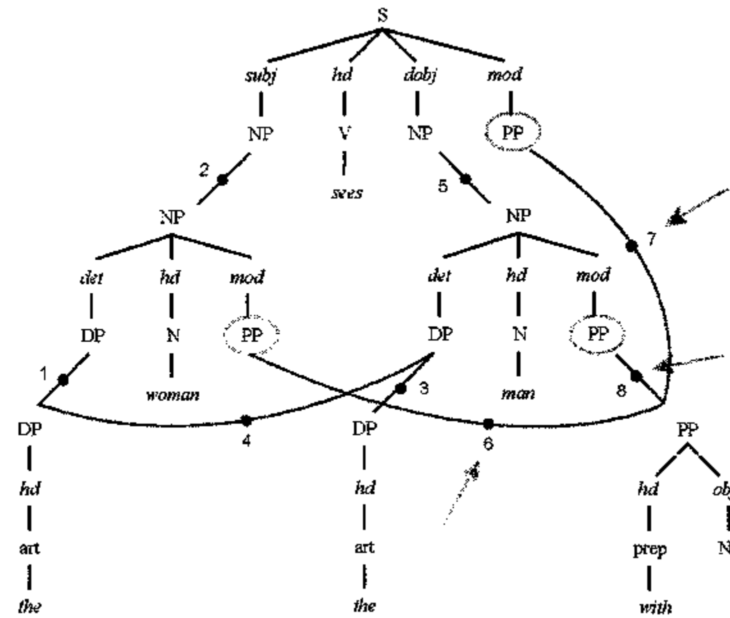

Figure 11.8 Lateral inhibition between three different PP-foot nodes that are candidate unification sites for the PP-root node of the preposition "with". The three possible unification links are indicated by arrows. Lateral inhibition between these three possible unifications (6, 7, and 8) ultimately results in one unification that wins the competition and remains active.

This model also nicely accounts for the two classes of syntax-related ERP effects reported in this and many other studies. 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 a (left) anterior negativity (AN) 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. 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 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 unification 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 unification 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 preliminary account of the collective body of ERP data on syntactic processing. Moreover, it does not assume a syntax-first architecture. It is, therefore, a better account of the empirical data, both behavioural and electrophysiological, than models that assume a syntax-first phase.

Semantic unification

Next to syntactic unification, semantic unification operations have to take place. Neuropsychological patient studies, as well as data from neuroimaging studies, suggest that semantic representations might be distributed with the involvement of areas that support the most salient aspects of a concept (e.g., visual, kinesthetic, linguistic/propositional) (Allport, 1985; Saffran & Sholl, 1999). Context can differentially activate/select the saliency of meaning aspects (as in "The girl gave a wonderful performance on the old *piano*" vs. "Four men were needed to transport the old *piano*"). At the same time, the semantic aspects retrieved on the basis of lexical access have to be integrated into a coherent interpretation of a multiword utterance. This I will refer to as *semantic unification*. It turns out that the left lateral prefrontal cortex is also crucial for semantic unification (see below). Binding-relevant areas within the left prefrontal cortex (LPC) might overlap, at least to some degree, for syntactic and semantic unification. But there is also evidence that semantic unification might involve more ventral areas (especially Brodmann's area 47) than syntactic unification. More research is needed to determine commonalities and differences in the LPC between areas involved in phonological, syntactic, and semantic unification. However, the qualitative differences between ERP effects of semantic (N400) and syntactic (LAN, P600) unification suggest that the brain honours the distinction between these two types of unification operations.

The level of semantic unification: Sentence vs. discourse

A central issue for semantic unification is whether or not a semantic representation at the sentence-level is built up first, before, in a second step, semantic information is integrated into a discourse model. For instance, in their blueprint of the listener, Cutler and Clifton (1999) assume that, based on syntactic analysis and thematic processing, utterance interpretation takes place first, before, in a next processing step, integration into a discourse model follows. Kintsch (Ericsson & Kintsch, 1995; Kintsch, 1998) has made similar claims. To investigate this issue, we conducted an ERP study to investigate how and when the language-comprehension system relates an incoming word to semantic representations of the unfolding local sentence and the wider discourse (Van Berkum et al., 1999b). In the first experiment, subjects were presented with short stories, of which the last sentence sometimes contained a critical word that was semantically anomalous with respect to the wider discourse (e.g., *Jane told the brother that he was exceptionally slow* in a discourse context where he had in fact been very quick). Relative to a discourse-coherent counterpart (e.g., *quick*), these discourse-anomalous words elicited a large N400 effect (i.e., a negative shift in the ERP that began at about 200–250 ms after word onset and peaked around 400 ms).

Next to the discourse-related anomalies, sentence-semantic anomaly effects were elicited under comparable experimental conditions. We found that the ERP effects elicited by both types of anomalies were highly similar. Relative to their coherent counterparts, discourse- and sentence-anomalous critical words elicited an N400 effect with an identical time-course and scalp topography (Figure 11.9). The similarity of these effects, particularly in polarity and scalp distribution, is compatible with the claim that they reflect the activity of a largely overlapping or identical set of underlying neural generators, indicating similar functional processes.

In summary, there is no indication that the language-comprehension system is slower in relating a new word to the semantics of the wider discourse than in relating it to local sentence context. Our data clearly do not support the idea that new words are related to the discourse model *after* they have been evaluated in terms of their contribution to local sentence semantics. The speed with which the discourse context affects processing of the current sentence appears to be at odds with recent estimates of how long it would take to retrieve information about prior discourse from long-term memory. In Van Berkum et al.'s materials, the relative coherence of a critical word usually hinged on rather subtle information that was implicit in the discourse and that required considerable inferencing about the discourse topic and the situation it described. Kintsch (Ericsson & Kintsch, 1995; Kintsch, 1998) has suggested that during online text comprehension, such subtle discourse information is not immediately available and must be retrieved from "long-term working memory" when needed. This is estimated to take some 300–400 ms at least. However, the results of our experiments suggest that the

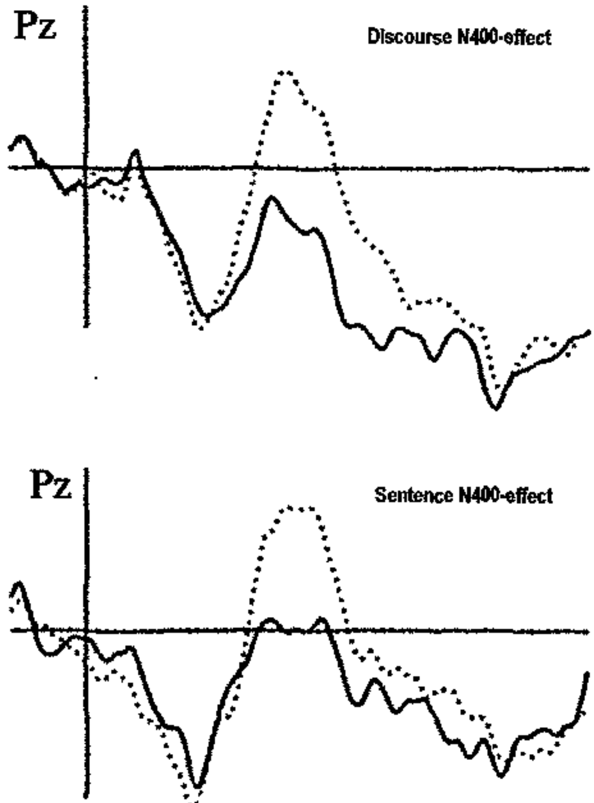

Figure 11.9 N400 effects triggered by discourse-related and sentence-related anomalies. Waveforms are presented for a representative electrode site. The latencies of the N400 effect in discourse and sentence contexts (both onset and peak latencies) are the same (after Van Berkum et al., 1999b).

relevant discourse information can be brought to bear on local processing within at most 200–250 ms.

The observed identity of discourse- and sentence-level N400 effects is most parsimoniously accounted for in terms of a processing model that abandons the distinction between sentence- and discourse-level semantic unification. This is compatible with the notion of *common ground* (Clark, 1996; Stalnaker, 1978). The analysis of Clark clearly demonstrates that the meaning of linguistic utterances cannot be determined without taking into account the knowledge that speaker and listener share and mutually believe they share. This common ground includes a model of the discourse itself, which is continually updated as the discourse unfolds. If listeners and readers always immediately evaluate new words relative to the discourse model and the associated information in common ground (i.e., immediately compute "contextual meaning"), the identity of the ERP effects generated by sentence- and discourse anomalies has a natural explanation. With a single sentence, the relevant common ground includes only whatever discourse and world knowledge has just been activated by the sentence fragment presented so far. With a sentence presented in discourse context, the relevant common ground will be somewhat richer, now also including information elicited by the specific earlier discourse. But the process that maps incoming words onto the relevant common ground can run into trouble either way. The N400 effects observed in the Van Berkum et al. study (1999b) reflect the activity of this unified unification process. Of course, this is not to deny the relevance of sentential structure for semantic interpretation. In particular, how the incoming words are related to the discourse model is co-constrained by sentence-level syntactic devices (such as word order, case marking, local phrase structure, or agreement) and the associated mapping onto thematic roles. However, this is fully compatible with the claim that there is no separate stage during which word meaning is exclusively evaluated with respect to "local sentence meaning", independent of the discourse context in which that sentence occurs.

The neural implementation of unification in language

In the context of the language system, the binding problem refers to the following issue: 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 (Jackendoff, 2002). So far, I have discussed the features of the cognitive architecture for syntactic and semantic unification. In this section, I will argue that the left inferior prefrontal cortex might have the characteristics necessary for performing the unification operations at the different levels of the language system.

One requirement for solving the binding problem for language is the availability of cortical tissue that is particularly suited for maintaining information online while unification operations take place. The prefrontal cortex seems to be especially well suited for doing exactly this. Areas in the prefrontal cortex are able to hold information online (Mesulam, 2002), and to select among competing alternatives (Thompson-Schill, D'Esposito, & Kan, 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 the prefrontal cortex to establish unifications between pieces of information that are perceived or retrieved from memory at different moments in time.

I will make some tentative suggestions about how the different components of the unification model for syntactic unification that I discussed above could be connected to our knowledge about the neural architecture.

This proposal is not yet explicitly tested, but, as I will argue, it makes good sense in the light of our current knowledge about the contributions of the areas involved. In a recent meta-analysis of 28 neuroimaging studies, Indefrey (2004) 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.

As is known from lesion studies in aphasic patients, lesions in different areas of the left perisylvian cortex can result in syntactic processing deficits in sentence comprehension (Caplan, Hildebrandt, & Makris, 1996). The idea that modality-independent grammatical knowledge was mainly represented in Broca's area (Zurif, 1998) has thus been proven to be incorrect. At the same time, the left posterior temporal cortex is known to be involved in lexical processing (Indefrey & Cutler, 2004). In connection to syntactic unification, 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. One of the main specializations of the prefrontal cortex is the holding online and binding of information (Mesulam, 2002). It might be the right area for providing the computational resources for binding together the lexical-syntactic frames through the dynamics of creating unification links between them (cf. Duncan & Miller, 2002). It thus seems that the components of the unification model and the areas known to be crucial for syntactic processing can be connected in a relatively natural way, with the left superior temporal cortex relevant to storage and retrieval of syntactic frames, and the left prefrontal cortex important for binding these frames together.

The need for combining independent bits and pieces into a single 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. Recent neuroimaging studies (cf. Bookheimer, 2002) suggest that parts of the prefrontal cortex in and around Broca's area might be involved in conceptual and phonological unification, with Brodmann's areas (BA) 47 and 45 involved in semantic unification, BA 45 and 44 in syntactic unification, and BA 44 and ventral BA 6 in phonological unification (Figure 11.10, see colour plate section).

Neuropsychological studies (Martin & He, 2004; Martin & Romani, 1994) further support the distinction between semantic and syntactic unification. These authors report patients that have difficulty either in integrating semantic information with increasing semantic load, or in maintaining structural information when it must be integrated across several intervening words. However, as often in patients studies, the lesion data lack the required precision to make strong claims about the crucial brain areas for these respective unification operations.

Seven principles of the processing architecture

In analogy to other domains of cognitive neuroscience, for language comprehension, I have made a distinction between memory retrieval and unification or binding. I have discussed features of the processing architecture for syntactic and semantic unification. Evidence from neuroimaging studies seems to support the distinction between brain areas recruited for memory retrieval and brain areas crucial for unification. From the evidence discussed in the preceding sections, I propose the following seven general architectural principles for comprehension beyond the single word level:

(1) The brain honours the distinction between syntactic and semantic unification. However, both involve contributions from the left prefrontal cortex (in and around Broca's area), as the workspace where unification operations take place. It is quite possible that this area is not language specific, but subserves other functions as well (e.g., binding in music; see Patel, 2003). The left prefrontal cortex is suggested to maintain the activation state of representational structures retrieved from memory (the mental lexicon), and to provide the necessary neuroanatomical space for unification operations.

(2) Immediacy is the general processing principle of unification. Semantic unification does not wait until relevant syntactic information (such as word class information) is available, but starts immediately with what it derives on the basis of the bottom-up input and the left context. The corollary of immediacy is incrementality: Output representations are built up from left to right in close temporal contiguity to the input signal.

(3) There does not seem to be a separate stage during which word meaning is exclusively integrated at the sentence level. Incremental interpretation is for the most part done by an immediate mapping onto a discourse model (Clark, 1996).

(4) In parsing, lexically specified structures enter the unification space. Lexical information (e.g., animacy), discourse information, and, according to recent data, other-modality inputs (e.g., visual world, gesture) immediately influence the competition between alternative unification options, and can change the unification links. However, in the absence of competing unification sites, assignment of structure is not influenced by nonsyntactic information types.

(5) There is no evidence for a privileged position of syntax and/or a processing priority for syntax, as assumed in syntax-first models. The different processing levels (phonological, syntactic, and semantic/pragmatic) operate in parallel, and, to some degree, independently. Where necessary, cross-talk takes place, and this is again characterized by the immediacy principle. That is, cross-talk takes place on a more or less moment-to-moment basis.

(6) The comprehension system operates according to the "loser-takes-all" principle. That is, if the syntactic cues are stronger than the semantic cues (e.g., thematic biases), the processing problem will be at the level of semantic unification. If the semantic cues are stronger than the syntactic cues, the processing problem will be shifted to the assignment of syntactic structure.

(7) Within certain limitations, the language-comprehension system can adapt the weight of evidence in the light of system-internal or system-external noise. The degrees of freedom in language comprehension are much greater than in language production.

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