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The Time Course of Syntactic Activation during Language Processing: A Model Based on Neuropsychological and Neurophysiological Data

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This paper presents a model describing the temporal and neurotopological structure of syntactic processes during comprehension. It postulates three distinct phases of language comprehension, two of which are primarily syntactic in nature. During the first phase the parser assigns the initial syntactic structure on the basis of word category information. These early structural processes are assumed to be subserved by the anterior parts of the left hemisphere, as event-related brain potentials show this area to be maximally activated when phrase structure violations are processed and as circumscribed lesions in this area lead to an impairment of the on-line structural assignment. During the second phase lexical-semantic and verb-argument structure information is processed. This phase is neurophysiologically manifest in a negative component in the event-related brain potential around 400 ms after stimulus onset which is distributed over the left and right temporo-parietal areas when lexical-semantic information is processed and over left anterior areas when verb-argument structure information is processed. During the third phase the parser tries to map the initial syntactic structure onto the available lexical-semantic and verb-argument structure information. In case of an unsuccessful match between the two types of information reanalyses may become necessary. These processes of structural reanalysis are correlated with a centro-parietally distributed late positive component in the event-related brain potential. The different temporal and topographical patterns of the event-related brain potentials as well as some aspects of aphasics' comprehension behavior are taken to support the view that these different processing phases are distinct and that the left anterior cortex, in particular, is responsible for the on-line assignment of syntactic structure. © 1995 Academic Press, Inc.

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INTRODUCTION

The basic mechanism underlying language comprehension is lexical access. Lexical entries by hypothesis hold all relevant information needed to structure the language input and to assign thematic roles. There are two general accounts framing how the language processor exploits syntactic and semantic information carried by lexical elements: the structure-driven and the lexical-driven account. The structure-driven account claims that there are two processing stages, an initial stage during which the parser identifies the structure of the input based on syntactic word category information and a second stage during which thematic role assignment takes place on the basis of structural and lexical information (e.g., Ferreira & Clifton, 1986; Frazier, 1978, 1990; Frazier & Fodor, 1978; Frazier & Rayner, 1982; Rayner, Carlson, & Frazier, 1983). During this initial first-pass parse lexical information other than word category information is irrelevant. The parser is driven by particular phrase structure heuristics rather than by lexical information. One such heuristic is the so-called minimal attachment principle which holds that phrases are initially assigned to the simplest structure defined by the least distant node in the phrase structure tree (Frazier, 1978, 1990). The lexical-driven account, in contrast, holds that initial sentence parsing is guided by lexical information, especially by the argument structure of the verb, i.e., its subcategorization information. In case of multiple argument structures (e.g., *John reads, John reads the book*) preferences as defined by the frequency of use operative in guiding the first parse (Ford, Bresnan, & Kaplan, 1982; Shapiro, Nagel, & Levine, 1992; Trueswell, Tanenhaus, & Kello, 1993).

From the outline of the two positions it is obvious that any empirical support for either position must focus on the temporal structure of the availability of different information types carried by lexical elements and functional elements during sentence processing. There are several ways to gain information about the temporal structure of comprehension processes. One is to conduct reaction time studies sensitive to the issue in focus. A second possibility is to look into language processing systems whose temporal structure deviates from normal subjects in defined and specific ways, such as in subjects with particular neuropsychological deficits. A third way to monitor the temporal structure of language processing is to register the brain activity as sentences are processed in time, as, for example, in event-related brain potential studies.

There is quite an extensive literature using reaction time paradigms in studies with normal subjects, i.e., non-brain-damage subjects (e.g., Altmann, 1989; Frauenfelder & Tyler, 1987), investigating how syntactic and lexical-semantic information is retrieved and used during normal comprehension. This paper will extend this view by focusing on neuropsychological evidence gathered from patients with circumscribed brain lesions in on-line comprehension studies and on neurophysiological evidence from normal subjects in event-related brain potential studies providing neurotopographic as well as temporal information correlated with semantic and syntactic processes during comprehension.

The model under consideration here is close to the structure-driven account holding that there is an initial parse solely based on word category information with lexical-semantic information coming in at a later point in time. In contrast to the original proposal of Frazier (1978), the present view is open to the possibility that preferences for first-pass parses may not necessarily follow the simplest structure, but rather the most frequent one used in the particular language under investigation. Although we are not able to present data of our own laboratory on the latter issue, findings from other groups suggest that this is possible (Altmann, Garnham, & Dennis, 1992; Crain & Steedmann, 1985).

It should be stated clearly that the experiments reported here were not set up to distinguish between the structure-driven and the lexical-driven account, but rather followed a processing view which assumes different processing systems for structural and lexical-semantic information showing different rise-times in normal subjects, different neuropsychological pattern in language breakdown, and different neurophysiological correlates as revealed by measuring subjects' brain activity during sentence processing. The findings from these experiments, however, suggest a view on the time course of language comprehension processes which is compatible with a modified structure-driven parsing account.

THE NEUROPSYCHOLOGICAL DATA

Earlier work (Friederici, 1985) had revealed differential reaction time patterns for the recognition of elements carrying mainly lexical-semantic information, i.e., open-class words and those carrying mainly structural information, i.e., closed-class words, when these were presented in sentence context. Elements of the closed-class were recognized faster than elements of the open class. Moreover, recognition of open-class words, but not of closed-class words, was a function of whether they appeared in sentence pairs in which the first sentence was semantically related to the second one or not. This result was taken to indicate that closed-class words carrying the structural information are accessed fast and independent of the semantic content given by sentential context.

Interestingly, agrammatic Broca patients with lesions in the anterior part of the left hemisphere, but not Wernicke patients with lesions in the posterior part of the left hemisphere, were selectively slowed down in recognizing closed-class words in a similar experiment (Friederici, 1983, 1985). As these patients' behavioral patterns with respect to the open-class elements were similar to normals, we reasoned that access to lexical-semantic information is relatively intact. Thus, these patients seem to provide a good test for the influence of slow-rise time for syntactic information. This view is supported by some studies showing delayed syntactic processes (Friederici & Kilborn, 1989; Haarmann & Kolk, 1994; Zurif, Swinney, Prather, Solomon, & Bushell, 1993) and intact semantic processes (Hagoort, 1993; Ostrin & Tyler, 1993), but not by other studies which found lexical-semantic processes to be slowed down in agrammatics as well (Blumstein, Milberg & Shrier, 1982; Milberg & Blumstein, 1981; Milberg, Blumstein, & Dworetzky, 1987; Prather, Shapiro, Zurif, & Swinney, 1991). However, unlike our own study, these studies had not compared processing of lexical-semantic and syntactic aspects directly. The data of our experiments also showed slowed recognition times for open-class words for agrammatic Broca's aphasics compared to normals; this effect, however, was minor compared to the massive slowing down in recognizing closed-class words. The latter elements were recognized about 250 ms slower by agrammatic Broca's aphasics compared to normal subjects.

Given this major slowing down in recognizing closed-class elements in spoken sentences, we wondered whether agrammatic Broca's aphasics were able to access the structural information encoded in these elements at all. This question was investigated by using a syntactic priming paradigm in which auditorily presented sentence fragments were continued by either a grammatical or an ungrammatical continuation, e.g., *Het meisje wordt geslagen* vs. *Het meisje wordt gereisd*/*The girl is being hit* vs. *The girl is being traveled* (Friederici & Kilborn, 1989). The grammaticality of the sentences depended on the combination of the auxiliary and the past participle. If agrammatic Broca's aphasics would be able to access the information carried by the auxiliary, although slowly, these patients should show a grammaticality effect in their lexical decision times on the sentence final word, i.e., faster reaction times in the grammatical than in the ungrammatical condition. The observed reaction times indicated that agrammatic Broca's aphasics are able to access and to use the information carried by the closed-class element under investigation; however, their overall lexical decision times for the past participles in sentence context were dramatically slowed down (by about 200–250 ms) compared to a baseline measure in which a lexical decision task had to be performed on past participle forms in isolation. The reverse was true for normal age matched subjects who demonstrated faster reaction times for targets presented in sentence context versus in isolation. This result was taken to support the hypothesis that a major aspect of agrammatic Broca's aphasia is the loss of fast, automatic access and the use of the structural information carried by grammatical elements.

These findings as well as the data of related studies (Prather et al., 1991) suggest that the Broca and/or adjacent areas subserve the fast syntactic procedures necessary to structure the incoming sequence of linguistic elements. These procedures are assumed to be highly automatic and informationally encapsulated in the adult brain, but only emerge in context with given language experience during development (Friederici, 1983, 1988, 1995). The particular and primary function of these established procedures may be defined as to realize fast buildup of phrasal structures including traces of vowed elements.

The outcome of these procedures, in any case, is a syntactic phrase structure providing the basis for thematic role assignment. The building up of a phrase structure, as well as the ability to keep this structure available until thematic role assignment has taken place, may be the heart of the normal comprehension process which derails in Broca's aphasics. This, in turn, would suggest that those cortical areas involved in Broca's aphasia subserve these procedures. The relation between brain areas involved in Broca's aphasia and the building up of phrasal structure has been discussed quite extensively over the last years in the field of aphasia research (Prather et al., 1991; Haarmann & Kolk, 1990; Frazier & Friederici, 1991; see also Grodzinsky 1984, for a linguistic specification of the agrammatic deficit).

The neuropsychological data reported here support the view that the Broca and adjacent areas subserve those syntactic procedures which guarantee normal on-line processing, i.e., the fast and automatic structuring of the incoming linguistic input into syntactic chains or phrases. A delay of these early structuring processes of about 200 to 250 ms seems to have severe consequences for subsequent processes such as on-line thematic role assignment. How can this be? The idea is that the early structuring processes support the comprehension system insofar as the language input does not have to be kept in verbal memory as a list of words, but can be chucked, i.e., parsed into phrases. This allows the system to keep more words which await thematic roles assignment in verbal memory. The assignment of thematic roles defined as the successful match of structural and lexical information may require the availability of quite a sequence of words in the actual verbal memory, as the entire input information must be available again in case no successful match is possible and a reanalysis of the input becomes necessary. The early structuring processes supported by brain systems located in the anterior part of the left hemisphere may thus provide the basis for an efficient verbal memory keeping information in the form of structured phrases rather than word lists (Friederici & Frazier, 1992).[1]

[1] Note that the assumption predicts poor memory performance of agrammatic subjects for structured sequences or elements herein, but not for function words when presented in isolation as proposed by Nicol and Rapscak (1994). What they showed is indeed agrammat-

So far, the present view is based solely on findings from studies with brain-damaged subjects. There is, however, a debate with respect to whether it is valid to generalize from lesion studies to the normal functioning of the brain.

THE EVENT-RELATED BRAIN POTENTIAL DATA

One possibility to investigate the temporal and neurotopological parameters of language processes in the normal brain is to register subjects' brain activity while reading or listening to sentences. A noninvasive registration of brain activity during cognitive processes is the electrophysiological measure of event-related brain potentials. The event-related brain potential (ERP) is the electrical activity of the brain time-locked to the presentation of a stimulus. Its temporal resolution is in the domain of milliseconds and its topographic resolution depends upon the amount of electrodes used for registration. Components of the ERP have been shown to be sensitive in polarity, amplitude, and latency to a variety of sensory and cognitive processes including those underlying language comprehension (Donchin & Coles, 1988; Hillyard & Picton, 1987; Kutas & van Petten, 1988; van Petten & Kutas, 1991).

LEXICALLY BOUND PROCESSES

The meanwhile classical experiment by Kutas and Hillyard (1983) demonstrated a specific waveform in the event-related brain potential measured during sentence reading correlated with the processing of semantic anomalies. This waveform had a negative polarity and peaked 400 ms after the onset of the critical word showing a wide distribution over the posterior areas of both hemispheres. The amplitude of this negativity was a reverse function of the semantic adequacy or fit of the target to the preceding context.

In the same experiment Kutas and Hillyard (1983) had also included sentences containing syntactic errors of subject–verb agreement, but did not find any reliable ERP correlate for this type of error. The absence of an ERP correlate for syntactic processes in this experiment could be due to several reasons. First, it could be due to the fact that agreement markers in English are not very prominent and, therefore, hard to detect. Second, a listener being exposed to language which is only weakly in-

ics' poor memory performance for closed-class elements when presented in sentences. They fail to show these subjects performance on word lists consisting of or containing function words. The data of Friederici and Frazier (1992) show that agrammatics' comprehension performance decreases when memory load of the task increases, despite the fact these patients show not particularly poor performance for function word memory versus content word memory when presented in lists.

flected such as English may not have developed a strong sensitivity to inflectional elements. Third, the fact that the stimulus material in this experiment was presented in a word-by-word presentation mode with pauses of 400 and 500 ms between each word may have blurred fast and automatic syntactic processes. We assumed that we might be able to observe an ERP correlate for fast syntactic processes when investigating more salient violations than those used by Kutas and Hillyard (1983) in a highly inflected language such as German in a rapid serial visual presentation mode with pauses of 100 to 200 ms between each word.

In a first experiment we evaluated a quite salient type of syntactic violation, namely, subcategorization violations, e.g., *Der Präsident wurde gefallen/The president is being fallen* (Rösler, Friederici, Pütz, & Hahne, 1993). This type of violation had been proven to show reliable effects in reaction time studies conducted with normal and aphasic subjects (Friederici & Kilborn, 1989). In order to be able to compare waveforms elicited by this type of violation to the known N400 component as a correlate of semantic processes, we also included sentences containing semantic anomalies, i.e., violations of selectional restriction information, e.g., *Der Präsident wurde gewürzt/The president is being spiced.* Sentences of these types together with correct sentences were presented visually in a word-by-word fashion with a 100-ms presentation time for each word and a 100-ms pause for the three words making up the context for the sentence final target word which was presented for 200 ms. Subjects were required to perform a delayed lexical decision task on the last word of the sentence. Brain activity was recorded from six electrodes [Fz, Pz, "Broca left" (Bl), "Wernicke left" (Wl), and the homologous areas of the right hemisphere, i.e., "Broca right" (Br) and "Wernicke right" (Wr)]. ERPs were averaged over 13 subjects in the semantic violation condition and over 15 subjects in the syntactic violation condition.

For the semantic violation we observed a N400 waveform, broadly distributed over the left and the right hemisphere. For the syntactic violation we found a negativity in the same temporal domain, but with a different topography. In contrast to the N400, the negativity elicited by the subcategorization violation had a left anterior distribution with maxima over the left anterior (Bl) and the frontal electrode (Fz).

We interpreted these data with respect to their temporal as well as to their topographic characteristics. The *temporal domain* around 400 ms was taken to reflect the time window at which the full information of a lexical entry is available, i.e., aspects of meaning, for example, selectional restriction information, as well as syntactic aspects, such as subcategorization information. The different *topography* was taken to indicate the respective brain systems involved in processing semantic versus syntactic aspects encoded in the lexical entry with syntactic processes, in particular being subserved by the anterior parts of the left hemisphere.

A similar left anterior negative component around 400 ms was recently observed independently in different laboratories to correlate with aspects of syntactic processes (e.g., Münte, Heinze, & Mangun, 1993; see Kluender and Kutas, 1993, for an overview.[2]

The observed ERP pattern for the subcategorization violation may be valid only for syntactic processes requiring the full access to the lexical entry. Other syntactic processes responsible for different aspects of syntactic parsing may, however, correlate with electrophysiological components different in polarity, amplitude, and timing. These are, for example, processes discussed in models of sentence comprehension assuming different stages of syntactic processing. The structure-driven model by Frazier (1978) assumes two stages: an initial stage, during which the parser builds a phrasal structure solely on the basis of word category information, and a second stage, during which thematic role assignment takes place integrating lexical-semantic and syntactic information (Frazier, 1978, 1987). This position has found its support in some studies (e.g., Frazier & Rayner, 1982; Mitchell, 1987; Rayner, Garrod, & Perfetti, 1992), while other studies rather suggest an approach allowing for preceding sentential and lexical information to influence the initial parse (e.g., Altmann et al., 1992; Shapiro et al., 1993). From the available empirical data it is not clear under which circumstances and at which point in time the reader or listener might consult lexical frame information to guide phrase structure assignment. In theory, the lexical-driven account would predict that full lexical information is available before or at the time when structure is assigned, whereas the structure-driven account would predict the first-pass parsing stage to be based primarily on word category information, with lexical and discourse information coming in only later.

Early Syntactic Processes

A next ERP experiment was carried out focusing on those early syntactic parsing processes which are assumed to be based on word category information (Friederici, Pfeifer, & Hahne, 1993). In this experiment we used an auditory presentation mode presenting the stimulus material as running speech. We reasoned that in this mode we might be able to detect fast and automatic processes which guarantee the early structuring of incoming linguistic information. Previous studies which set out to evaluate syntactic processes during comprehension by event-related brain potentials had mostly used a word-by-word visual presentation mode with

[2] Kluender and Kutas (1993) interpret this left anterior negativity around 400 ms to be correlated with working memory involved in gap-filling operations. This interpretation may not hold for the present data, as the stimulus material used did not require an extensive load on working memory.

pauses between each word of 300, 500, or 700 ms long (Kutas & Hillyard, 1983; Münte et al., 1993; Osterhout & Holcomb, 1992). This presentation mode may have covered those early syntactic processes assumed by structure-driven comprehension models.

In our study we included correct sentences and sentences containing violations of three different types. A semantic violation condition, similar to the one used in the previous experiment, i.e., a selectional restriction violation (e.g., *Die Wolke wurde begraben/The cloud is being buried*) was included, in order to see whether we could replicate the N400 effect in the running speech mode (see also Holcomb & Neville, 1990, 1991). In addition, we included sentences containing a morphological error (e.g., *Das Parkett wurde bohnere/The parquet is being polish*) and most importantly sentences containing a phrase structure violation (e.g., *Der Freund wurde im besucht/The friend is being in the visited*). In this latter type of sentences the last word of the sentence violates the syntactically required word category. The preposition indicates a prepositional phrase requiring a noun phrase consisting of either an article and a noun or a pronoun. In this experiment subjects heard the preposition together with the article, which in German is marked for case and in this example glutinated with the preposition, e.g., (*in dem* → *im/in the*). This prepositional form certainly requires the next word to be a noun. In the incorrect version, subjects, however, heard an inflected verbform (past participle) instead representing an obvious violation of the structure initiated by the preposition. All sentences were presented in random order. After each sentence subjects heard a probe word and had to decide whether this had occurred in the previous sentence. Brain potentials elicited by sentence final words (recorded from seven electrodes (Fz, Cz, Pz, Bl, Wl, Br, Wr) are displayed in Fig. 1.

The results from 16 subjects displayed different patterns of brain potentials as a function of the sentence types. For the semantic condition we observed a N400 waveform previously found in other studies (Kutas & Hillyard, 1989, 1983). For the morphological condition we also observed a negativity around 400 ms, peaking slightly earlier and being somewhat less pronounced at left and right posterior sites (Wl, Wr) than that observed for the semantic condition, but otherwise similar to the semantic N400 in its distribution. This negativity was followed by a posteriorly distributed positivity. For the phrase structure violation we observed an early negativity at the frontal electrodes peaking around 200 ms being only significantly larger than for the correct condition at the left anterior electrode (Bl). A similar early left anterior negativity was reported in correlation with phrase structure violations in a rapid serial visual presentation experiment (Neville, Nicol, Barss, Forster, & Garrett, 1991) and a left anterior negativity with a somewhat later peak was found to correlate with verbal memory functions involved in long-distance syntactic

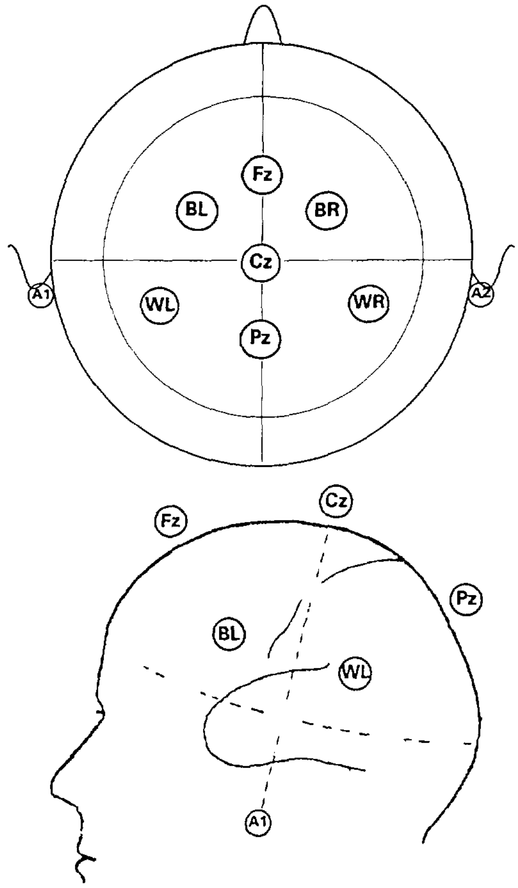


FIG. 1. Placement of the scalp electrodes. Reference electrodes linked mastoids A1 + A2.

operations such as gap-filling (Kluender & Kutas, 1993). This left anterior negative component contrasts to another component identified to correlate with syntactic processes (e.g., Neville et al., 1991; Osterhout & Holcomb, 1992; Hagoort, Brown, & Groothusen, 1993) which will be discussed below.

The different patterns in the distribution and the time-course of the waveforms for the different types of linguistic violations in this experiment suggest that different brain systems are involved in the processes dealing with lexical-semantic information as opposed to local phrasal information and that these are activated at different points in time. The anterior parts of the left hemisphere seem to particularly support those early syntactic processes responsible for structure building and maintenance as assumed by structure-driven models. These processes seem to precede processes requiring full lexical information.

Before drawing firm conclusions on the nature of the early left anterior negativity, we felt that a further investigation concentrating on the processing of phrase structure violations was necessary (Friederici, Hahne, & Mecklinger, submitted). This study's goal was twofold. First, it was designed to allow for a higher topographic resolution using a total of 25 electrodes. Second, it was planned to allow a direct comparison of syntactic processes involved in parsing connected speech. Moreover, in contrast to the experiment discussed above, we investigated not only the processing of phrase structure violations, but also the processing of phrase structure preferences.

The stimulus material used in this study consisted of sentences containing a violation of an obligatory phrase structure induced by an incorrect word category (1) or a violation of a preferred phrase structure induced by a nonpreferred word category (3) or represented the correct counterparts, (2) and (4).

(1) *Das Metall wurde zur veredelt von einem Goldschmied den man auszeichnete.*
The metal was to the refined by a goldsmith who was honored. (literal translation)

(2) *Das Metall wurde veredelt von einem Goldschmied den man auszeichnete.*
The metal was refined by the goldsmith who was honored.

(3) *Das Metall wurde Veredelung von einem Goldschmied den man auszeichnete.*
The metal was refinement by a goldsmith who was honored.

(4) *Das Metall wurde zur Veredelung gebracht von einem Goldschmied den man auszeichnete.*
The metal was to the refinement given by a goldsmith who was honored. (literal translation)

The critical word (*veredelt/refined*) in the obligatory phrase structure violation condition (1) created a mismatch between the obligatory phrasal context (noun-context) and the actual target (verb). In the preferred phrase structure violation condition (3), the critical word (*Veredelung/refinement*) created a mismatch between the preferred phrase structure (verb-context) and the actual target (noun). The nonpreferred structure, however, can take a noun after the word *wurde*, as this word has two readings, (a) an auxiliary reading, i.e., *wurde/is being*, and (b) a main verb reading, i.e., *wurde/became*. The latter reading allows the sentence to be continued with a noun (e.g., *Das Gesetz wurde Standard/The law became standard*). Thus, the actual sentence *Das Gesetz wurde Veredelung/The law is being/became refinement* could either be viewed to contain a syntactic violation when considered the preferred reading of *wurde*, namely, the auxiliary reading, or as a lexical error when considering the nonpreferred reading of *wurde*, namely, the main verb reading. Sentences were constructed in a way that would allow us to determine the word category uniqueness point between the noun and the verb reading. The vowel in the syllable prior to the disambiguating suffix was defined as the uniqueness point in order to stay free of the possible influence of coarticulation effects that the suffix might have on the consonant immediately preceding it.

Results from 17 subjects listening to 40 sentences with violations of obligatory phrase structure and their correct counterparts are displayed in Fig. 2a and to 40 sentences with violations of the preferred structure and their correct counterparts are displayed in Fig. 2b. The waveforms are elicited by the critical words in each of the conditions.

Similar to the previous experiment violations of obligatory phrase structure elicited a left anterior negativity peaking about 270 ms after the defined word category uniqueness point. The early negative peak was followed by a sustained negativity most pronounced over the left anterior electrodes. Around 600 ms after the word category uniqueness point we observed a positivity widely distributed over the posterior electrodes of both hemispheres (T_5, P_3, O_1, O_2, P_4, T_6 and Wl, Po, Wr). For the violation of the preferred phrase structure we also found a negativity most prominent over left anterior electrode sites which, however, started somewhat later than for the obligatory phrase structure violation condition. In this condition the negativity was also followed by a centroparietal positivity.

The data of the phrase structure violation condition of this experiment replicate the early left anterior syntactic negativity observed in the earlier study. This early negativity is correlated with local phrase structure violations induced by word category errors. The negativity observed in the phrase structure preference condition started only around 400 ms after the word category uniqueness point, suggesting that this negativity reflects processes different from those eliciting the early left anterior negativity. Under this condition the parser may keep the preferred and the nonpreferred structure active until lexical access of the critical element is completed. Differently in the phrase structure violation condition, in which ungrammaticality can be flagged on the basis of word category information alone, ungrammaticality in the phrase structure preference condition can be flagged only once lexical access is completed. Thus, the left anterior negativity around 400 ms may well be correlated with syntactic processes based on lexical information other than word category information (see also Rösler et al., 1993, for a similar temporal and topographic component correlated with the processing of subcategorization information).

Given the two different latencies of the left anterior negativity observed in correlation with the processing of two different aspects of syntactic information encoded in a verb's lexical entry, one could assume a temporally (hierarchically) ordered access to these different aspects of syntactic information, with syntactic word category information being available earlier (Friederici Pfeifer et al., 1993; Friederici et al., submitted) than argument structure information (Rösler et al., 1993).

Late Syntactic Processes

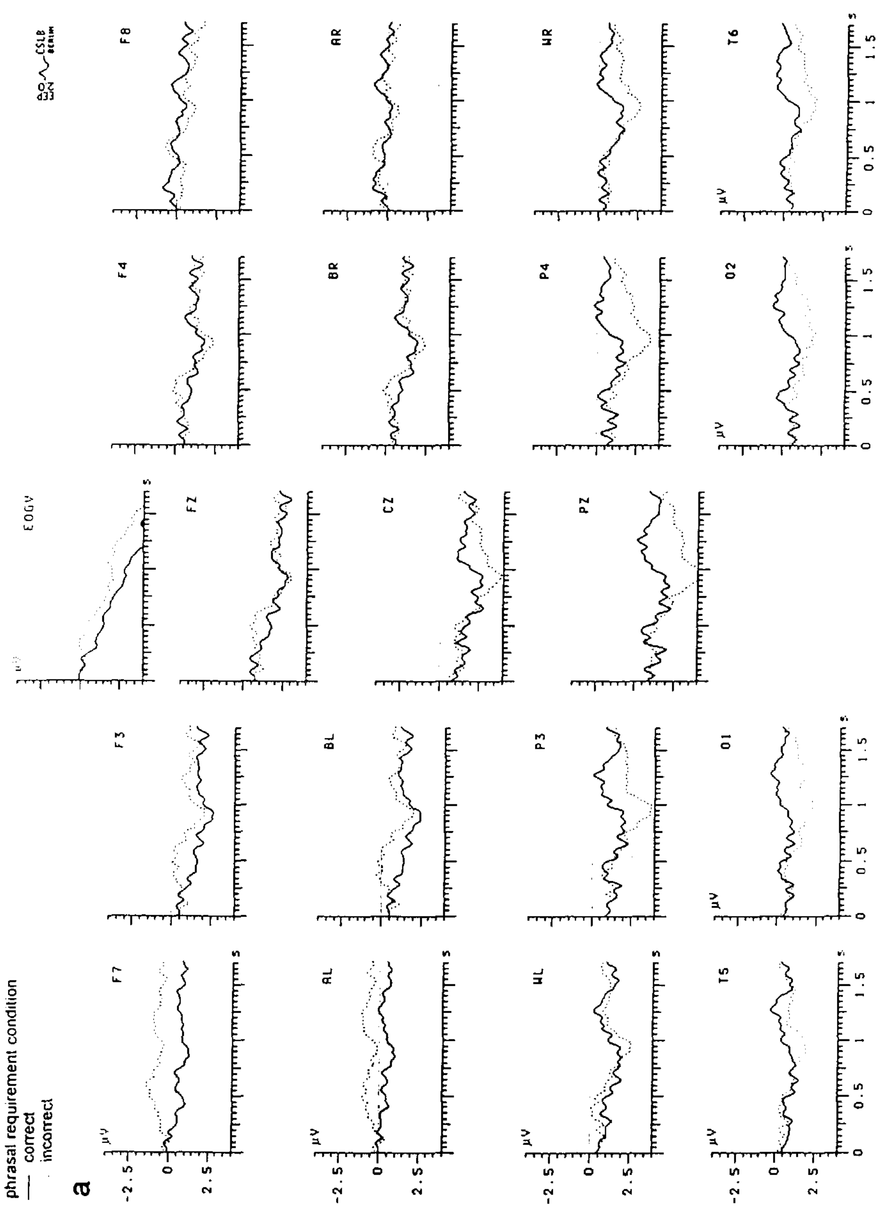
Other groups investigating syntactic processes during language comprehension using ERP as the dependent variable found yet another component related to syntactic processes, that is a positivity around 600 ms and later widely distributed over the posterior parts of both hemispheres (Osterhout & Holcomb, 1992; Osterhout, Holcomb, & Swinney, 1995; Hagoort, Brown, & Groothusen, 1993). This positivity was observed for the processing of sentences which either lead subjects up to a garden-path (Osterhout, Holcomb, & Swinney, 1995) or an incorrect structure (Osterhout & Holcomb, 1992; Hagoort et al., 1993). Garden-path sentences allow for more than one syntactic structure up to a certain point. Mostly one of these structures can be viewed as highly preferred. At some critical point in the sentence, it becomes clear which of the different structures is the valid one. In case a nonpreferred structure turns out to be valid, reanalysis of the initially preferred structure becomes necessary. As similar positivities were also observed for sentences containing syntactic anomalies indicating at some point in the sentence that the structural analysis carried out was incorrect (Osterhout & Holcomb, 1992; Hagoort et al., 1993), this positive component may be correlated with the necessity for syntactic reanalysis,[3] rather than with the initial build up of a syntactic chain.

In a next study we investigated these processes of syntactic reanalysis further. We focused on the processes of syntactic ambiguity resolution using event-related brain potentials as the dependent variable (Mecklinger, Schriefers, Steinhauer, & Friederici, in press). The stimulus material consisted of relative clause sentences which were structurally ambiguous up to the last word in the clause (5).

(5) *Das ist die Managerin, die die Arbeiterinnen gesehen [hat/haben].*
This is the manager who the workers seen [has/have]. [literal translation]).

The last word in the clause, i.e., the auxiliary, determined whether the clause had to be read as a subject relative clause or an object relative clause. In addition to this factor, we varied the factor of semantic bias either using a "neutral" verb (e.g., *sehen/to see*) or a semantically biasing verb (e.g., *entlassen/to fire*, assuming that it is more plausible that manager fire workers than workers manager).

[3] The distribution of this late positivity is similar to that of the so-called P300 which has been correlated with a general (non-language-specific) context updating process (Donchin, 1981). It is discussed whether the observed positivity in relation to processes of reanalysis is language specific or not (Osterhout & Holcomb, 1992).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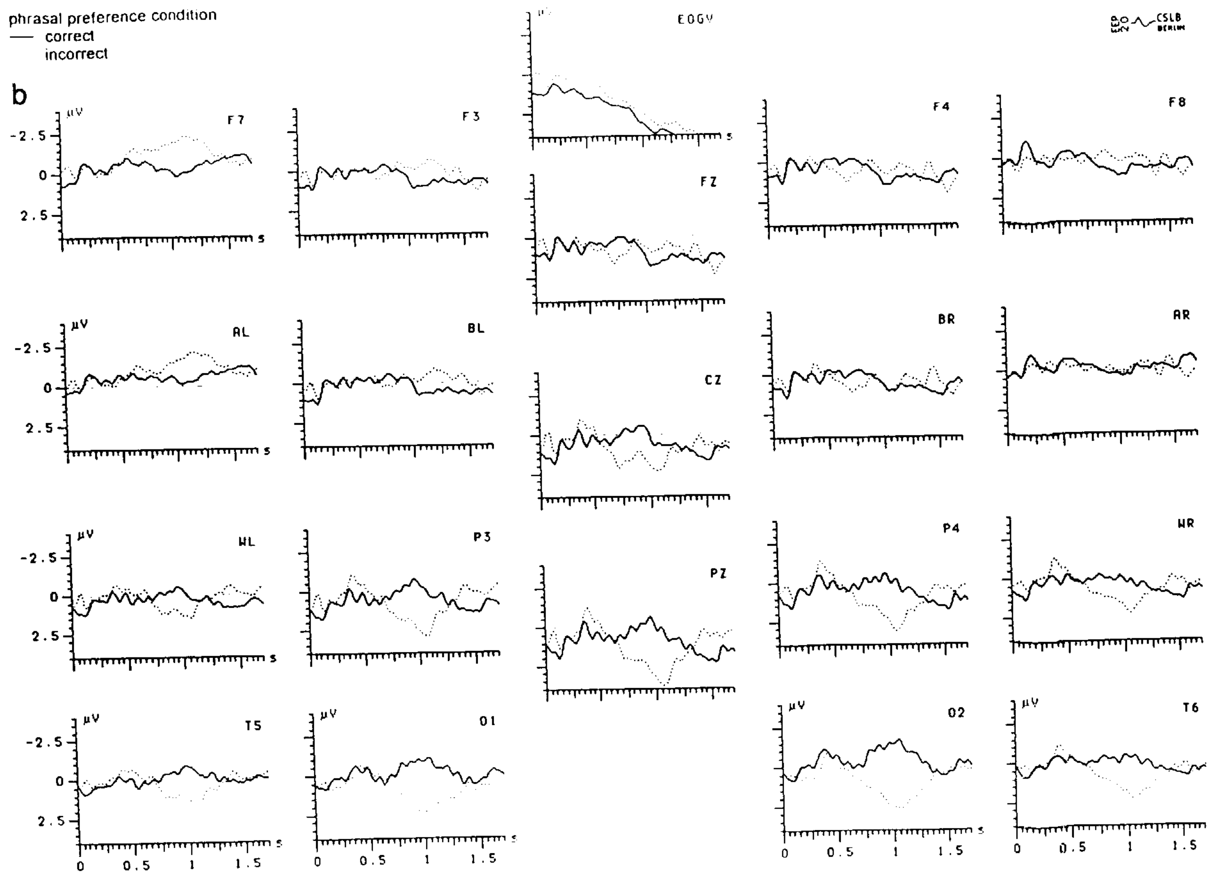
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FIGURE 2

Thus, in this experiment only syntactically correct subject and object relative clause sentences were presented. They were displayed visually in a word-by-word fashion. Sentences containing the biasing verb were constructed such that the semantic bias always supported the ultimate reading of the sentence, i.e., the bias never ran against the ultimate reading of the sentence. After each sentence subjects had to answer a question concerning the agent and the patient of the sentence just read. As the subjects' behavioral performance on this task had a bimodal distribution, they were subgrouped into a fast comprehension group with short answering latencies and a slow comprehension group with long answering latencies. The fast comprehension group showed particularly interesting results. The ERPs for the reading of the past participle of the main verb (e.g., *gesehen/seen* vs. *entlassen/fired*) differed in their amplitude around 400 ms post onset. The "neutral" verb elicited a larger negativity than the semantically "biasing" verb. The distribution of this negativity resembled that of a classical N400 and was taken to reflect lexical-semantic integration processes which are easier in case of "biasing" verbs than in case of "neutral" verbs.[4]

For the disambiguating auxiliary we observed a positivity peaking 345 ms post onset with a larger amplitude in the object relative clause sentences than in the subject relative clause sentences (Fig. 3). Note that this effect was observed independent of the semantic bias of the preceding main verb.[5]

This positivity's distributional pattern was similar to that found in other studies investigating the processing of garden-path sentences and syntactic anomalies (Osterhout & Holcomb, 1992; Osterhout et al., 1995; Hagoort et al., 1993). The positivity observed in the latter studies, however, differed from that observed in the former study in its latency. While the

[4] We also observed a syntactically induced N400 amplitude difference. In the condition with semantically biased verbs, the N400 amplitude was larger when they biased an objective reading than when they biased a subject relative reading. To interpret this result, it is important to recall that the two relative clause types differed only with respect to the order of the two nouns preceding the past participle. An explanation for this N400 effect might be that readers initially assume the syntactic structure of a subject relative clause. When the past participle is encountered in the subject relative condition, the chosen syntactic preference and semantic information are consistent resulting in less effort to integrate the past participle's semantic information. In contrast, in the object relative condition, the initially preferred syntactic structure does not match the semantic information carried by the past participle. In this case the past participle receives less priming from the preceding context resulting in more effort to integrate the past participle.

[5] This independence of semantic and syntactic aspects during sentence processing is furthermore supported by a reaction time study with similar material (Schriefers, Friederici, & Kühn, in press) in which we found a main effect of semantic bias for the processing of the main verb and a main effect of clause type for the processing of the auxiliary, but no interaction of the factor verb bias and clause type for the auxiliary reading times.

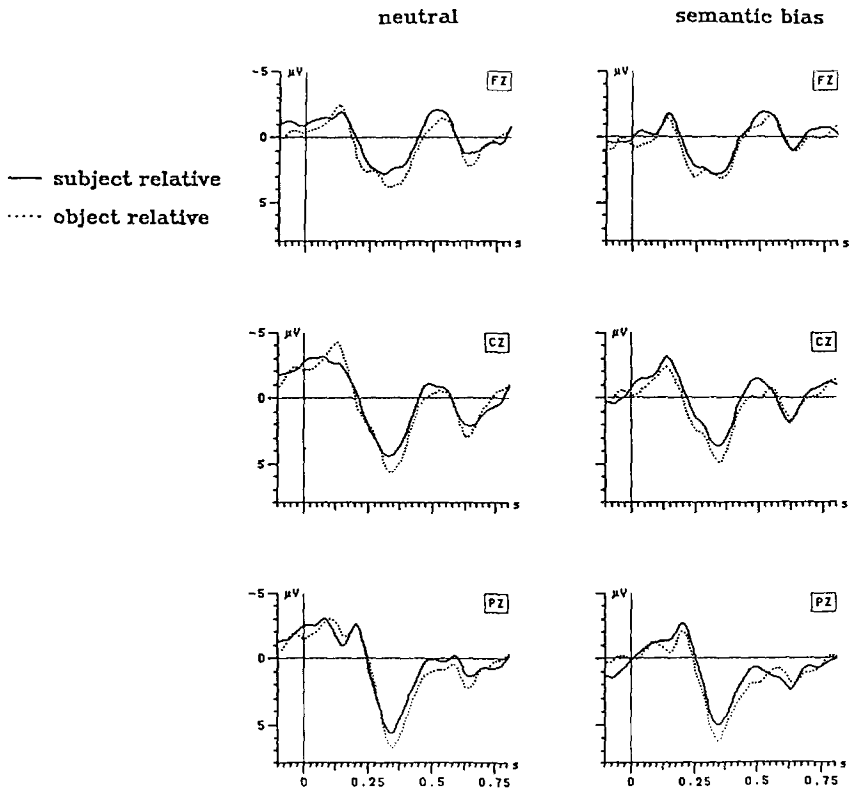

FIGURE 3

positivities in the latter studies was found at 600 ms and later, the positivity in the former peaked at 345 ms. The difference in latency may reflect the complexity of processing necessary for the revision of the initially preferred reading. The structure-driven model (Frazier, 1978) would predict that during the initial parse only one structure is built up, i.e., in case of structural ambiguities the least complex one. Furthermore, this may lead to a situation in which the parser has considered the incorrect structure and will have to reanalyze the initially considered structure. For the sentences used in the studies by Osterhout and co-workers (1992, 1993, 1995), the parser has to revise the hierarchical structural tree in order to achieve a correct structural representation. This, however, is not the case for the subject and object relative clause sentences used by Mecklinger, Schriefers, Steinhauer, and Friederici (in press). In case of an incorrect reading of the critical German relative clause the parser only has to reindex the subject noun phrase and the object noun phrase to the relative pronoun, while the hierarchical structure of the sentence remains the same. The process of hierarchical restructuring is more complex than the process of reindexation, and this may be reflected in the differential latencies observed for the positivity under the different processing conditions in the studies discussed above. The shorter latency seems to be correlated with processes of reindexation, and the longer latency with processes of structural reanalyses requiring a complete restructuring of the hierarchical tree.

The data reported by Mecklinger, Schriefers, Steinhauer, and Friederici (in press) were taken to support a comprehension model in which syntactic processes are independent of lexical-semantic processes. Only such a model would predict the syntactic effect to be uninfluenced of the semantic bias of the preceding verb with respect to the thematic role assignment. The ERP results strongly support a structure-driven account (Frazier, 1978) according to which the parser considers only one, namely, the least complex structure in case of syntactic ambiguity, such as the subject–object relative clause ambiguity tested. The data indicate that subjects primarily considered the subject relative clause reading, even when the lexical-semantic information biased an object relative clause reading.

A SYNTACTIC PROCESSING MODEL BASED ON NEUROCOGNITIVE DATA

When reviewing the event-related brain potential data with respect to language comprehension, we are left with four different language-related ERP components manifest in three different time windows: first, an early negativity around 200 ms at the left anterior sites associated with the processing of local phrase structure information; second, two negativities with different distributions around 400 ms, (a) the N400 elicited by semantic anomalies widely distributed over the posterior areas and (b) a more localized negativity in the same time window with left anterior maxima associated with the processing of lexically bound syntactic information, such as subcategorization information; and third, a late positivity which is widely distributed centrally and over the posterior parts of both hemispheres and which seems to correlate with processes of structural reanalysis.[6]

A review of the neuropsychological findings suggests that those anterior parts of the left hemisphere, usually lesioned in Broca's aphasia, subserve the fast and early structuring processes necessary to build up

[6] Note that a left anterior negativity around 400 ms has also been found to correlate with the processing of filler-gap dependencies. Whether the left anterior negativities observed at different time windows are variants of one component or two different components cannot be univocally decided by the data at hand and must await further confirmation.

syntactic structure including traces of moved elements on-line. The alteration of lexical processes often coincides with lesions in the posterior parts of the left hemisphere. The selective breakdown of processes of syntactic reanalysis has not been identified so far. However, it may be interesting to note that patients with lesions in the posterior part of the left hemisphere are far worse in judging a sentence's grammaticality than those with lesions in the anterior parts of the left hemisphere (Huber, Cholewa, Wilbertz, & Friederici, 1990; Linebarger, Schwartz, & Saffran, 1983).

The combined findings from neuropsychological and electrophysiological studies may suggest the following temporal and neurotopographically specified language comprehension model with three phases, two of which are primarily syntactic in nature. A first syntactic processing phase reflected by the early left anterior negativity correlates with a first-pass parse defined as the assignment of the initial phrase structure including traces of moved elements. A second phase reflected by negativities around 400 ms seems to represent the phase during which full lexical access is completed and during which lexically bound semantic (meaning and selectional restrictions) and syntactic information (subcategorization information) is processed to achieve the thematic role assignment. The differential scalp distribution of these two negative components around 400 ms suggests that the processing of the subcategorization information, in particular, is subserved by the anterior parts of the left hemisphere, whereas the processing of lexical-semantic is subserved by brain systems distributed over both hemispheres.[7] The third phase reflected by the broadly distributed late positivity appears to be related to processes of structural reanalysis which may become necessary when the initially build syntactic structure cannot be successfully mapped onto the semantic information and verb argument information provided by the lexical elements.

However, in the view of the finding that structure building processes are correlated with activities in the left anterior cortex, one might expect these cortical areas to be involved in processes of syntactic reanalysis as well. In the absence of such an ERP pattern one might be inclined to take the data reported here and in the literature to support the modified structure-driven view according to which in case of structural ambiguity

[7] The finding that word category information is processed prior to all other types of information carried by a lexical element requires a specific assumption about the organization of the lexical entry or its access to it. Under a structural view we would have to assume a lexical entry with a hierarchical structure in which word category information is at the top of the hierarchy and therefore available first. Under an activation view we would have to assume that word category information reaches the critical threshold for activation more easily and therefore earlier than other types of information.

the parser activates both structures, not, however, without giving a clear preference to one of them (Hickok, 1993). Depending on heuristics which are either guided by structural simplicity, as proposed by Frazier (1978), by language-specific frequencies for particular structures (e.g., subject versus object relative clauses in English, German, and Italian), or even by individual preferences (Shapiro et al., 1993), structural preferences may be set during the first-pass parse. Thus, when the need for the recovery of the nonpreferred structure is detected, this structure may be made available by raising the amount of activation for the initially nonpreferred structure. This assumption would be compatible with a computational model proposed by Kempen and Vosse (1989).

The finding, however, that the latency of the late positivity has been found to be related to the type of reanalysis required, i.e., reindexation versus hierarchical restructuring, could be taken to challenge this latter assumption. If both structures of an ambiguous sentence are active, one might expect the activation of the nonpreferred structure to be equally fast and easily retrievable, independent of whether the nonpreferred structure differs from the preferred one minimally or maximally. The observed difference in the latency of the late positivity in the different studies rather seems to suggest that these processes of reanalysis are not independent of the degree of structural similarity between the initially preferred and the nonpreferred structure.

The combined findings discussed here suggest that on-line structuring processes are subserved by brain systems located in the anterior part of the left hemisphere, whereas processes of structural reanalysis seem to involve different brain systems. The former processes may be instantiated as highly automatic procedures working on the given linguistic input and outputting structured sequences. The latter processes which take place only when structural and semantic information cannot be matched successfully on-line may require the involvement of different processing components. Further research investigating this issue may help to resolve the open questions concerning the processes of reanalysis during language comprehension.

For the time being we may take the available data to suggest a parser with two subcomponents, a first subcomponent responsible for the early structuring of the input seemingly working in a highly time-dependent procedural manner and a second subcomponent responsible for syntactic integration and reanalysis consulting grammatical knowledge which may be represented in a less time-dependent form. With such an architecture the human syntactic processing system would (a) be fast in assigning structure to the incoming information and would (b) be most flexible in selecting the valid structure for adequate thematic role assignment and the ultimate interpretation.

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