Christian Jens Fiebach: Working Memory and Syntax during Sentence Processing: A Neurocognitive Investigation with Event-Related Brain Potentials and Functional Magnetic Resonance Imaging. Leipzig: Max Planck Institute of Cognitive Neuroscience, 1998 (MPI Series in Cognitive Neuroscience; 23)

Working Memory and Syntax during Sentence Processing

A neurocognitive investigation with event-related brain potentials and functional magnetic resonance imaging

Von der Fakultät für Biowissenschaften, Pharmazie und Psychologie
der Universität Leipzig
genehmigte

DISSERTATION

zur Erlangung des akademischen Grades

doctor rerum naturalium
Dr. rer. nat.

vorgelegt
von Diplom-Psychologe Christian Jens Fiebach
geboren am 3. Mai 1971 in Köln

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Tag der Verteidigung: 15. November 2001

Acknowledgements

The work on which this thesis is based was supported by many people in the last three years. First of all, I want to express my special thanks to Prof. Angela D. Friederici who introduced me to the fascinating research fields of language processing and cognitive neuroscience and who gave me the possibility of conducting the research that is reported here. Without her continuous support and feedback, the present thesis would not have been possible. I am also thankful to Prof. Yves D. von Cramon from whom I learned a lot about the anatomical and functional organization of the human brain.

Many other persons at the Max Planck Institute supported my work in different ways. Colleagues from the different research groups were always available for discussing theoretical and methodological issues. I am thankful to Stefan Frisch, Burkhard Maess, and Christoph Herrmann, who introduced me to the ERP method. One of them always knew an answer to the many questions I had. Matthias Schlesewsky patiently helped me finding a way into the difficult but fascinating field of syntax. Stefan Zysset, Bertram Opitz, Gabriele Lohmann, Christopher Wiggins, and Karsten Müller supported me in designing, conducting, and analyzing the fMRI experiment reported in Chapter 7. Thanks for help with data acquisition are due to Cornelia Schmidt, Anke Mempel, Mandy Naumann, and Kathrin Wiesner. Andrea Gast-Sandmann and Stephan Liebig provided many helpful advices for the production of graphical figures. The present work was financed by the Max Planck Society for the Advancement of Science.

I also want to thank Stefan Frisch, Matthias Schlesewsky, Britta Stolterfoht, Sandra Vos, and Christopher Wiggins, who contributed to the present thesis by reading carefully different parts of the manuscript and by giving many helpful comments.

Für die kontinuierliche Unterstützung in vielerlei Hinsicht, die ich in den letzten Jahren erhalten habe und die mir das verfolgen meiner bisherigen Ziele ermöglicht hat, möchte ich mich ganz herzlich bei meinen Eltern Karl-Heinz und Gisela Fiebach bedanken.

Von tiefstem Herzen bedanke ich mich bei Gundhild Leifert dafür, daß sie in den letzten Monaten, die von starken Veränderungen geprägt waren, es toleriert hat, daß ich einen Großteil meiner Zeit auf die Fertigstellung dieser Arbeit verwendet habe. Ich weiß, daß dies nicht immer leicht war. Unserem Sohn Niklas danke ich für jeden Tag in den letzten fünf Monaten.

Contents

Preface

The present thesis investigates a rather old assumption in psycholinguistic. Nevertheless, the topic of this thesis is still of great relevance to current theorizing in psycholinguistics. The work that will be presented in the following chapters is concerned with the involvement of working memory resources during on-line processing of sentences. As such, it is a topic that was already around in the early days of psycholinguistics. However, as a look into the relevant literature reveals, research initiated by the question of what the relevant cognitive resources are that support language processing, and how working memory mechanisms contribute to the successful understanding of a sentence, has never been outside the focus of interest. Although a lot of research has been done and new theoretical models have been proposed, the questions to be asked have not been answered to a satisfying degree yet. When are working memory resources required to support sentence processing? Are there limitations in the resources available for sentence processing? Do these capacity limitations differ between individuals? Do they apply to all aspects of language processing or only to certain sub-components?

With the availability of new research techniques that offer either a very good view on the temporal dynamics of sentence processing or a very good window on the neuroanatomical correlates of sentence processing, the discussion has been revived and extended. What brain regions subserve working memory processes during language processing? How do working memory processes and the actual computational mechanisms of analyzing a sentence interact? How can the temporal interplay between the different cognitive processes and brain areas best be characterized?

The present thesis is an attempt at integrating two neurocognitive methods to receive some answers on some of these questions. On the one hand, event-related brain potentials, which can measure electrophysiological activity of the brain during cognitive processing, was employed as a technique that offers a temporal resolution in the order of a few milliseconds. On the other hand, functional magnetic resonance imaging offers a high spatial resolution and thus allows to identify brain regions that are active during ongoing sentence processing. These two methods were used to measure brain activity while participants performed in the same psycholinguistic paradigm, thereby yielding a number of new insights concerning, as mentioned above, an old but still important discussion in experimental psycholinguistics.

In the first chapter of the present thesis, an introduction into the psycholinguistics of sentence processing will be given. Special emphasis was put on research on the processing of syntactically complex sentences. In Chapter 2, theoretical models of working memory, and especially of working memory during language procesing, will be discussed. Following this, the next chapter covers a wide range of research on language processing and the brain. A short overview over brain regions that are relevant for the understanding of the thesis will be given, followed by a description of the ERP method and a review of relevant studies using this method. The same is done for neuroimaging methods (i.e., PET and fMRI).

Chapter 4 specifies the main goals of the present thesis. The following three chapters describe two ERP experiments and an fMRI study. The results are discussed in detail in these chapters. In the final chapter, the results are repeated and integratively discussed.

Chapter 1

Sentence Processing

1.1 Psycholinguistic Models of Parsing

The comprehension of language almost inevitably requires that the listener or reader structures the words that are being perceived. In general, meaning is not conveyed by randomly connecting words that are associated with the intended message. Instead, words are grouped into phrases and the phrases in turn are forming clauses and sentences according to the principles of grammar. The hierarchical relationships among these different structural categories enable us to derive the meaning of a sentence. When comprehending a sentence, a mental representation of the hierarchical structure of its constituents is reconstructed from the surface structure of the sentence. The phrase structure representation plays a critical role in determining the meaning of a sentence (e.g., Frazier, 1987a; Clifton & Frazier, 1989; Fodor, 1995; Friederici, 1995; Gorrell, 1995).

The process of syntactically analyzing a sentence is called *parsing*. As we all know, it is performed very fast and with very few errors (for empirical evidence regarding the immediacy or incrementality of syntactic processing see, e.g., Just & Carpenter, 1980; Frazier & Rayner, 1982). Example [1], which was taken from Fodor (1995), illustrates the role of structure in sentence comprehension. Upon reading sentences [1a], we directly understand that both pigs and rabbits can not fly, like the brackets in [1b] suggest and not that pigs can fly and rabbits can not, like the incorrect structuring of [1c] might suggest[1].

[1] a. Pigs and rabbits can't fly.

[1] b. [Pigs and rabbits] [can't fly].

[1] c. *[Pigs [and rabbits can't] fly].

Without overt cues in the sentence, we are able to project structure onto the incoming linguistic

[1]Throughout the text, ungrammatical sentence examples are indicated by an asterisk (*) and semantic anomalies by a double-cross (♯).

signal in a way that tells us which words of the sentence are the subject, the verb and (if present) the object. We also derive the semantic relationships that the different verbal arguments in a sentence have (i.e., the thematic structure of the verb). For example, sentence [2a] (see below) contains a verb which requires two arguments (i.e., 'asked'). It also contains a subject noun phrase ('the psychologist') and a direct object noun phrase ('the linguist').

[2] a. The psychologist asked the linguist.

[2] b. The psychologist was asked by the linguist.

In [2a], the subject argument is also the person that initiates the action expressed in the sentence. Thus, this argument is assigned the thematic (or theta) role AGENT or ACTOR, while the object of the sentence undergoes the action and, accordingly, is assigned the PATIENT role (e.g., Haegeman, 1994). In contrast, the passivized sentence construction in [2b] has the patient of the verb in subject position, while the agent is introduced through an adjunct prepositional phrase (PP) headed by the preposition 'by'. The thematic structure of the sentence, thus, is not necessarily linked to the grammatical roles of the verbal arguments. It can be indicated by syntactic cues such as the morphology of the verbal phrase (i.e., the participle which is preceded by an auxiliary) or the by-phrase that introduces the agent.

In some cases, structural information is the only cue that allows to interpret the meaning of a sentence correctly. While in sentences [3a] and [3b] semantics tell us who is the actor of the sentence, this is not possible in a globally ambiguous sentence like [3c]. In this case, both nouns could potentially be the actor of the sentence. Accordingly, the thematic relations have to be determined on the basis of syntactic information or preferences of the parser. Here, it is the order of verbal arguments that helps us with the interpretation. In German, there is a strong preference for interpreting the first argument of an ambiguous sentence as its subject (e.g., Gorrell, 2000). However, in sentence [3b], this preference (which would initially assign the grammatical role of subject to the first noun phrase) leads to a wrong analysis of the sentence and has to be revised later. In [3d], in contrast, the object initiality is overtly indicated by the case morphology of the noun phrases.

[3] a. Die Frau kauft die Statue.
the woman buys the statue[2]

[3] b. Die Statue kauft die Frau.
? the statue buys the woman
(= The woman buys the statue.)

[3] c. Die Frau tritt die Giraffe.
the woman kicks the giraffe

[2] German sentence examples will be accompanied by a word-by-word translation or a literal translation or both. Word-by-word translations are all written in lower case and do not have the normal punctuation.

[3] d. Den Dieb sah der Junge.
the_{ACC} thieve saw the_{NOM} boy

A phrase structure representation of a sentence contains nodes that stand for different categories on the clausal, phrasal or lexical level, as well as relations of dominance and precedence among those nodes and other (secondary) relations that are described by theories of syntax (e.g., Haegeman, 1994; Gorrell, 1995). A schematic representation of such a phrase structure, like it is frequently used in theoretical linguistics, is displayed for example in Figure 1.1.

Psycholinguistic research on parsing aims at describing how the human sentence processor derives the structure and meaning of a sentence from a spoken or written input signal. The interest of this field of research is not on how individual words are recognized but on the question of how postlexical processes derive the correct interpretation of a sentence. The goal of this research is to establish a cognitive architecture of the human parser (e.g., Frazier, 1987a, 1990; Mitchell, 1994; Fodor, 1995; Pickering et al., 2000; Schlesewsky & Friederici, in press).

The parser can be thought of as a computational device that is tuned to process linguistic input and has as its result a representation of the meaning of a sentence. The static organization of such a processor is what is referred to as its COGNITIVE ARCHITECTURE (e.g., Pickering et al., 2000). Generally, the architecture of a cognitive system describes a set of different subcomponents or modules that are responsible for different aspects of processing (cf. Fodor, 1983). The subcomponents that constitute the language processor encompass a number of basic principles and rules that are applied to the information being processed (Frazier, 1987a, 1990; Friederici, 1995; Schlesewsky & Friederici, in press). However, the cognitive architecture of a certain processing domain is not to be equated with the neuroanatomical organization of certain functions. It is restricted to the level of representations, percepts, and memories (Green, 1996). A theory of sentence comprehension has the goal of describing the cognitive architecture of the parser, as well as the dynamic interactions among its modular components.

A core operation of the parser is the construction of a mental representation of the phrase structure of the processed sentence (Gorrell, 1995). If a word is recognized and specific syntactic properties that are stored in the mental lexicon (namely syntactic word category information) become available, the parser creates a corresponding phrasal node[3] which is motivated by syntactic requirements. For example, upon identification of a verb, a verbal phrase (VP) is projected and attached into the existing phrase structure representation by determining its hierarchical relations to other nodes. Possibly, certain expectations can be made regarding further input that is required. For example, the lexical entry of a transitive verb (i.e., its subcategorization frame) demands an object argument.

In the context of this thesis, a structure-driven parser is assumed (e.g., Ferreira & Clifton, 1986;

[3]According to Chomsky's Government and Binding approach (e.g., Chomsky, 1981), all phrase categories have the same structural form as specified in the X-bar schema (e.g., Haegeman, 1994; Shapiro, 1997).

Frazier, 1987a; Friederici, 1995). According to this model of sentence processing, initial decisions in phrase structure building (i.e., the 'first pass parse') are made exclusively on the basis of syntactic information. Under this view, phrase structure information is available to the parser earlier than semantic information (e.g., Frazier, 1987a; McElree & Griffith, 1995; Friederici, 1999; Schlesewsky & Friederici, in press). Models of this kind are called modular (Frazier, 1990) or restricted (Pickering et al., 2000) in the sense that at least during initial stages of processing, certain cognitive mechanisms are active that are specially tuned to specific types of information and that can not be influenced by other sources of information (i.e., they are informationally encapsulated; Fodor, 1983). Such models assume a hierarchical cascade of processes during which different pieces of information influence the analysis of a sentence independently (at least during the early stages of processing).

Friederici (1995) has proposed a three-stage model of parsing which assumes that the initial first pass parse is performed within 150 to 200 ms after the processing of a word and is based exclusively on information about the category of the current word. Later in the processing cascade (i.e., around 400 ms after the onset of the word), the lexical entry of the word is available and lexical-semantic and structural requirements will be checked between the input and the previously processed parts of the sentence. The linking of postulated phrasal nodes into the existing representation is guided by general parsing principles such as the *Minimal Attachment Principle* (e.g., Frazier, 1987a) or the *Simplicity Principle* (e.g., Gorrell, 1995). In the same time domain, lexical information is used for the assignment of thematic roles. In a third phase, (i.e., at around 600 ms), processes of reanalysis and repair (if necessary) can be observed (cf. Friederici, 1995).

Friederici's (1995) three-stage model takes up ideas that have been discussed for a long time already (e.g., Frazier, 1978; Frazier & Fodor, 1978). The stages of the parsing process have been linked to different time windows on the basis of results from event-related brain potentials (Friederici, 1995). Furthermore, the different processing stages have been attributed to neuroanatomically specified brain regions on the basis of neuropsychological studies of neurological patients and cognitive neuroscientific studies of human brain function in healthy adults (Friederici, 1999). The neurocognitive aspects of the three-stage parsing model will be described in more detail in Chapter 3.

Psycholinguistic research has developed different approaches that allow to observe the architecture and mechanisms of the parser. For example, the study of how (temporarily or fully) ambiguous sentences are processed has made it possible to observe the behavior of the parser when it is not strictly guided by linguistic cues. A sentence is ambiguous with respect to its structural analysis if the new input word can be linked into the phrase structure in more than one way. Under such conditions, the human sentence processor exhibits an intricate and very consistent pattern of preferences and strategies. The investigation of ambiguity resolution has triggered a considerable amount of research in empirical psycholinguistics and led to the formulation of a wide range of parsing models. The theoretical approaches differ especially with regard to the types of linguistic information that the parser uses in deriving early decisions in phrase structure building (see, e.g., Mitchell, 1994, for a thorough review of models of ambiguity resolution). Similarly, studying sentences that vary in the degree of their structural complexity has been assumed to give insights into the nature of syntactic processing mechanisms and the cognitive resources that are involved in parsing (see, e.g., Wanner & Maratsos, 1978; Just & Carpenter, 1992; Gibson, 1998; Caplan & Waters, 1999). The study of syntactic complexity and the role of working memory capacity in the processing of structurally complex sentences is the focus of this thesis. In the next section, some typical features of German will be described that are helpful for an understanding of the German examples given in the text and the stimulus material used in the experiments to be reported. Following this, previous research on the processing of syntactic complexity will be introduced and models that account for the way complex sentences are processed will be outlined.

1.2 Some Characteristics of German Grammar

Ideally, a model of sentence processing should be universal in the sense that if provided with the grammar of a certain language, the parsing principles specified by the model should yield correct structural analyses of a wide range of sentences in this language (Frazier, 1987a). Therefore, the investigation of parsing performance in different languages is crucial to the formulation of models of sentence processing. There are three major features in which German differs significantly from the English grammar and which affect the way sentences are processed in German. Utilizing these peculiartities of German in designing psycholinguistic experiments can yield insights into parsing mechanisms that can not be obtained by the investigation of English sentences.

1. Unlike in English, which is an SVO language, the finite verb is canonically found at the end of the clause in German. This property of German becomes visible when considering subordinate clauses like [5a].

   [5] a. Ich weiß, daß der Psychologe dem Linguisten den Koffer trägt.

   I know that the$_{NOM}$ psychologist the$_{DAT}$ linguist the$_{ACC}$ suitcase carries

   (= I know, that the psychologist carries the suitcase for the linguist.)

   [5] b. Der Linguist trägt dem Psychologen den Koffer.

   the$_{NOM}$ linguist carries the$_{DAT}$ psychologist the$_{ACC}$ suitcase

   (= The linguist carries the suitcase for the psychologist.)

   In main clauses, however, the finite verb occupies the second position (cf. [5b]). It is generally assumed that the verb is base-generated in sentence-final position and moved into the second position by a transformation operation (e.g., Fanselow & Felix, 1987). Furthermore, the canonical order of the two object arguments (i.e., direct and indirect object) also differs between German and English. While in English, the direct object preceeds the indirect object (S > DO > IO; e.g., 'John gave a book to Mary.'), it follows the indirect object in German (S > IO > DO; cf. example [5a]; see also Lenerz, 1977; Hoberg, 1981; Pechmann et al., 1996)

2. German displays a relatively free order of verbal arguments as compared, for example, to English. In English, which is characterized by a strict word order, the grammatical roles of the different noun phrases can be determined on the basis of the surface ordering. In general, the verb follows the subject immediately. There is considerably more variability in German. Without significant changes of the thematic relations of the sentence, each of the two object arguments can be moved to the clause-initial position:

   [6] a. Ich weiß, daß dem Linguisten der Psychologe den Satz vorliest.

   I know that the$_{DAT}$ linguist the$_{NOM}$ psychologist the$_{ACC}$ sentence reads to

   (= I know that the psychologist reads the sentence to the linguist.)

   [6] b. Ich weiß, daß den Satz der Linguist dem Psychologen vorliest.

   I know that the$_{ACC}$ sentence the$_{NOM}$ linguist the$_{DAT}$ psychologist reads to

   (= I know that the linguist reads the sentence to the psychologist.)

3. German, as compared to English, has a richer case and gender marking system. Like in English, some noun phrases are not overtly marked for case. For example, feminine and neuter noun phrases (i.e., 'die Frau'/'the woman', 'das Kind'/'the child') are case-ambiguous between nominative and accusative. In contrast, other noun phrases have specific overt markers for nominative (e.g., the masculine determiner: 'der Junge'/'the boy'), accusative ('den Jungen'), dative ('dem Jungen'), and genitive case (i.e., 'des Jungen'/'of the boy'). While in English, in sentences like [7a] and [7b] the functional roles can only be determined on the basis of argument order, the overt morphology of some NPs in German can give significant cues concerning the structure of the sentence (e.g., [7c,d]).

   [7] a. The doctor visited the patient.

   [7] b. The doctor who the patient visited, ...

   [7] c. Der Doktor besuchte den Patienten.

   the$_{NOM}$ doctor visited the$_{ACC}$ patient

   (= The doctor visited the patient.)

[7] d. Den Doktor besuchte der Patient.

the$_{ACC}$ doctor visited the$_{NOM}$ patient

(= The patient visited the doctor.)

An excellent overview of the peculiarities of parsing in German and the insights that can be gained from investigating them is given by the contributions from different research groups that are included in a recently published volume edited by Hemforth and Konieczny (2000).

1.3 Syntactic Complexity

As already stated above, an important experimental approach to identifying the mechanisms of syntactic processing is to investigate how sentences of varying structural complexity are processed. Consider for example sentences [8a] and [8b] (taken from Stromswold et al., 1996). Both sentences express essentially the same but differ in their phrase structure, as indicated by the brackets in [8a,b]. Both contain a relative clause (printed in italics) that modifies one of the noun phrase arguments. However, in [8b] this relative clause is center-embedded (i.e., it interrupts the clause in which it is embedded) while it is attached at the end of the main clause in [8a] (i.e., a right-branching relative clause construction).

[8] a. [The child [VP spilled [NP the juice *that stained the rug*]]].

[8] b. [[NP The juice *that the child spilled*] [VP stained the rug]].

It has been demonstrated using different behavioral paradigms, such as phoneme monitoring (Foss & Lynch, 1969) or sentence comprehension tasks (Blaubergs & Braine, 1974), that the processing of sentences with center-embedded relative clauses is more difficult than the processing of sentences with right-branching relatives. This finding has been attributed to the increased short-term or working memory load associated with the interruption of the main clause in center-embedded sentences. In order to correctly resume the processing of an interrupted clause after the embedded relative is processed, the point at which the clause is disrupted and the material analyzed so far has to be stored temporarily (*Interruption Hypothesis*; Miller & Isard, 1964). In contrast, in right-branching relatives, the main clause can be analyzed completely before the parser reaches the relative clause.

However, several of these early studies (e.g., Miller & Isard, 1964; Wright, 1968; Blaubergs & Braine, 1974) have also shown that there is no difference in processing difficulty between sentences with one level of center-embedding and sentences with right-branching relatives[4]. In most of the studies investigating these structures, center-embedded relatives were only more difficult to process than

[4]Note, however, that the difficulty of processing a center-embedded relative clause might also depend upon the structural complexity of the matrix clause in which it is embedded.

right-branching relatives when they containted multiple levels of center-embedding (i.e., when more than one modifying relative clause was embedded in the sentence). Furthermore, there are also reports of the opposite pattern of results. For example, Holmes (1973) reported that right-branching relatives were more difficult to process than center-embedded relatives in a rapid serial visual processing task. Hakes and colleagues (1976) made a similar observation using phoneme monitoring and paraphrasing tasks. These authors further pointed out that previous studies have confounded the nature of embedding (i.e., right-branching vs. center-embedded) with the internal structure of the sentences by comparing center-embedded object relatives with right-branching subject relatives. That is, in the center-embedded relative clauses used in most studies, the relative pronoun (and accordingly also the head noun of the relative clause to which it refers) was the object of the embedded clause while in right-branching relatives, it was the subject of the clause. When the internal grammatical structure of the subordinate clauses was controlled for, Hakes and colleagues (1976) did not find any evidence for the fact that center-embedded relatives are more difficult to process than right-branching relatives (in the case of one level of embedding). Similar results were reported by Hudgins and Cullinan (1978).

Taken together, these data suggest that the order of verbal arguments within a subordinate clause (and probably in sentences in general) is a stronger predictor of processing difficulty than the nature of the embedding. Early on, it has been noted that the perceptual complexity of a sentence, i.e., the difficulty that arises during processing the sentence, increases if the order of constituents in the surface structure of the sentence (i.e., in the configuration that is actually perceived) differs from the canonical SVO order (e.g., Fodor, 1971). This is the case for example in object relative clauses like [8b] where the object is encountered before the subject (i.e., OSV). The underlying or deep structure of the sentence is relevant for comprehension and therefore has to be reconstructed from the surface structure (e.g., Fanselow et al., 1999). For example, the underlying sentence structure is required for correctly assigning a thematic role to the dislocated element and thus for deriving the semantic structure of the sentence. The number of computations required for bridging the transformational distance between the surface and the deep structure increases with the structural complexity (or the degree of deviance from the canonical form) of the sentence. The increased number of computations that are required when an object argument has been moved to the clause initial position was assumed to make sentence processing more difficult (e.g., Fodor et al., 1974).

A number of studies have followed up this proposal by investigating sentences with subject-first and object-first center-embedded relative clauses like [9a] and [9b]. All of these studies found that object-initial relatives were more difficult to process than subject-initial relatives (e.g., Walker, 1969; Wanner & Maratsos, 1971; both cited after Fodor et al., 1974).

[9] a. The reporter *who attacked the senator* admitted the error.

[9] b. The reporter *who the senator attacked* admitted the error.

In order to derive insights about the exact locus of this processing difficulty, researchers in psycholinguistics developed behavioral on-line measures which allow to map sentence processing with a better temporal resolution. According to the interruption hypothesis (Miller & Isard, 1964), the processing load should be greatest in the region of the relative clause due to storage of the head NP of the relative clause in working memory. However, this prediction holds for both sentence types as both relatives in [9] (again indicated by italic font) are center-embedded. Accordingly, the interruption hypothesis would predict that [9a] and [9b] do not differ in processing difficulty.

Frauenfelder and colleagues (1980), investigating similar center-embedded subject and object relatives in French, reported increased reaction times in a phoneme monitoring task for object relatives as compared to subject relatives at the position of the main clause verb but not at the position of the second noun phrase in the relative clause. The authors concluded that ”additional mental work which would correspond to the computation of the basic grammatical relationships” (p. 331) is reflected in the increased reaction times for object relatives. These processes apparently are carried out when all arguments and predicates of the relative clause have been processed. However, by presenting a working memory task to the participants at an interruption point in the relative clause region, Wanner and Maratsos (1978) observed that processing load (as indexed by the number of errors in comprehending the sentence as well as in the concurrent working memory task) was increased when an object relative clause but not when a subject relative clause was processed. While the results of the second study do not contradict the assumption of an activation of additional processes when processing the more difficult object relatives, they locate the processing difficulty in the region of the relative clause rather than at the main clause verb as was proposed by Frauenfelder et al. (1980).

Both studies can not exclude that increased processing difficulty existed at other regions in the object relative sentence because measurements were only carried out at selected positions. Holmes and O'Regan (1981), Ford (1983), and King and Just (1991) demonstrated this point by applying techniques that allowed to monitor processing load at all positions in the sentence. Holmes and O'Regan (1981), using eye movement measurements in French participants, reported an increased number of regressive eye movements starting from the relative clause verb that directly followed the object relative pronoun (which was case marked in French; i.e., 'que' vs. 'qui'). Ford (1983), examining continuous lexical decisions, and King and Just (1991) who used the self-paced reading technique observed that processing difficulty was increased at both the relative clause verb and the main clause verb.

What do these results tell us about the mechanisms that are involved in processing such structurally complex sentences? It appears to be clear that the processing difficulty which object relatives exhibit is contingent upon the internal grammatical configuration of the object relative clause. While in subject relatives, the surface order of arguments parallels the underlying structure, this is not the case in object relatives. In these sentences, the object NP has been moved to the clause initial position by a syntactic transformation operation that is generally referred to as *wh-movement*[5] (e.g., Chomsky, 1981; Haegeman, 1994). Apparently, this transformation induces the processing diffficulty. However, in subject relatives the subject NP is also moved into clause initial position. Thus, it is not the presence of a transformational movement operation per se that makes a sentence more difficult to comprehend. Furthermore, as Figure 1.1 indicates, both moved elements, i.e., the subject and the object, do have the same landing site in the phrase structure of the sentence (i.e., the specifier position of the complementizer phrase; [Spec,CP][6]). Because the landing sites of the moved subject and object are identical, the phrase structure representations of subject and object relatives are equally complex in terms of the number of non-terminal phrase structure nodes (which can be taken as a measure of the structural complexity of a sentence; e.g., in the context of minimal attachment, Frazier, 1987a).

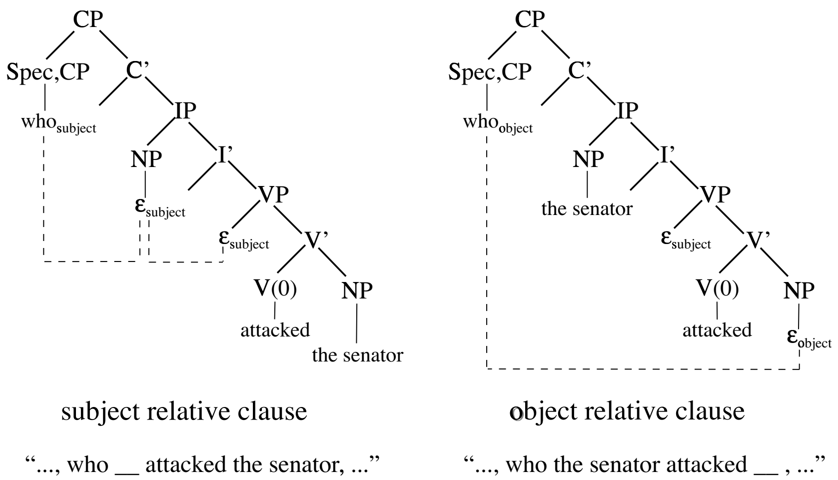

Figure 1.1: *Phrase structure tree diagrams of a subject-initial relative clause and an object-intitial relative clause (compare [9a,b] and [10a,b]). Empty categories (i.e., traces) are indicated by 'ε'. Dashed lines represent the dependency between the wh-filler and its trace.*

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[5]Wh-movement is a transformational operation which moves question words and relative pronouns into clause initial position in the formation of constituent questions and relative clauses. It has as its target a wh-phrase or wh-constituent (e.g., 'who', 'whom', or 'which woman'). The landing site of the wh-phrase in the surface structure is the specifier position of the complementizer phrase (i.e., [Spec,CP]; cf. Figure 1.1). Movement of a wh-phrase leaves behind an empty category (also referred to as trace or gap) which is co-indexed with the moved constituent. Wh-movement has to be dissociated from other types of movement transformations such as, e.g., NP-movement in the context of passivization. In NP-movement, a noun phrase is moved from inside the VP to the VP-external subject position of the sentence (e.g., Haegeman, 1994).

[6]Syntactic categories are named following Haegeman (1994). 'CP' = complementizer phrase, 'IP' = inflectional phrase, 'VP' = verb phrase, and 'NP' = noun phrase.

What appears to cause the processing difficulty of object relatives is the distance between the moved constituent and its gap position that has to be bridged when the sentence is perceived. Due to the canonical order of subject before object, the movement operation spans a longer distance in object relatives than in subject relatives. This is displayed by the dashed lines in the phrase structure diagrams in Figure 1.1. The important question is now: What are the actual operations that are more costly in the on-line parsing of object relatives than in the parsing of subject relatives?

The models that were proposed to account for the empirical findings can be broadly segregated into two different approaches[7]. On the one hand, there exist models that stress the increased computational processing demands that are observed over restricted regions of the sentence. These models will be referred to as COMPUTATIONAL LOAD MODELS in the following. For example, Ford (1983) suggested that increased processing difficulty of object relatives at the relative clause verb and the main clause verb stems from the assignment of the functional role *object* to the relative pronoun (and thus to the head noun of the relative clause to which the relative pronoun refers). In this region of the sentence (i.e., after the relative clause verb), syntactic theory (e.g., Chomsky, 1981; Haegeman, 1994) postulates the phonologically empty *gap* or *trace* position in the phrase structure which represents the syntactic features of the dislocated element at its original position (cf. [10a,b] and Figure 1.1). The account given by Ford (1983) assumes that during comprehension of a sentence, the moved object (i.e., the *filler*) has to be linked to its gap position in order to allow for the correct assignment of its functional role. This process, under this view, is more costly when it takes place in an object relative clause than when it happens in a subject relative clause.

[10] a. The reporter$_i$ who$_i$ $\_\__i$ attacked the senator admitted the error.

[10] b. The reporter$_i$ who$_i$ the senator attacked $\_\__i$ admitted the error.

When, like Ford (1983) has done, the processing times at the relative clause verb are directly compared between subject and object-first structures (i.e., by comparing reading times elicited by the verb which is located at different positions in subject and object relative clauses; cf. [10a,b]), there is one apparent difference between subject and object relatives: In the subject version of the sentence, the gap has already been 'filled' before the verb was encountered. In object relatives, on the other hand, the gap has not yet been filled. It can be assumed (e.g., with Crocker, 1994) that the gap only becomes available when the verb is being processed. Thus, the decision times at and following the relative clause verb reflect the filling of the object gap with the moved constituent. It should be noted that King and Just (1991) pointed out that it is not plausible to see a reflection of this process at the

[7] Note, however, that the distinction introduced here is not established in the literature. In the context of the present thesis, this grouping of different theoretical approaches serves the purpose of providing the reader with a structured overview and also to make it easier to refer to certain theoretical models that share certain assumptions.

position after the object NP gap (i.e., at the main clause verb). In sentence examples [10a,b], the gap positions are indicated by underscores and are coindexed with their fillers and head nouns).

MacWhinney and Pleh (1988, cf. also Bever, 1970) have introduced the principle of perspective maintenance as an account of the processing difficulty of object relatives like the ones discussed here. MacWhinney and Pleh (1988) argued that within an object relative clause, a competition will arise between the moved object and the subject for the perspective to be taken. This conflict will cause errors in parsing the relative clause (p. 136). In sentences such as [10b], the comprehender has to reverse the current perspective associated with the head NP 'the reporter' twice, once from the subject of the main clause to the object of the relative clause and, upon resuming the processing of the main clause, back to the main clause subject. In subject relatives, in contrast, the perspective remains the same throughout the sentence. As the shifting of perspective between subject and object is most probably a processes that takes place quickly, this account was subsumed under the models that assume an increase in computational processes at circumscribed positions in the sentence.

On the other hand, MEMORY RESOURCE MODELS assume that the involvement of working memory resources during the processing of object-first sentences is greater than during the processing of sentences or clauses that have a canonical argument order. In the context of the Competition Model, MacWhinney (1987, cited after MacWhinney & Pleh, 1988) suggested that if a noun is processed before its verb, it has to be held in working memory as an unbound element until it can be linked to a verb. This account has also been referred to as noun stacking. The increased processing difficulty of object-first relatives (i.e., OSV sentences) is caused by the need to maintain two NPs in working memory instead of one, as in SVO structures. Gibson (1991) modified this approach by suggesting that it is not the stacking of noun phrases as such that is causing the increased processing difficulty but that memory cost during the processing of complex relative clause constructions is caused by the maintenance of NPs in working memory that have not yet been assigned their thematic roles as well as by the need to maintain thematic roles that have not found their arguments yet.

However, it is important to note that there is evidence that noun phrases can be attached into the phrase structure analysis incrementally before the verb is encountered (e.g., Bader & Lasser, 1994; Frazier, 1987b; Muckel & Pechmann, manuscript). For example, Muckel and Pechmann (manuscript) investigated the reactivation of dislocated (i.e., topicalized) dative and nominative NPs in verb-final ergative sentences using the cross-modal lexical priming paradigm. These authors found preverbal activation for direct objects which are assumed to be base-generated in front of the verb. Similar evidence was reported by Clahsen and Featherston (1999, Experiment 2). Such findings suggest that the processing difficulty of object relatives can not be induced by noun stacking as such. A noun stacking explanation only yields a reasonably good account for data from SVO languages such as English. In this case, wh-movement of the direct object NP transforms an SVO structure into an OSV structure which changes the number of unbound NPs that are encountered prior to the verb. In contrast, in verb-final languages such as German, the number of unbound NPs does not differ because an SOV structure is transformed into an OSV structure.

The HOLD hypothesis proposed by Wanner and Maratsos (1978) provides a better account of the data by assuming that the head noun of the relative clause, which has to be linked to the gap position, has to be retained in working memory (i.e., on the HOLD list) while processing of the relative clause continues. The distance over which the memory load has to be maintained is greater in object relatives than in subject relatives (compare [10b] to [10a]; cf. Wanner & Maratsos, 1978).

1.4 The Processing of Filler-Gap Dependencies

Given the accounts of processing difficulty in relative clause constructions that were discussed in the previous section, it appears that a considerable part of the theoretical models draw in one way or another upon the concept of empty categories. A construction containing an empty category (such as [10a] or [10b]) is derived by syntactic transformation (i.e., wh-movement; see above footnote 5) from an underlying or deep structure. A constituent is moved to the initial position of the clause, thereby leaving behind an empty category in the phrase structure. In the deep structure, the empty category is filled by the moved element. Although not undebated, it is generally assumed that empty categories have a psychological reality in that they are categories which are relevant for the on-line parsing of sentences (see below). Empty categories are treated as syntactic categories that are represented in the phrase structure of sentences, without being phonologically or orthographically realized.

It has already been pointed out above that constituent questions, as well as relative clauses, are derived by wh-movement, i.e., the movement of wh-elements into clause-initial position. However, there are also other types of movement, such as NP-movement, which will not be considered here (see, e.g., Chomsky, 1981; Fodor, 1995). In the course of comprehending a sentence, the relationship between the dislocated element (or filler) and the empty category (i.e., its gap or trace position) has to be reconstructed (e.g., Crocker, 1994; Fanselow et al., 1999) because the dislocated phrase receives its functional and thematic roles via the syntactic chain that relates it with its gap position (e.g., Rizzi, 1990; De Vincenzi, 1996).

The present discussion is restricted to the case that an obligatory filler such as a wh-element (e.g., 'who', 'what', 'wer', 'wen', or 'was') or a relative pronoun (like 'who', 'der', 'den', etc.) has been moved (e.g., examples [10a,b]). For these elements, it becomes immediately clear that they have to be treated as dislocated elements. There are, however, also many cases in which it turns out only later in the sentence that a phrase has to be treated as a filler and has to be associated with a gap (cf. Clifton & Frazier, 1989). These cases will not be considered in the present context as only sentences with obligatory fillers will be investigated.

What remains to be considered are two questions. First, how is the correct gap out of all potential gap positions identified? Second, how are fillers assigned to gaps? The latter point, however, only becomes problematic when there is more than one potential filler available that might be assigned to the gap (cf. Clifton & Frazier, 1989). As this is clearly not the case in the relative clause constructions discussed in the previous section, and also not in the types of sentences investigated in the experiments reported in this thesis, this line of research will not be introduced here. Before discussing empirical findings regarding gap localization, some evidence for the psychological reality of gaps will be reviewed.

1.4.1 The Psychological Reality of Empty Categories

Although widely accepted, the assumption of empty categories is just one possible linguistic explanation of certain phenomena and it is not easy to determine the validity of this assumption on purely linguistic grounds (Fodor, 1995). However, empirical work in experimental psycholinguistics can give an answer to the question of whether or not empty categories are psychologically real. The answer appears to be 'yes'. Strong evidence in favor of empty categories is given by a series of experiments performed by Swinney and colleagues using the cross-modal lexical priming technique. For example, Swinney, Ford, Frauenfelder and Bresnan (unpublished manuscript; results cited after Nicol & Swinney, 1989) examined the patterns of reactivation of an antecedent at the wh-trace position in sentences like [12].

> [12] The policeman saw the boy$_i$ that$_i$ the crowd at the party (*1) accused t$_i$ (*2) of the (*3) crime.

Sentences were presented auditorily to the participants. At the positions indicated by asterisks in [12], participants made lexical decisions to visually presented words that were either semantically related or unrelated to the NP to which the wh-trace referred (i.e., 'the boy' in example [12]). At the position of the postulated gap (i.e., '*2'), lexical decisions to semantically related target words (e.g., 'girl') were significantly faster than those to unrelated targets. This finding suggested that the antecedent of the wh-trace was reactivated at its canonical position. Semantic associates of the other NPs of the sentence (i.e., of 'the policeman' and 'the crowd') were not primed at the trace position. In addition, there was no priming of the semantically related target word at control positions (i.e., '*1' and '*2'), suggesting that the observed effect was specifically related to the gap position.

Similar data, partly for other types of antecedent-trace relationships, were reported by McElree and Bever (1989), Nicol and Swinney (1989), Osterhout and Swinney (1993), and MacDonald (1989) for English, as well as by Clahsen and Featherston (1999, Experiment 2) and Muckel and Pechmann (manuscript) for German. These findings, among others, were considered to be strong evidence for the fact that empty categories are relevant during parsing. However, it shall be noted that there are also opposing views. For example, Pickering and Barry (1991) argued that without having to postulate empty categories, it can be assumed that elements encountered in non-canonical sentence positions can be directly associated with their subcategorizing verb. The *Direct Association Hypothesis* (Pickering & Barry, 1991) is illustrated by sentence [13b], which features a direct coindexation of the dislocated object argument with the subcategorizing verb. In contrast, [13a] displays the same sentence with a trace in the canonical object position (examples taken from Pickering & Barry, 1991).

[13] a. [Which man]$_a$ do you think Mary loves $\_\_{}_a$?

[13] b. [Which man]$_1$ do you think Mary loves$_1$?

This proposal, however, has been criticized on theoretical grounds (e.g., Gibson & Hickok, 1993; Gorrell, 1993) as well as on empirical grounds. Especially in German, it could be demonstrated that antecedent reactivation can take place at theoretically postulated trace positions that are not directly adjacent to the corresponding subcategorizers (Bader & Lasser, 1994; Crocker, 1994; Clahsen & Featherston, 1999; Muckel & Pechmann, manuscript; see also above Section 1.3).

1.4.2 Gap Localization

A gap can, in principle, occur at any position in the sentence where a phrase of the corresponding type is allowed. The fact that empty categories are not overtly realized implies that they have to be inferred during sentence processing. While the location of the gap is often clear (like in sentence [14a]), there can also be doubtful gaps that require a decision from the parser. For example in [14b], the parser has the option of positing a gap after the verb (like in [14a]). It turns out, however, that the object position is filled by a lexical item (i.e., 'Mary') and that the filler has to be linked to the prepositional phrase following the object.

[14] a. Who did you ask _?

[14] b. Who did you ask (_) Mary about _?

In locating the gap, the parser has some grammatical information at its hand. For example, the parser can infer from the fact that a wh-filler constitutes an NP, that the filler is probably the subject or the object of a verb. In a case-marking language like German, the grammatical role of the wh-phrase is often indicated by the case morphology of the interrogative pronoun (e.g., 'wer$_{NOM}$' vs. 'wen$_{ACC}$'). These different types of information can help the parser to constrain possible gap positions to be considered. However, as [14b] demonstrates, the parser can also be led to make a wrong decision on-line which has to be revised later.

One of the main questions with respect to gap finding centers around the discussion of whether or not the parser waits and sees if there is input coming to fill the next position in the phrase structure or whether it postulates gaps in a predictive way. The first of the two strategies, known as the *Last-resort Model of Gap Finding* (Jackendoff & Cullicover, 1971, see also Fodor, 1978, and Clifton & Frazier, 1989), prevents the parser from making wrong decisions on-line, i.e., it prevents the parser from positing a gap when there is in fact none. Under the last-resort assumption, including a gap into the phrase structure would be delayed as long as possible. A gap would only be postulated if regular phrase structure building breaks down, i.e., when no other structural hypothesis can be maintained given the actual lexical input. In this case, the parser would look back and see whether there was a moved element present that could fill the gap. This approach, as well as others such as the lexical expectation model (Fodor, 1978) or a gap-as-first-resort strategy, is not widely accepted anymore today.

On the basis of a number of empirical studies, mainly performed in Dutch, Frazier and colleagues (e.g., Frazier, 1987b; Frazier & Clifton, 1989; Frazier & Flores D'Arcais, 1989) proposed a model which proved to be successful in terms of accounting for a wide range of data. The *Active Filler Hypothesis* (AFH; see [15]) suggests that, given a filler has been identified in a non-argument position (i.e., a position into which it has been moved by a grammatical transformation), a gap is posited at the first possible position, i.e., before processing new lexical input. Given that a filler is stored in working memory and that this storage is costly, linking the filler to the next-possible gap (and thereby freeing working memory resources from the load of maintaining the filler in memory) is an effective strategy of reducing cognitive costs. Sentence examples that give the reader an intuition for the AFH are found in Clifton and Frazier (1989).

[15] ACTIVE FILLER HYPOTHESIS (in different formulations)

> Empty HOLD as soon as possible. (Frazier, 1987b)
>
> Assign an identified filler as soon as possible; i.e., rank the option of a gap above the option of a lexical noun phrase within the domain of the identified filler. (Frazier & Flores D'Arcais, 1989)
>
> When a filler of category XP has been identified in a non-argument position such as COMP, rank the option of assigning its corresponding gap to the sentence over the option of identifying a lexical phrase of category XP. (Clifton & Frazier, 1989)

The AFH has been cited in different formulations here because each highlights a special feature of this principle. The first definition implies that the dislocated filler is maintained actively in working memory. Frazier (1987b) refers to the HOLD list of Wanner and Maratsos (1978, see above) as well as to "a special memory buffer" (p. 548). This feature of the AFH allows the filler to be rapidly available before new input is being perceived during ongoing comprehension.

The second formulation of the AFH constrains the gap-before-lexical NP preference to the domain of the identified filler. This might be taken to suggest that "a phrase of a given category is posited after a filler only when lexical subcategorization information makes such a phrase highly likely, which is then preferentially taken as a gap" (Clifton & Frazier, 1989, p. 293). However, it was also suggested that lexical information might have the effect of rapidly filtering out gaps that are unlikely while, as long as there is an unassigned filler, a gap is posited by the parser at each grammatically legal position ('lexical filtering'; Frazier, 1987b; Clifton & Frazier, 1989). Third, it was stressed that the suggested mechanisms apply when a filler was identified in a non-argument position such as the clause-initial position.

It has been pointed out (e.g., Fanselow et al., 1999) that the AFH parallels basic principles of syntactic theory such as, for example, the *Minimal Link Condition*[8](MLC; Chomsky, 1995). The MLC states that structures with a shorter distance between a moved phrase and its trace are favored. Similarly, the AFH assumes that the parser tries to integrate a moved element that is held in working memory into the phrase structure as soon as possible. The AFH correctly predicts the preference for subject relative clauses over object relatives in sentences with ambiguous relative pronouns. This holds for SVO languages such as English or French (e.g., Wanner & Maratsos, 1978; Frauenfelder et al., 1980; Ford, 1983; King & Just, 1991) as well as for SOV languages such as Dutch (Frazier, 1987b; Kaan, 1997) or German (e.g., Hemforth, 1993; Bader & Lasser, 1994; Schriefers et al., 1995; Bader, 1996).

Similar evidence was obtained for the processing of wh-questions (e.g., Frazier, 1987b; Frazier & Flores D'Arcais, 1989; Frazier & Clifton, 1989; De Vincenzi, 1996; Meng, 1997; Schlesewsky et al., 2000) which is not surprising because wh-movement is the underlying grammatical transformation in relative clauses and wh-questions. Crain and Fodor (1985) and Stowe (1986) demonstrated that at the position of a possible gap, which turns out not to be available for housing a gap because a lexical NP is present, reading times are slowed down. This finding strongly supports the assumption that gaps are postulated before the lexical input is considered. The increased processing load has been interpreted as reflecting the reanalysis of the over-hastily postulated gap (i.e., 'filled gap effect') and, accordingly, been taken as support for the AFH.

How can the AFH be brought together with the accounts of syntactic complexity that were described in the previous section? Memory resource models assumed that certain information was held in working memory for a longer duration when processing a construction with a moved object than when processing a sentence with a moved subject. This idea is very close to the assumption of the AFH that the preposed wh-filler is actively maintained in working memory until the gap can be located. Note, however, that different from the assumption of the HOLD list of Wanner and Maratsos (1978, especially p. 133/134), the AFH postulates that it is the filler that is maintained in working

[8]I.e., "α can rise to target K only if there is no legitimate operation Move β targeting K, where β is closer to K" (Chomsky, 1995). The MLC has been rephrased by Fanselow and colleagues (1999) in the following way: "[...] the grammar accepts structure S and rejects structure T if the distance between a moved phrase a and its trace is shorter in S than in T."

memory and not the head noun to which it is, at least in relative clauses, referential. Only after the gap has been identified and the syntactic chain between the filler and the gap can be established, the semantics of the antecedent head noun are reactivated (cf. Section 1.4.1).

At first glance, the AFH is not compatible with empirical findings that lead to explanations subsumed under the term of computational load models in the previous section. While the AFH predicts increased processing load at positions early within the relative clause because certain preferences of the parser are not fulfilled (i.e., filled-gap effects), most studies reported processing effects at the relative clause verb and the main clause verb. However, as Ford (1983) suggested, such findings might reflect the successful filling of the gap which takes place when the gap postion has finally been located. Thus, the group of models that was subsumed under the term computational load models and AFH do not necessarily exclude each other. Instead, they appear to work hand in hand. AFH can furthermore serve as an explanation for the sustained working memory load as assumed by theoretical approaches introduced above as memory load models.

There can be a lot of ambiguity with regard to where gaps might be located in the sentence (Clifton & Frazier, 1989; Fanselow et al., 1999, see also sentence 16).

[16] What did (_) you want (_) Mother to make _ for (_) Mary?

The resolution of such ambiguities can pose a considerable amount of processing load on the parser. Actually, the AFH can be conceived as an ambiguity resolution strategy which guides parsing decisions at certain choice points during phrase structure building (cf., Frazier, 1987b). In wh-constructions with case-marked fillers there is much less ambiguity. For example, in masculine German wh-questions (e.g., sentences [17a,b]), the functional role (i.e., subject or object) is directly indicated by the nominative ('wer') or accusative ('wen') case marking of the filler. Fanselow, Schlesewsky and colleagues (Fanselow et al., 1999; Schlesewsky, Fanselow & Kliegl, manuscript), investigating the processing of such wh-questions, repeatedly demonstrated that embedded object wh-questions elicit increased reading times at the wh-phrase (marginally significant) as well as reliably at the following adverbials. The disadvantage for object-initial questions disappears at the second noun phrase, i.e., at the position where the subject of the embedded object-question is encountered ('die Botschafterin' in [17b]). This object-initiality effect was replicated both when interrogative pronouns (i.e., 'wer' vs 'wen') or wh-questions with 'which'-wh phrases (i.e., 'welcher' vs. 'welchen') were used.

[17] a. Ich wüßte gerne, wer$_i$ $\__i$ vermutlich unnoetigerweise die Botschafterin entlassen hat.

I would like to know who$_{NOM}$ probably unnecessarily the ambassa-dor$_{ACC}$ fired has

(= I would like to know, who had fired the ambassador probably unnecessarily.)

[17] b. Ich wüßte gerne, wen$_i$ vermutlich unnoetigerweise die Botschafterin $\_\_{i}$ entlassen hat.

I would like to know who$_{ACC}$ probably unnecessarily the ambassador$_{NOM}$ fired has

(= I would like to know, who the ambassador had fired probably unnecessarily.)

These data were taken to suggest that wh-movement, as defined in syntactic theory, is associated with cognitive costs in sentence processing. The duration during which this additional cost component can be observed is proportional to the distance between the moved phrase and the trace position. The data also indicate that the parser does not wait before linking filler and gap until the gap has been unambiguously located. Instead, "as soon as the position has been reached (viz. the subject) which allows the postulation of the object trace and its integration into the parse tree without violating strict left-to-right incrementality", the filler is integrated (Fanselow et al., 1999, p. 178). A similar model was proposed by Crocker (1994). According to his *Active Trace Strategy* (ATS), the trace can be predicted earlier than assumed in the context of AFH. Crocker (1994) assumes that if the parser identifies a dislocated element in clause initial position (i.e., in [Spec,CP]), it can project CP, and furthermore predict the functional node IP from C, and the lexical node VP from I (cf. Figure 1.1). Accordingly, the trace for the head of the VP (i.e., of the subject) can be posited immediately. However, Crocker (1994) does not discuss how this model would behave when encountering a dislocated element that is case-marked for accusative.

Fanselow and collaborators (Fanselow et al., 1999) argued convincingly that the reading time effects reported for object wh-questions are not likely to be caused by non-syntactic aspects of sentence processing such as, e.g., pragmatic factors (like frequency differences in the usage of subject vs. object initial wh-questions), problems with lexical access in accusative-marked items, or other potential confounds (see also Schlesewsky, Fanselow & Kliegl, manuscript). Furthermore, it was demonstrated that whether-questions, in which the subject also comes late in the clause but which have no underlying movement operation, were processed faster than object questions (but more slowly than subject questions). Thus, the object-initiality effects are unlikely to be caused by strategic differences associated with waiting for the subject. The authors concluded that the increased processing load that was observed for object questions was due (at least in part) to an unreducible structural effect that is related to working memory.

The AFH takes profit from the need of the parser to reduce costs in the resolution of structural ambiguity. The data presented by Fanselow and colleagues (Fanselow et al., 1999; Schlesewsky, Fanselow & Kliegl, manuscript), however, demonstrated that the cognitive cost associated with long movement paths (e.g., [17b]) is a more general feature of grammar and parsing that is not restricted to ambiguitiy resolution. These data suggest that if the parser is confronted with a constituent that is not encountered in its canonical position, and if the corresponding gap position can not be predicted yet, the dislocated element (or some of its syntactic features) has to be maintained temporarily in working memory. Maintenance in working memory, thus, appears to be the parsing mechanism that allows to establish a link between a preposed filler and its canonical gap position.

1.5 Summary

After a short introduction into the psycholinguistics of sentence processing, the outline of a structure-driven model of sentence processing which is taken as a basis for the present work, and a brief introduction into some specificities of German grammar that are relevant for this thesis, early findings regarding the processing of structurally complex sentences were reviewed. The accounts given for these data were related to more recent assumptions regarding the processing of filler-gap dependencies. The data discussed so far suggest that movement of argument noun phrases into non-argument positions causes processing difficulty over prolonged regions of a sentence. It has been suggested that this cognitive cost reflects processes of a working memory mechanism which enables the parser to establish the relation between the preposed constituent and its canonical gap position in the phrase structure.

However, the assumption that this processing cost component is in fact due to an involvement of ongoing working memory processes spanning the distance between filler and gap can not be taken as empirically established yet. The behavioral effects reported so far do not give clues regarding the nature of the underlying cognitive processes. There have also been consistent reports of more local effects of increased processing costs over single words in complex sentences. This finding suggests that the processing difficulty in parsing structurally complex sentences is due to an interplay of maintenance mechanisms on the one hand and computational processes of syntactic structure building, confined to circumscribed regions of the sentence, on the other. However, the fact that sustained differences in processing difficulty are actually due to sustained working memory processes specifically associated with processing the moved element and its gap, as well as the fact that both sustained and local aspects of parsing can be observed during processing a sentence have yet to be demonstrated.

Chapter 2

Working Memory and Sentence Processing

As became evident in the previous chapter, many authors have used working memory as an explanatory construct to explain the processing difficulty of sentences that are syntactically complex. Within psycholinguistics the notion of working memory as a constraint on parsing processes has been present (implicitly or explicitly) for a long time. To give one example: A relative clause sentence can in principle have an indefinite number of center-embeddings, without rendering the sentence ungrammatical. Nevertheless, a sentence like [18] (from Miller & Isard, 1964) is not acceptable and this is generally attributed to the fact that the parser does not have enough resources at hand to support the complex processes of intermediate storage and integration that would be necessary to correctly parse this sentence on-line.

[18] The man who said that a cat that a dog that a boy owns chased killed the rat is a liar.

A limited working memory resource has been assumed already in early accounts of sentence processing. In 1973, Kimball, who proposed seven principles of surface structure parsing, included the notion of a limited capacity short-term memory space in one of his parsing principles (and claimed that the inherent capacity of the parser is two sentences). This notion is supported by empirical data provided by Blaubergs and Braine (1974) who observed that comprehension breaks down in sentences with three or more center-embeddings. Similarly, Frazier and Fodor (1978) suggested a two-stage model of parsing with specific limitations in capacity at each of these stages. For example, the so-called preliminary phrase packager which constitutes the first level of analysis in the model is able to process a viewing window of up to six words of a sentence. Kintsch and van Dijk (1978), in the context of a model of text comprehension, postulated that capacity limitation constrains the way coherence is determined between different propositions of the meassage. A limited number of memory chunks is available to store propositions derived from the text. The amount of processing resources was assumed to be distributed among storage units which store propositions and computational mechanisms such as inference generation.

Working memory, as viewed in early psycholinguistic research, was a rather heterogenous concept that was not clearly defined. In this chapter, current models of working memory and sentence comprehension will be introduced. Before this will be done, the following two sections give a short overview over the concept of working memory and the way it influenced research on language processing.

2.1 The Concept of Working Memory

Working memory is assumed to reflect the ability to maintain information available within the cognitive system and at the same time manipulate this information (e.g., Atkinson & Shiffrin, 1971; Baddeley & Hitch, 1974; Just & Carpenter, 1992; Caplan & Waters, 1999). This definition differs from earlier models of short-term memory in that the memory system is not considered to be merely a passive storage unit any more (cf. Miller, 1956; Atkinson & Shiffrin, 1968). Instead, when assuming a working memory, resources are also required to actually perform computations on the contents of memory. Differently phrased, the term working memory refers to a system or mechanism underlying the maintenance of task-relevant information during the performance of a cognitive task (e.g., Miyake & Shah, 1999). Or, as Richardson (1996) put it, working memory is "... intrinsic to human cognition in all its forms" (p. 5).

A predominant view in cognitive science is to think of working memory as some variant of the very influential model of working memory that was introduced by Baddeley and colleagues (e.g., Baddeley & Hitch, 1974; Baddeley, 1995; Baddeley & Logie, 1999). In this multiple-component model, the working memory system is subdivided into a central executive and (at least) two slave systems responsible for storage of modality-specific information (i.e., the phonological loop and the visuo-spatial sketch pad). The role of the central executive component is to control and regulate the distribution of resources between the different subcomponents of the system and, in general, to direct the processes of cognitive functions. The specialized systems are responsible for actively maintaining memory traces within the system. In recent years, there have been suggestions of additional specialized subsystems or further fractionations within the existing systems (e.g. Martin & Romani, 1994; see also below). Although the central executive has long been said to be made up of a general-purpose resource that supports processing and storage, Baddeley and Logie (1999) stated that the assumption of temporary storage within the central executive has subsequently been given up. The executive system is thus restricted to the control of the processes of the working memory system.

However, there are also theoreticians who adopt a radically different view by postulating that working memory is a unitary entity (e.g., Engle et al., 1992; Anderson et al., 1996). Although all approaches to working memory share the underlying assumption of storage limitations, unitary accounts of working memory appear to be even more strongly rooted in the idea of a cognitive system that is limited in the total amount of activation resources that are available both for storage and for processing. Accordingly, in such models, a competition can arise in the distribution of working memory resources between computational routines and storage mechanisms. For more detailed discussions of working memory and for an overview of the different theoretical approaches to working memory, the reader is referred for example to the volumes edited by Richardson and others (1996) and by Miyake and Shah (1999).

2.2 Working Memory and Language

In varying formulations and implementations, the notion that short-term memory or working memory plays a role during language processing has been present in the literature for a long time already. This is for obvious reasons, given the seriality of language processing. Be it a word, a phrase, a sentence, or a longer text, one inherent property of language is that it unfolds in time. Especially in the comprehension of spoken language, going back to earlier parts of a linguistic input signal means to go back into a stored copy of the perceived material. But even with written text, working memory plays an enormous role. When processing a sentence or a text, a large number of intermediate products of the comprehension process has to be stored before they can be linked with what has already been processed and with what is yet to come (e.g., Just & Carpenter, 1992; Gathercole & Baddeley, 1993; Daneman & Merikle, 1996).

One possibility for modeling working memory in sentence comprehension obviously is the verbal subcomponent of Baddeley's multiple-component model of working memory. This system is assumed to store verbal material on the basis of phonological codes. It consists of a passive phonological store and a subvocal rehearsal loop for refreshing the contents of the storage component. Clark and Clark (1977) suggested that when processing a (spoken) sentence, the complete sentence is held in a verbatim form in phonological working memory until syntactic and semantic analysis is finished (see also, e.g., Caramazza et al., 1981).

Baddeley and colleagues (e.g., Baddeley et al., 1987; Vallar & Baddeley, 1987) proposed a weaker role for the phonological slave system in sentence comprehension. These authors investigated patients that exhibited severe deficits regarding their phonological storage capacities. The sentence comprehension performance of these patients was tested using a variety of short and long sentences and prose passages in sentence-picture matching and anomaly detection tasks. Some of the sentences contained semantic or syntactic anomalies. It turned out that the patients had no difficulty with comprehending a variety of syntactic structures (if they occurred in short sentences). However, they had severe problems in detecting syntactic anomaly in long sentences, when the retention of the surface structure was important for understanding, and when mismatches existed in anaphoric relationships over longer distances. The specific pattern of breakdown in these sentence conditions has been explained by assuming that the phonological slave system serves as a "mnemonic window" (Baddeley et al., 1987) which temporarily stores the perceived words in the order in which they were encountered. Importantly, the phonological loop system was concluded to play a role in comprehension but it was not assumed to be involved in syntactic on-line processing. Rather, it was said to provide a phonological back-up store (Gathercole & Baddeley, 1993; Romani, 1994) which may be required in off-line processes such as reanalysis of initially misparsed sentences.

Similarly, Caplan, Waters, and colleagues (1990, 1991) suggested that phonological storage may be involved not in first-pass parsing processes (see above Section 1.1) but in second pass processes like recovery from misinterpretation. A similar conclusion has been reached by Martin and colleagues (e.g., Martin & Feher, 1990; Martin, 1993; Martin & Romani, 1994). These authors also concluded from their work that phonological working memory does not play a critical role in syntactic processing. With respect to language processing, they suggested that the phonological storage component contributes mainly to verbatim repetition and long-term learning of phonological forms (Martin, 1993).

Martin and collaborators have taken the view that specialized working memory components exist for semantic and syntactic information (e.g., Martin & Romani, 1994; Martin et al., 1994). These authors argued that according to the working memory model proposed by Baddeley and colleagues, semantic and syntactic aspects of verbal input would have to be retained in the general storage capacities of the central executive (if these exist). On the basis of a number of neuropsychological studies with aphasics and patients exhibiting working memory deficits, they proposed that it is more likely that there exist additional capacities specific to verbal processing within the verbal domain of the multiple-component architecture of working memory that support the temporary storage of semantic or syntactic information.

It has been known for some time that semantic information contributes to verbal working memory performance (e.g., Crowder, 1978; Hulme, Maughan & Brown, 1991). Martin and colleagues (Martin, Shelton & Yaffee, 1994) reported data from patients that reacted differently to phonological and semantic manipulations in a word span task. Furthermore, they demonstrated that this dissociation was also present in sentence processing tasks, where sentence repetition (assumed to require a phonological representation) was more impaired in a patient with a phonological retention deficit and sentence comprehension (relying on a meaning representation of the sentence) was more impaired in a patient who had greater problems with semantic retention. This finding was taken as evidence in favor of the assumption of separable aspects of working memory for semantic and phonological information.

Furthermore, another patient (M.W.; cf. Martin & Romani, 1994) was reported who exhibited difficulties in maintaining incomplete syntactic structures although working memory span was in the normal range. On the basis of this result, as well as on the basis of other findings of patients with deficits in phonological storage but preserved sentence comprehension abilities, a further level of verbal working memory, namely a syntactic component, was postulated. However, these levels of working memory were not argued to be independent like, for example, the verbal and the visual slave systems are assumed to be. It was assumed that maintenance of semantic and syntactic aspects of verbal material, just like maintenance of phonological information, contributes to retention performance in verbal working memory tasks and to sentence comprehension. Martin and Romani (1994) suggested that in normal performance, the different components interact and support each other.

Most of the case reports cited above were characterized by deficits in simple measures of phonological working memory capacity such as the digit span task or the word span task. However, it has been pointed out that these and similar measures might be inadequate for identifying the specific cognitive resources required in sentence comprehension (Perfetti & Goldman, 1976; Daneman & Carpenter, 1980; Richardson, 1996). Indeed, although earlier theoretical models of language processing had attributed a role to working memory in language (see above), there were almost no empirical demonstrations of this relation. The investigation of working memory in the context of language processing, especially in healthy individuals, has been considerably influenced by the development of the *reading span task* which was introduced by Daneman and Carpenter (1980). In this test, participants have to read a set of sentences and remember the final word of each sentence. The reading span is defined as the maximum number of sentences in a set for which the final words can be correctly recalled. As Daneman and Carpenter (1980) report, the set size that could be remembered varied between two and five in a population of college students[1]. A number of related tasks has been developed by different researchers such as the listening span (Daneman & Carpenter, 1980), the counting span task (Baddeley et al., 1985), arithmetic operations span tasks (e.g. Daneman & Tardif, 1987; Engle et al., 1992), or variants of the reading span task that require, for example, judgments of acceptability after each sentence (Waters et al., 1987).

Daneman and Carpenter (1980) reported that working memory capacity as determined by the reading span task correlated with different measures of reading ability. In a more experimental approach, the same authors (1983) demonstrated that individual differences in working memory capacity were related to the integration of information between and within sentences. Employing a word-by-word reading paradigm, they observed that low capacity readers had more difficulty in detecting and resolving inconsistencies between an initial interpretation of a homonym and its disambiguation.

[1]It is important to note that the difficulty of the task, and thus the range of scores obtained in a sample, is dependent upon the complexity of the sentences used. This aspect is relevant when comparing results from different versions of the reading span task like, for example, translations into different languages.

This effect was especially pronounced if a sentence boundary had to be crossed in order to relate the disambiguating word to the homonym. King and Just (1991) reported that individuals with a low working memory capacity had greater difficulty in the processing of object-relative clause sentences (as compared to subject relatives) than high span individuals.

Daneman and Carpenter (1980, 1983) suggested that the type of working memory measured with the reading span task is specific for language processing (see also Daneman & Tardif, 1987; Just & Carpenter, 1992). However, Baddeley and colleagues (1985) reported that a counting span task also was correlated with reading comprehension, leading to the conclusion that the working memory resource in question is likely to be a general-purpose system for processing and temporary storage (see also Logie, 1996). Initially, it was assumed by Daneman, Carpenter and colleagues (e.g., Daneman & Carpenter, 1980; Just & Carpenter, 1980) that the difference in capacity between individuals was due to the efficiency with which the limited capacity that was available could be used. However, in light of more recent empirical evidence (e.g., Engle et al., 1992), the view has been adopted that individual differences in working memory capacity are largely due to differences in the total amount of storage capacity that is available (Just & Carpenter, 1992).

Notwithstanding these theoretical debates, the availability of the reading span task as a measure for determining language-relevant working memory capacity has initiated a vast amount of research in the last two decades (see Daneman & Merikle, 1996, for a meta-analytic review of this work). Part of this work has lead to an influential theory of sentence comprehension, namely the *Capacity Theory of Comprehension* (Just & Carpenter, 1992) which will be introduced, together with other approaches, in the following section.

2.3 Working Memory Capacity as a Constraint on Parsing

The research described in Chapter 1 suggests that working memory resources are assumed both for temporary maintenance of syntactic information within the sentence processing system (e.g., Wanner & Maratsos, 1978) and for computational processes of parsing (e.g., Ford, 1983; King & Just, 1991). The limited nature of these processing resources constrains the complexity of sentences that can be parsed without problems. The literature review in the previous section has revealed that empirical data do not lend themselves to the assumption that the phonological slave system of the multiple-component model of working memory supports the function of on-line parsing. On the other hand, research using the readig span task has demonstrated relationships between individual working memory capacity and on-line sentence processing. In this section, three models of resource distribution during sentence comprehension will be introduced and it will be examined to what extent these models can be related to the processing effects of syntactic complexity described in Chapter 1.

2.3.1 The Capacity Theory of Comprehension

The first model to be considered is the Capacity Theory of Comprehension (CTC) which was introduced by Just and Carpenter (1992). These authors suggested an activation based framework for modeling both storage aspects of sentence comprehension and the symbolic computational processes that actually perform language comprehension. Working memory, under this view, is seen as a pool of operational resources that fuel both aspects of parsing. The CTC is mainly an account of individual differences in reading performance based on the reading span task.

The Capacity Theory of Comprehension was implemented as a simulation model called CC READER (i.e., a capacity constrained version of the earlier READER model; cf. Thibadeau et al., 1982). This model is described as a parallel architecture that incorporates aspects of connectionist networks and production system mechanisms. Symbolic computations, like processes of phrase structure building, are implemented as production rules that propagate activation from source elements to target elements reiteratively. Each production cycle consumes a certain amount of activation. Maintenance of information (e.g., an unbound element that has not yet been integrated into the phrase structure) in working memory also consumes activation units because elements in working memory are subject to decay. The capacity limitation is imposed by limiting the amount of total activation available. If storage and computational load exceed the limited capacity that is available, the penalty that results is distributed evenly between all aspects of processing.

This model differs from the multiple-component view (e.g., Baddeley, 1995) in that a general resource is assumed both for storage and computation. However, this model is not based on a unitary account of working memory. The authors stress that the resource in question is specific for language processing. Regarding the relation to the multiple-component model, Just and Carpenter (1992) state that "the working memory in our theory corresponds approximately to the part of the central executive in Baddeley's theory that deals with language comprehension" (p. 123). Just and Carpenter imply that the central executive, as postulated by Baddeley and others (see above Section 2.1), is a general-purpose resource for storage and processing that has subdivisions, one of which is responsible for language processing. This view, however, appears not to be corresponding directly to the way the central executive is described by Baddeley and colleagues. Especially, as discussed above, it has been assumed more recently that the function of the central executive is restricted to processes of executive control proper (cf. Baddeley & Logie, 1999).

The Capacity Theory of Comprehension is based mainly on studies investigating the processing of sentences with varying syntactic complexity in groups with high and low working memory capacity (as determined on the basis of the reading span task; Daneman & Carpenter, 1980). The data reviewed by Just and Carpenter (1992) include eye movement measurements during processing of reduced and unreduced relative clauses, self-paced reading times obtained during the processing of sentences with complex embeddings (King & Just, 1991) and during the processing of ambiguous sentences

(MacDonald et al., 1992). Furthermore, sentence processing under conditions of concurrent external working memory load was investigated (King & Just, 1991) as well as the effects of distance between constituents to be related (either within or between sentences; e.g., Daneman & Carpenter, 1980). The groups investigated were, for example, college students that were divided into high and low capacity groups on the basis of their reading span score (e.g., King & Just, 1991) or individuals of different age groups (e.g., Kemper, 1986).

In close relation to the work cited in Chapter 1 is the word-by-word reading study reported by King and Just (1991). These researchers investigated the processing of center-embedded subject and object relatives like they were presented in sentence examples [10a,b], repeated here as [19a,b], under conditions of concurrent working memory load.

[10] a. The reporter$_i$ who$_i$ $\__i$ attacked the senator admitted the error.

[10] b. The reporter$_i$ who$_i$ the senator attacked $\__i$ admitted the error.

In this study, the finding that object-first relatives are more difficult to process than subject relatives (cf. Section 1.3) was replicated in all participants. As already described earlier, the locus of the processing load was at the verbs of the relative clause and the main clause (i.e., 'attacked' and 'admitted'), the two elements surrounding the gap position (cf. [19b]). King and Just (1991) observed that low capacity readers had more difficulty with object relatives than high capacity readers (already under conditions of no or little external load). This effect was especially prominent at the main clause verb. In contrast, there was no effect of span group for subject relative clause sentences. Furthermore, despite the slower reading times of low capacity individuals, their comprehension accuracy was poorer than that of the high span readers.

These and other data were taken to suggest that the amount and the efficiency of usage of working memory resources differ between individuals. Furthermore, the results of King and Just (1991) can be taken as evidence that the processing costs observable over certain regions of embedded sentence structures that contain filler-gap dependencies are related to processes that draw upon working memory resources.

The CTC approach has the advantage of accounting reasonably well for the empirical data discussed, as well as of providing an implemented model. Furthermore, it can potentially account for both aspects of processing difficulty identified in previous work on syntactic complexity, namely for local computational processes and for sustained processes of temporary storage. The CTC approach indeed predicts increased processing effects for object as opposed to subject relatives and it also predicts differences between individuals with high and low working memory capacity. However, on the basis of the description of the model that is made available to the reader (i.e., the not-implemented version), the CTC does not allow to derive quantitative predictions regarding the processing of specific types of sentences. Especially, CTC does not allow to predict where in the sentence processing difficulty should arise. This is so because the model does not provide a description of the actual parsing processes assumed and a way to calculate the activation units consumed at different positions in the sentence when performing these processes.

2.3.2 Separate-Sentence-Interpretation-Resource Model

While investigators favoring the Capacity Theory of Comprehension stressed the fact that the reading span task taps a unitary resource for language processing, Caplan and Waters (e.g., Caplan & Waters, 1999; Waters & Caplan, 1996) seriously question this single-resource approach. Their own research with healthy individuals as well as with neurological patients has led Caplan and colleagues to develop a different view of the relation between syntactic processing and the type of memory resource that is measured with the reading span task. In contrast to what they refer to as the single-resource model (i.e., the CTC; Just & Carpenter, 1992), Caplan and Waters (1999) proposed a model of working memory during sentence comprehension that encompasses two components, one dedicated to on-line interpretive processes (i.e., the actual computations performing sentence comprehension) and one supporting a second aspect of working memory, namely postinterpretive processes.

Interpretive processing refers to "the process whereby a listener or reader extracts the meaning of the sentence from the signal" (p. 79). Interpretive processes are highly automatic and might include processes such as word recognition and lexical access, the construction of syntactic and prosodic representations, or the assignment of thematic roles and focus (p. 78). *Postinterpretive processing* refers to all kinds of secondary processes that utilize the meaning that has been extracted from the linguistic input. With respect to the reading span task, the maintenance of the last word of each sentence in working memory can be attributed to the postinterpretive processing resource while the on-line processes of reading each sentence are supported by the interpretive processing resource. On the basis of these assumptions, Caplan and Waters (1999) predicted that manipulating the complexity of the syntactic structure of a sentence should pose a demand on the interpretive processing resource while increasing the propositional weight of a sentence (i.e., including one or more additional propositions) should tap postinterpretive resources. Caplan and Waters (1999) cite a number of empirical findings from healthy individuals and from different neurological populations to support this assumption, thus calling the single-resource approach postulated in the context of CTC into question. This work will not be reviewed here because postinterpretive resources are not in the focus of the present thesis. However, it shall be noted that Caplan and Waters (1999) also criticized Just and Carpenter on methodological grounds. Especially, they pointed out that in the reading-time study reported by King and Just (1991), the relevant statistical interactions that would justify the conclusions drawn by these authors regarding the competitive distribution of a common resource were not reported.

Although the work by Caplan and Waters can be considered as an important step towards a clarification of the role of working memory during language comprehension, it has to be noted that this approach has a similar problem as the one proposed by Just and Carpenter (1992). By assuming that there is a resource that is responsible for interpretive processing, no quantiative predictions for the on-line processing of different sentence types can be derived that would specify where in the sentences working memory load should be taxed to what degree. Rather, it appears that assumptions regarding the processes underlying on-line sentence comprehension are less specific within the Caplan and Waters model than in the Capacity Theory of Comprehension. With regard to the present work, whose focus is on the resource usage during on-line parsing, the separate-sentence-interpretation-resource model makes the prediction that mechanisms of on-line sentence interpretation should not be influenced by individual differences in working memory capacity. This prediction will be tested in the first experiment of this thesis.

2.3.3 The Syntactic Prediction Locality Theory

The third model to be presented here is the *Syntactic Prediction Locality Theory* (i.e., SPLT) which was recently put forward by Gibson (1998). SPLT is not a genuinely psychological theory of working memory and language in the sense of the previous two models. Instead, it is an attempt at explaining how the limited resources available to the parser are distributed during on-line comprehension of sentences by providing a complexity metric that allows to predict processing difficulty very precisely at different positions in a sentence. In this sense, it is closer to the central question of this thesis. SPLT has the advantage of providing quantitative predictions for different types of structural configurations in sentences.

The SPLT approach is based on an interactive account of parsing according to which a variety of different sources of information (e.g., lexical constraints, plausibility constraints and discourse context constraints) interact in the on-line interpretation of a sentence. These constraints are implemented in an activation based framework, similar to the one described by Just and Carpenter (1992). Each representation of the input is associated with an activation value. Only discourse representations above a certain threshold will be considered by the parser.

In the context of SPLT it is also assumed that computational resources are limited. Two "primary aspects of resource use" (Gibson, 1998, p. 9) are postulated that contribute to the processing difficulty of certain sentence structures, namely processes of *structural integration* and processes of *structural maintenance*. The integration cost component (see below) specifies the quantity of computational resources that have to be spent when new words are integrated into the current syntactic and discourse structure representations. The maintenance cost component, on the other hand, determines the resource usage when partial linguistic input needs to be stored. A critical concept in this model is the notion of *locality*. The greater the distance over which information has to be maintained in memory or the greater the distance between two elements to be integrated, the more resources have to be spent for this process and the less resources are available for other processes active at the same time. According to the principle of locality the parser seeks to minimize these distances.

The integration cost component (see [20]) is assumed to reflect syntactic processes such as attaching structures or linking elements in a dependency chain. Furthermore, it also encompasses integration processes at the semantic and discourse level. For example, thematic role assignment could be reflected here. Each integration is assumed to cost a fixed amount of cognitive resources. The integration costs are increased if the distance between two elements to be integrated increases. This distance was operationalized in the SPLT as the number of intervening discourse referents. Similar to the CC READER (Just & Carpenter, 1992), each item has an activation level that decays over time. If an element has to be integrated whose activation has already decayed because new material has been processed, more resources have to be spent for reactivation to a critical threshold. It was also noted that the complexity of an integrations determines the amount of resources that has to be spent (cf. [20,(1)].

[20] LINGUISTIC INTEGRATION COST

> The integration cost associated with integrating a new input head h_2 with a head h_1 that is part of the current structure of the input consists of two parts:
> (1) a cost dependent on the complexity of the integration (e.g. constructing a new discourse referent); plus
> (2) a distance-based cost: a monotone increasing function I(n) energy units (EUs) of the number of new discourse referents that have been processed since h_1 was last highly activated. For simplicity, it is assumed that I(n) = n EUs.
> (Gibson, 1998, p. 12/13)

The maintenance or memory cost component (see [21]), on the other hand, is a cognitive cost that is associated with remembering the syntactic predictions of the categories that are minimally required to complete the input as a grammatical sentence (Gibson, 1998). Based on grammatical knowledge in the form of phrase structure rules, the parser expects certain categories of words in a sentence. For example, the minimal number of constituents (i.e., "syntactic head categories"; Gibson, 1998) in each sentence that is predicted is two. These are the head noun for the subject of the sentence and the head verb for the predicate. Processing difficulty arises when the parser maintains syntactic predictions in working memory that are not yet fulfilled. The syntactic memory component is also distance-based as it becomes more and more expensive to maintain a prediction activated the more intervening material has to be processed.

[21] SYNTACTIC PREDICTION MEMORY COST

> (a) (...)
> (b) For each required syntactic head C_i other than V_0, associate a memory cost of M(n) memory units MUs where M(n) is a monotone increasing function and n is the number of new discourse referents that have been processed since C_i was initially predicted. (Gibson, 1998, p. 15)

It shall be noted at this point that, although making very similar predictions as the Active Filler Hypothesis (see above Section 1.4.2) for certain structures, SPLT assumes a different underlying process. While AFH assumes that the preposed filler is identified and then actively kept available in working memory, SPLT proposes that on the basis of syntactic information of a clause-initial filler, a prediction is issued that specifies the categories that are minimally required to complete the sentence. Accordingly, upon encountering for example an overtly marked object in clause initial position, AFH would predict that the syntactic features of the object filler are maintained in working memory. SPLT, in contrast, would assume that the prediction of a subject and a predicate (and of an object trace) are maintained in memory. The predictions of the two models are difficult to dissociate empirically because the content of working memory is not directly accessible. In the contrast between object-first and subject-first sentences (like it was discussed extensively in Chapter 1), both models propose a greater memory load for object-first structures. A possible way of dissociating the two approaches would be to compare subject-first structures with 'if'- or 'whether'-questions (e.g., 'He wants to know, whether ...'). While in a subject-first question, the syntactic prediction that has to be maintained according to SPLT consists of the predicate, it encompasses the subject and the predicate in 'whether'-questions. Thus, the load over the initial elements of the embedded question would be greater for whether-questions than for subject questions according to SPLT. AFH, in contrast, would not predict an increased load in whether-questions as no filler is identified in clause-initial position. However, it does not necessarily have to be assumed that AFH applies to the processing of whether-questions at all because this type of structure is not characterized by an ambiguity like the structures AFH is normally applied to.

Although SPLT has a broader range of applications (e.g., by assuming that integration costs are elicited by all kinds of integration processes such as syntactic, semantic, etc.), it can be very well applied to the phenomena of syntactic complexity that were introduced in Chapter 1. In sentences like [9] and [10], repeated here for convenience as [22], the integration cost calculation proposed by Gibson (1998) yields three integration cost units at the verb of the object relative clause (i.e., 'attacked' in [22b]). At this position, the relative clause verb has to be integrated with the subject NP which directly preceeds it (i.e., one integration cost unit) and also with the clause initial object relative pronoun. This latter integration costs two units because an intervening discourse referent (i.e., the subject NP) has to be crossed. In contrast, at the same position in the subject relative clause, the object NP is encountered (i.e., 'senator' in [22a]). This constituent has merely to be integrated with the preceding verb, thereby consuming one integration cost unit. The difference can account for the processing difficulty reported (e.g., Ford, 1983; Just & Carpenter, 1992). A more detailed description of these calculations is found in Gibson (1998).

[22] a. The reporter$_i$ who$_i$ $\_\_i$ attacked the senator admitted the error.

[22] b. The reporter$_i$ who$_i$ the senator attacked $\_\_i$ admitted the error.

Interestingly, at the position of the main clause verb, this calculation yields the same prediction for both object and subject relatives (i.e., three integration cost units). This prediction is not supported by the pattern of data described for example by King and Just (1991). In their experiment, reading time effects were greatest at the main clause verb (see also Ford, 1983). As Gibson (1998) suggested, the effects at the main clause verb can probably be attributed to differences in the complexity of the integration processes taking place after the processing of subject or object relative clauses. This aspect of integration cost was not accounted for by the model.

Due to the verb-final nature of German, the predictions derived above do not hold for sentences like [17a,b] (repeated here as [23a,b]; cf. Fanselow et al., 1999; Schlesewsky, Fanselow & Kliegl, manuscript). As fronting of the object argument does not change the number of preverbal NPs like in English (cf. Section 1.3), the distance to be spanned when, for example, integrating the verb with the two argument NPs is exactly the same in subject-first as in object-first constructions. Therefore, the distance-based integration cost component as it was suggested by Gibson (1998) does not predict local differences in processing cost between [23a] and [23b].

[23] a. Ich wüßte gerne, wer$_i$ $\_\_i$ vermutlich unnoetigerweise die Botschafterin entlassen hat.

[23] b. Ich wüßte gerne, wen$_i$ vermutlich unnoetigerweise die Botschafterin $\_\_i$ entlassen hat.

In the framework delivered by the SPLT, it follows that in German the difference between unambiguous object-first and subject-first constructions is either due to the complexity of the syntactic prediction that is made at the beginning of the clause, i.e., due to differences in the working memory load during sentence processing, or due to differences in the complexity-dependent aspect of the integration cost component specified within SPLT. When processing the case marked wh-filler, a more complex phrase structure can be predicted for [23b] (including, at least, a subject, an object trace and a transitive verb) than for [23a] (containing only a subject and an intransitive verb). This prediction is in line with the sustained reading time effects reported by Schlesewsky, Fanselow and colleagues (Fanselow et al., 1999; Schlesewsky, Fanselow & Kliegl, manuscript; see Section 1.4.2). In English, in contrast, the clause-initial wh-filler is always case-ambiguous and therefore by default always interpreted as subject. Accordingly, SPLT would not predict sustained differences in working memory load in English sentences, at least not as being triggered by the clause-initial wh-filler.

2.4 Summary

In this chapter, an introduction into different approaches to modelling working memory and its role in language processing was given, followed by a more detailed description of prominent models of working memory during parsing. The approaches covered range from suggestions for a specific working memory component dedicated to syntax to activation-based accounts of resource usage that assume one or more language-specific resource pools. Furthermore, a model of the quantitative estimation of resource usage by different parsing processes was introduced.

Empirical evidence indicates that the phonological subcomponent of the widely accepted multiple-component model of working memory does not support on-line parsing operations. Rather, there appears to be (at least) one language-specific processing resource that fuels both storage and computation during on-line processing of language. It has been demonstrated that there are relations between this working memory resource and parsing operations. Increased demands on language-specific or even syntax-specific working memory resources might thus be taken to account for the cognitive processing costs observed for structurally complex sentences that were discussed in detail in Chapter 1. However, this conclusion mainly rests on evidence from individual differences in working memory capacity and from studies of sentence processing under conditions of concurrent load. In this thesis, I will present evidence from a manipulation of structural aspects of sentences that leads to an increased distance over which a syntactically driven load has to be maintained in working memory. The relation of this kind of structurally induced working memory load and individual differences in working memory capacity will be investigated.

Chapter 3

Language and the Brain

3.1 The Neurocognitive Approach to Language Processing

The aim of neurocognitive research on sentence processing is to identify the brain regions that support the different processes and mechanisms postulated by cognitive models of parsing. Early models of language and the brain, such as the neurological model proposed by Wernicke and Lichtheim (e.g., Wernicke, 1874, see also Geschwind, 1970) were based on post-mortem studies of neurological patients with deficits in the language domain. With the advent of structural brain imaging like Computer Aided Tomography (CT) and Magnetic Resonance Imaging (MRI), correlations between behavioral deficits and underlying brain damage could be obtained more systematically and from larger groups of neurological patients (e.g. Alexander et al., 1990; Caplan et al., 1996).

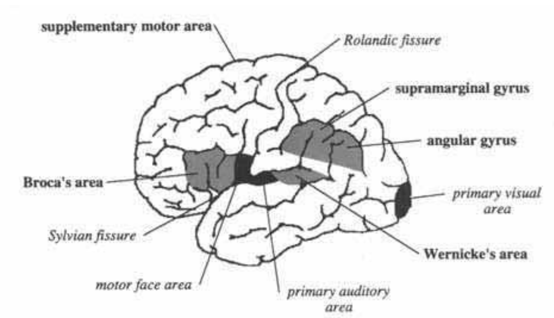

Figure 3.1: *Schematic view of the lateral surface of the left hemisphere (Dronkers, Redfern & Knight, 2000). Brain areas implicated in language processing according to the neurological model of language are printed in boldface.*

Classically, Broca's area (cf. Figure 3.1) has been related to processes of language production (i.e., the articulation of speech). This assumption is based on the non-fluent nature of Broca's aphasics spontaneous speech, which is agrammatic in the sense that function words and syntactic forms are only sparsely produced. Wernickes's area, on the other hand, has been associated with the storage of sensory memories of words, a representation that is needed for comprehension (e.g., Wernicke, 1874; Geschwind, 1970). This hypothesis is rooted in the severe comprehension problems of patients suffering from Wernicke's aphasia.

Today, the roles attributed to these two major language areas have changed. Especially with respect to Broca's area, it has been recognized on the basis of neurolinguistic studies conducted first in the nineteen seventies that Broca's aphasics experience problems also with receptive processing of complex grammatical structures (e.g. Caramazza & Zurif, 1976; Heilman & Scholes, 1976; Friederici & Schoenle, 1980; Heeschen, 1980). Thus, it turned out that in addition to not producing functors, agrammatic Broca aphasics also do not utilize grammatical information provided by function words and inflectional morphology for comprehension. For example, these patients could interpret sentences with center-embedded relative clauses correctly only when semantic cues supported the interpretation (like in sentence [24a]). If, however, there was no disambiguating information available other than syntactic information (e.g., [24b]), these Broca aphasics performed at chance level (Caramazza & Zurif, 1976). This phenomenon has been attributed to a central deficit in the representation of syntactic knowledge which, in turn, has been linked to Broca's area (see Zurif & Swinney, 1994; Friederici, 1999; Grodzinsky, 2000, for reviews).

[24] a. The coat that the girl is wearing is new.

[24] b. The girl that the boy is tickling is happy.

Some theories have tried to specify the nature of this central deficit in more detail on the basis of linguistic approaches. Recently, it has been proposed that Broca's aphasics have difficulty in recovering structural dependencies like filler-gap relations in structurally complex sentences (e.g., Swinney & Zurif, 1995; Swinney et al., 1996; Grodzinsky, 2000). However, even the role of Broca's area in Broca's aphasia is not perfectly clear. For example, Mohr and colleagues (Mohr et al., 1978) pointed out that the typical syndrome of Broca's aphasia is only observable when regions of the frontal cortex extending well beyond the classical area of Broca are impaired, including the frontal operculum, the insula and surrounding white matter. Caplan, Hildebrandt and Makris (1996) reported that there was no clear-cut correlation between lesion site and the nature of sentence comprehension deficits in a group of 18 patients with left-hemisphere lesions in the perisylvian region that underwent structural imaging (see also Willmes & Poeck, 1993). To make the matter even more complicated, there is a disagreement with regard to the correct neuroanatomical definition of Broca's area (see Section 3.2).

The study of the neuroanatomical correlates underlying cognitive functions has changed significantly with the development and distribution of new methods like event-related brain potentials (ERPs), Positron Emission Tomography (PET), or functional Magnetic Resonance Imaging (fMRI).

From the view of modern cognitive neuroscience, it is not enough to identify anatomical regions whose impairment can lead to a breakdown of certain cognitive functions such as sentence processing. A convincing model of the functional neuroanatomy of language processing requires also insights into the working of the brain under healthy conditions, as well as assumptions regarding the temporal dynamics of the interplay between different brain areas (cf. Friederici, 1999).

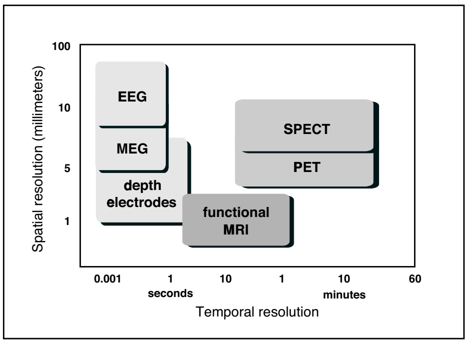

Figure 3.2: *Overview over the spatial and temporal resolution of different brain imaging techniques.*

Figure 3.2 summarizes the temporal and spatial resolution of different methods of brain imaging. Given the differences in these parameters between methods, it became clear that it is not possible to obtain a satisfying account of how the brain processes language by considering data from one methodological source alone. Instead, insights from different methodologies have to be integrated. Most research groups working with brain imaging in humans currently employ PET and fMRI scanning because these methods offer a satisfactory spatial resolution and, in the case of fMRI, are non-invasive. In psycholinguistic research, on the other hand, the ERP method gained more importance in recent years because it allows to track mental processes in a time domain of a few milliseconds. The present work is an attempt at using these two approaches with the same sentence processing paradigm.

In the next sections, the methods and important findings will be introduced. This overview, however, will remain shallow at some points and concentrate mainly on results that are important for the present thesis. It would go beyond the scope of this thesis to give in-depth introductions into multiple neuroscientific methods and exhaustive reviews of their contributions to the neurocognition of language. The interested reader is referred to methodological textbooks (e.g., Regan, 1989; Orrison et al., 1995; Rugg & Coles, 1995; Toga & Mazziotta, 1996; Frackowiak et al., 1997; Moonen & Bandettini, 2000) and reviews summarizing the contributions of cognitive neuroscience to the understanding of language processing (e.g. Zurif & Swinney, 1994; Kutas, 1997; Osterhout et al., 1997; Binder

& Frost, 1998; Brown & Hagoort, 1999; Friederici, 1999; Cabeza & Nyberg, 2000; Grabowski & Damasio, 2000; Indefrey & Levelt, 2000; Norris & Wise, 2000; Friederici, in press).

3.2 Language Regions in the Brain

In this section, a short overview over the neuroanatomically relevant brain regions that will be mentioned in the course of this thesis will be given. This is supposed to make the reader familiar with the terminology used throughout the thesis. Subcortical brain regions, although involved in the processing of language (e.g. Crosson, 1992; Caplan, 1994), will not be considered here. Generally, the brain regions relevant for non-primary processing of language (i.e., processing at levels higher than primary sensory processes) are located in the perisylvian region of the dominant hemisphere (i.e., of the left hemisphere in most right handers). The perisylvian region encompasses the cortical areas that are in the vicinity of the sylvian fissure (which is also known as lateral sulcus; see Figure 3.1).

The brain can be broadly segregated into four lobes (per hemisphere) which are further subdivided into gyri and sulci. While Broca's area is part of the frontal lobe of the human brain, Wernicke's area is located posteriorly in the superior part of the temporal lobe. A comparison of the functional language areas indicated in Figure 3.1 with the cytoarchitectonically defined regions of Brodmann as shown in Figure 3.3 indicates that Broca's area appears to be located within Brodmann areas (BA) 44 and 45 of the inferior frontal gyrus (IFG). These areas constitute two of three subdivisions of the inferior frontal gyrus, namely pars opercularis (BA 44) at the most posterior portion and pars triangularis (BA 45) more anteriorly. The most anterior portion of the IFG is called pars orbitalis (BA 47).

It is undisputed that Broca's area is part of the inferior frontal gyrus (or, in a different nomenclature, of F3; Duvernoy, 1999). However, there is disagreement in the literature as to the question of whether Broca's area is restricted to BA 44 or whether it encompasses parts of BA 45. Broca (1865) described the posterior third of the IFG as language area and Brodmann (1909) noted that this area is equivalent to BA 44. However, the actual lesion of Broca's classical case involved much larger regions of the supply territory of the upper division of the middle cerebral artery, including the insula and the basal ganglia (e.g., Signoret et al., 1984).

Many recent neuroanatomical studies have defined Broca's area as including also posterior apects of BA 45 (e.g., Amunts et al., 1999; Foundas et al., 1998; Uylings et al., 1999). Interestingly, while Amunts and colleagues (1999) reported a left-lateralization in total volume only for pars opercularis but not for pars triangularis, Foundas et al. (1998) observed a left-lateralization corresponding with language dominance also for pars triangularis. On the basis of structural MR mapping of brain damaged patients exhibiting Broca's aphasia, H. Damasio (1998) defined Broca's area also as encompassing BA 44 and 45.

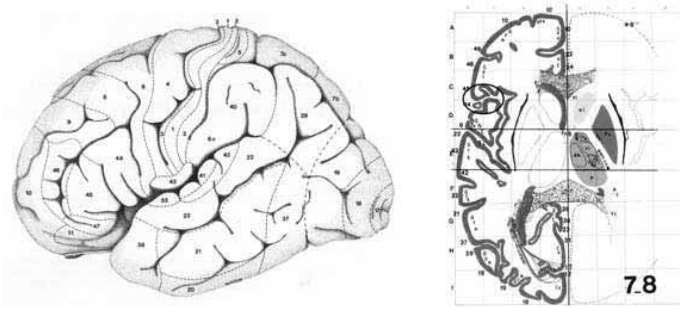

Figure 3.3: *Schematic drawings of the brain with Brodmann areas indicated. (Left) Lateral view (from Duvernoy, 1999). (Right) Axial section from the stereotaxic atlas of Talairach and Tournoux (1988) with the fronto-opercular region indicated by a circle.*

The term 'frontal operculum' is a more general expression which refers to the cortical tissue that encompasses the inferior frontal gyrus (especially BAs 44 and 45) and underlying cortex. This region is approximately marked in the axial section through the brain that is displayed in Figure 3.3. In this Figure, one can see that the cortical grey matter extends from the inferior frontal gyrus through the frontal operculum into the anterior insula.

Wernicke's area is part of the superior temporal gyrus (i.e., BA 22; cf. Figure 3.1). Areas 41 and 42 constitute the auditory cortex. These areas are located deep within the sylvian fissure on the surface of the temporal lobe. Two additional regions that are relevant for language functions are indicated in Figure 3.1, the supramarginal gyrus and the angular gyrus of the inferior parietal lobe. These areas correspond to BAs 40 and 39, respectively. Lesions of the supramarginal gyrus have been associated with conduction aphasia, a syndrome that is characterized by good comprehension, fluent speech but poor repetition (both with literal paraphasias). The angular gyrus has been found to be impaired when patients exhibit transcortical sensory aphasia. This aphasic syndrome is characterized by fluent spontaneous speech, poor comprehension but preserved repetition (e.g., Benson & Ardila, 1996).

3.3 Event-Related Brain Potentials and Sentence Processing

3.3.1 Electroencephalography and Event-Related Brain Potentials

A continuous electroencephalogram (EEG) is acquired by measuring the difference in potential between scalp electrodes, which pick up electrical activity of the cortex, and one or more reference electrodes which do not pick up brain activity. The reference(s) can be placed, for example, at the nose or at the mastoid bones behind the ears, or, as an alternative, can be calculated from the average of all scalp electrodes (e.g., Regan, 1989). Generally, the EEG is measured in a standard electrode montage (i.e., the 10-20 system; cf. Jasper, 1958; Sharbrough et al., 1991) or some extension of it that includes the original 10-20 electrode positions (see Figure 3.4 for the electrode configuration used in the present ERP studies).

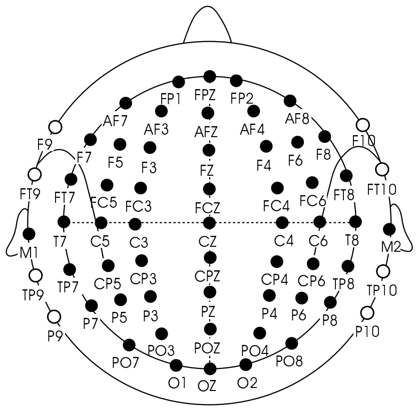

Figure 3.4: *Schematic drawing of an extended 10-20 system montage that displays the positions and labels of the electrodes. Electrodes not measured in the present studies are not filled. Mastoid reference electrodes are labelled M1 and M2. This figure was kindly provided by Andrea Gast-Sandmann.*

The EEG signal is amplified (and often also filtered) and then digitized by sampling the continuous signal at a high frequency (e.g., a sampling rate of 250 Hz, like it was used in the present experiments, yields one sample point every 4 ms). The digital signal is then stored for further off-line processing.

Perceptual or cognitive events can lead to potential changes in the EEG. However, these are much smaller in amplitude (i.e., often between around +5 and -5 μV) than the background activity of the brain which can have amplitudes in the range of several tens of μV (e.g., Coles & Rugg, 1995). For this reason, single events can hardly be identified in the spontaneous EEG. By considering the spontaneous EEG as acquired from one or more scalp electrodes, no inferences regarding brain responses to experimental manipulations can be made (at least not with common analysis methods). However, by averaging the EEG time-locked to the onset of repeated events of the same type, a characteristic pattern of voltage deflections can be extracted from the uncorrelated background noise. This waveform is known as the *event-related brain potential* (i.e., ERP). In psycholinguistic research on sentence processing, average ERPs are generally based on 30 to 40 trials (e.g., Hahne, 1998).

The neuronal events that underly the potential changes reflected in ERP waveforms are summed activations of large numbers of parallely arranged neurons firing in synchrony. In this kind of configuration, neuronal activity summates, when measured from a distance of a few centimeters, to produce a dipolar field (i.e., a field with a positive and a negative pole between which electrical current flows).

Such configurations are mainly found in the large pyramidal cells of cortical layer V (cf. Zschocke, 1995, see also Figure 3.5). The electric circuit of the dipolar current source is closed by currents that distribute through the different types of tissue in the head, passing also the skull and the scalp where they can be measured. What is reflected in the ERP is only a subset of the electrical processes that take place when neurons are active, namely postsynaptic dendritic potentials (Allison et al., 1986). Firing of action potentials and potential differences along the cell membranes have been claimed to cancel out because of asynchrony or their geometric arrangements (e.g., Lewine & Orrison, 1995). As Coles and Rugg (1995) point out, "there is undoubtedly much neural activity that is never apparent at the scalp" (p. 2).

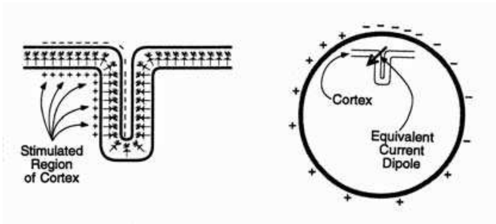

Figure 3.5: *Microscopic (left) and macroscopic (right) view of the dipolar nature of the current flow detectable by electroencephalography.*

The deflections of the ERP (see, for example, Figure 3.6 below) are defined by timing parameters (i.e., onset, peak latency, and duration) and by their polarity (i.e., positive or negative). The parameters that are most often used to name ERP components are the polarity and the peak latency (e.g., N170, P200, N400, P600). It has been discussed (e.g., Birbaumer et al., 1990) that negative deflections of the ERP might be caused by excitatory postsynaptic potentials while positive deflections might be elicited by inhibitory postsynaptic activity. Note, in this context, that throughout this work, negative potentials are plotted upwards and positivity is plotted downwards.

While early sensory components of the ERP (i.e., arising before about 80 ms) are referred to as *exogenous* components, late components elicited after 200 ms post stimulus onset are often referred to as *endogenous* components. This terminology is due to the fact that later components reflect processes that are dependent upon internally mediated determinants such as the general state of the participant, allocation of attention, task relevance of the stimuli, and so on (Coles & Rugg, 1995). Exogenous ERP components, in contrast, are driven by physical properties of the stimulus. Intermediate components of the event-related response (i.e., around 70 to 200 ms) are assumed to be responsive both to physical characteristics of the stimulus and cognitive events (e.g., Regan, 1989).

In addition to timing and polarity, ERP components are further characterized by their scalp topography (i.e., the distribution over the electrode positions) and by their sensitivity to experimental manipulations that elicit them (cf. Donchin et al., 1978; Coles & Rugg, 1995)[1]. In the following

[1]A further criterium can be the neuroanatomical localization of the generators of specific ERP components (Näätänen

sub-sections, a number of ERP components will be introduced that have been demonstrated to be reliably associated with certain aspects of language processing. This overview will not be exhaustive. ERP components that will become relevant for the experiments reported in this thesis will be treated in more detail than other components. Especially, ERP effects elicited in single-word paradigms will only be mentioned briefly (see, e.g., Osterhout & Holcomb, 1995; Osterhout et al., 1997; Friederici, 1999; Hagoort et al., 1999, for more detailed reviews). An introductory overview over ERP components outside the language domain was given, for example, by Coles and Rugg (1995).

3.3.2 ERP Components Related to Semantic Anomaly

The first ERP component that could be connected to language processing is the so-called *N400* which was first reported by Kutas and Hillyard (1980a,b,c). The N400 is a negative ERP component that starts at around 250 ms and peaks at about 400 ms (see Figure 3.6A). The N400 is distributed broadly over centro-parietal electrode sites. Although it is present bilaterally, some researchers claim that the N400 exhibits a slight lateralization to the right (e.g., Garnsey, 1993). It is elicited by semantically anomalous sentences as compared to semantically correct sentences. In sentences like [25] (taken from Kutas & Hillyard, 1980c) or [26] (Rösler et al., 1993), the N400 component was elicited when participants read the sentence final word. In these studies, sentences were presented in a word-by-word manner on a computer screen. The finding of an N400 in semantically anomalous sentences has been replicated many times (see, e.g., Kutas & Federmeier, 2000, for a recent review of the N400 literature). Kutas and Hillyard (1980a) also demonstrated that the N400 is not a reflection of a general effect of surprise due to a mismatch. Sentence final words that were semantically congruous but printed in upper case (i.e., words that deviated only in their physical appearance from the rest of the sentence) elicited a P300 component (see Coles & Rugg, 1995) but not an N400, suggesting that the N400 was indeed related to sentence processing.

[25] ♯He shaved off his mustache and ♯CITY.[2]

[26] ♯Der Honig wurde ♯ERMORDET.
(= ♯The honey was ♯murdered.)

However, the N400 is not a specific index only of semantic anomaly in sentences. An N400 is elicited by every single word in the sentence. It is also elicited by words presented in isolation. Furthermore, non-words demonstrate an increased N400 when compared to words (e.g., Bentin et al., 1985; Rugg & Nagy, 1987) and reliable variations in N400 amplitude have been observed in single

& Picton, 1987). However, the exact location of these neuronal sources is difficult to determine (and can often not be modelled by a single source). A detailed discussion of inverse modeling of neural sources from extracranially recorded electrophysiological signals has been given, for example, by Knösche (1997).

[2] Critical words at which ERPs were analyzed in the reported examples are printed in upper case.

word paradigms as a response to manipulations of, e.g., word frequency and word repetition (Rugg, 1990) or when words are primed (e.g., Anderson & Holcomb, 1995; Chwilla et al., 1995).

In the context of sentence processing, the N400 is interpreted as reflecting difficulty with integrating a new word into the current meaning representation of the sentence context (e.g., Kutas & Hillyard, 1980c; Osterhout et al., 1997). The higher the expectation built up by the previous sentence fragment (as determined using the cloze procedure; cf. Taylor, 1953), the greater the N400 if this expectation is violated (e.g., Holcomb & Neville, 1991). In a different sense, the N400 indexes the ease of processing when strong contextual constraints are active. When processing a sentence, the amplitude of the N400 elicited on every single word is inversely related with the position of the word within the sentence. This constraining effect on the N400 amplitude is not observed when sentence content makes no sense (Van Petten & Kutas, 1991). It has also been demonstrated that discourse level constraints have a similar effect on the N400 amplitude as sentence-level semantic constraints (van Berkum et al., 1999).

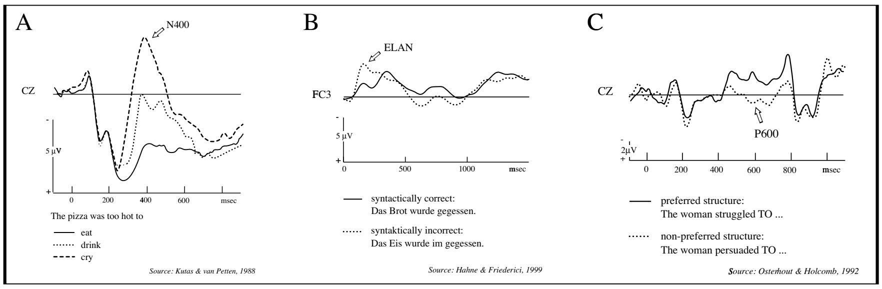

Figure 3.6: *Event-related brain potentials elicited by semantic anomaly (A), syntactic anomaly (B), and in ambiguous sentences at the element that disambiguates towards the non-preferred structures (C).*

3.3.3 ERP Components Related to Syntactic Anomaly

Encouraged by the finding of an ERP correlate of semantic processes, researchers have also investigated syntactic processes of sentence comprehension with ERPs. Applying the same violation logic as in the N400 studies, sentences were constructed that were semantically legal but contained grammatical errors. ERPs at the word at which the syntactic violation becomes evident are compared to ERPs elicited at the corresponding position in a grammatically well-formed sentence. The first ones to report an ERP experiment containing grammatical errors, again, were Kutas and Hillyard (1983) who investigated violations of agreement in number or tense between subject and verb. It was found that such agreement violations did not elicit an N400. However, a negativity in a slightly earlier time window (i.e., between 200 and 400 ms) was observed. Furthermore, a positivity with a parietal maximum appeared to be elicited by the next word. Many experiments later (e.g., Neville et al., 1991; Friederici et al., 1993; Hagoort et al., 1993; Rösler et al., 1993; Osterhout & Mobley, 1995; Friederici et al., 1996; Hahne & Friederici, 1999, to cite just a few studies) we know that most grammatical violations elicit a negativity which is maximal over left anterior electrode sites followed by a late parietal positivity.

Dependent upon the nature of the violation, the negativity sometimes appears earlier (i.e., early left anterior negativity or ELAN) or somewhat later (i.e., left anterior negativity or LAN). The *LAN*, which is generally observed between 300 and 500 ms after the onset of the critical word, is elicited for example by agreement violations. In sentence [27a] (from Osterhout & Mobley, 1995), the verb and the subject fail to agree in number. In [27b] (cf. Gunter et al., 2000), determiner and noun of the object NP do not agree in their gender.

[27] a. *The elected officials *HOPES to succeed.

[27] b. *Sie bereist den *LAND auf einem kräftigen Kamel.
*(= *She travels the$_{masc}$ *land$_{neuter}$ on a strong camel.)*

The *ELAN*, which appears between 120 and 200 ms, is elicited when phrase structure rules are violated. It has been observed repeatedly in cases where the category of a word can not be integrated into the present phrase structure. For example, Neville and colleagues (1991) observed an early left-anterior negativity peaking at 125 ms when a preposition was observed where a noun was expected (e.g., '*... Ted's ABOUT films America'). Friederici, Hahne and colleagues (1993) observed an early left anterior negativity peaking at about 180 ms after the onset of the critical word when a preposition that subcategorizes for a noun was followed by a verb (e.g., [28a] as compared to [28b]; cf. also Friderici, Hahne & Mecklinger, 1996, and Figure 3.6B).

[28] a *Der Freund wurde im *BESUCHT.
*the friend was (in the) *visited

[28] b Der Freund wurde BELOHNT.
the friend was rewarded

The ELAN was demonstrated to reflect an automatic process that could not be influenced by attentional factors (Hahne & Friederici, 1999). However, it was shown to vary with the perceptual quality of the physical input (Gunter et al., 1999a). The short latency of the ELAN component strongly supports the notion that initial first-pass parsing processes in phrase structure building are based solely on word category information (see Frazier, 1987a; Friederici, 1995). The fact that the appearance of the ELAN is neither influenced by probability manipulations (cf. Hahne & Friederici, 1999) nor by additional (e.g., semantic; Friederici, Steinhauer & Frisch, 1999) violations supports the assumption that initial syntactic processes are informationally encapsulated or modular (as suggested by Fodor, 1983; Frazier, 1990).

The early negativities elicited by syntactic violations are followed by a late positivity that was termed *P600* (because it generally peaks at about 600 ms) or *Syntactic Positive Shift* (i.e., SPS). While the anterior negativities appear to reflect the detection of violations, the P600 has been associated with processes of reanalysis and repair (e.g., Osterhout et al., 1997; Friederici, 1998).

P600 effects are also observable in violations of preferences in phrase structure building. In so called garden-path sentences, which are characterized by a temporary ambiguity with regard to the correct structural analysis of the sentences, later disambiguation to an unpreferred interpretation requires a revision of the initial analysis (Mitchell, 1994). In such sentences, late positivities are elicited by the disambiguating constituent. For example in sentence [29a], the ambiguous relative pronoun 'die' is initially interpreted as the subject of the relative clause. However, the clause-final auxiliary 'haben' indicates that the plural noun phrase following the relative pronoun is the actual subject of the sentence. The auxiliary 'hat' in [29b], in contrast, disambiguates the sentence to the preferred subject reading. The revision of the initial analysis in [29a] into an unpreferred object-initial structure elicited a centro-parietally distributed positivity with a peak at 345 ms (Mecklinger et al., 1995).

[29] a. Das ist die Professorin, die die Studentinnen gesehen HABEN.
this is the professor who$_{fem,S/P}$ the students$_{fem,P}$ seen have$_P$

[29] b. Das ist die Professorin, die die Studentinnen gesehen HAT.
this is the professor who$_{fem,S/P}$ the students$_{fem,P}$ seen has$_S$

[30] The broker persuaded TO sell the stock was sent to jail.

Osterhout and Holcomb (1992) observed a P600 between 500 and 800 ms at the word 'to' in garden path sentences like [30] (cf, also Figure 3.6C). At this position, it becomes clear that persuaded is not the verb of the main clause but part of a reduced relative clause (i.e., '... who was persuaded to ...'). Differences in latency and amplitude of P600 effects between studies have been attributed to differences in the difficulty of the reanalysis processes triggered by different garden-path sentences (e.g., Osterhout et al., 1994; Friederici & Mecklinger, 1996).

3.3.4 Modulation of ERP Components by Working Memory Load and Working Memory Capacity

Given the predominant assumption that parsing processes are dependent upon working memory resources (cf. Chapters 1 and 2), it has been investigated whether or not ERP effects elicited by sentence anomaly or by violations of syntactic preferences are influenced by the amount of memory resources available. Using an individual differences approach, Friederici and colleagues (1998) investigated the effects of individual working memory capacity (as measured by the reading span task; Daneman &

Carpenter, 1980) on the processing of the temporarily ambiguous relative clause sentences displayed in [29]. As expected from the results reported by Mecklinger et al. (1995), individuals with high working memory capacity (i.e., reading span between 4 and 6) exhibited a late positivity at the auxiliary where sentences were disambiguated towards the dispreferred interpretation. However, low-span participants (which had a reading span between 2.5 and 3.5) did not show this effect. This finding was taken to suggest that low span readers do not initiate processes of reanalysis. Because this group performed clearly above chance, which suggested that these individuals were able to parse the sentences correctly, it was concluded that these subjects probably maintained both possible interpretations of the ambiguous sentences in working memory. A reanalysis in the sense of structurally organizing the input in a different way, then, was not necessary because the dispreferred analysis was also available. According to this interpretation, the reading span task would bne assumed to index differences in the strategies with which working memory resources are used rather than absolute differences in capacity.

In the same study, it was demonstrated that a P600 was elicited at the relative pronoun if it was case-marked for accusative. In this case, the relative pronoun immediately indicated that the object of the relative clause was fronted. This object-initiality effect was taken to reflect a violation of structural preference or, differently phrased, the processing cost elicited by the necessity to build up a more complex phrase structure. This effect, however, was present in both groups.

In addition to individual differences, Vos and colleagues (Vos, Gunter, Schriefers & Friederici, 2001b) investigated the effects of an additional external working memory load on the resolution of the temporary ambiguity in sentences like [29a,b]. Under conditions of concurrent working memory load, the disambiguating auxiliary elicited a positivity in object relatives for both low and high capacity readers (Vos et al., 2001b). High span readers exhibited an early positivity which was independent of load. For individuals with a low working memory capacity, on the other hand, a late frontal positivity was found that was delayed when concurrent working memory load was high. In both groups, a broadly distributed negative ERP component was observed on the critical word for high working memory load (i.e., three words in memory) as opposed to the low-load condition (i.e., one word).

In an other study, the processing of sentences with morpho-syntactic violations was investigated under concurrent working memory load (Vos, Gunter, Kolk & Mulder, 2001a). It was demonstrated that the amplitude of an anterior negativity, elicited by a syntactic violation of subject-verb agreement, was modulated by syntactic complexity, concurrent load, and individual working memory capacity. The anterior negativity was present only in high span readers, it was only seen in complex embedded sentences under low additional load and in easier sentences (i.e., conjoined structures) under high concurrent load. It was not present, however, in the high-complexity high-load condition. The authors argued that these data speak in favor of a single-resource model as proposed, for example, in the context of the Capacity Theory of Comprehension (Just & Carpenter, 1992).

A different kind of individual differences approach can be realized by investigating age-related differences in language processing. Gunter and co-workers (Gunter, Vos & Friederici, 1999b) reported a number of ERP studies on language processing in elderly individuals. Most importantly, they concluded that when sentence comprehension can proceed normally, there are no ERP differences observable between young and elderly individuals. Furthermore, they demonstrated that first-pass parsing processes, as reflected in the ELAN component elicited by phrase structure violations, were not affected by age. However, the N400 to semantic violations and the P600 to syntactic violations were delayed and stronger in elderly participants as compared to younger individuals. The authors pointed out that working memory capacity, which is often reduced in elderly individuals (e.g., Light & Burke, 1988; Norman et al., 1991), might play a key role in these age-related effects. For example, Gunter, Jackson and Mulder (1995) investigated N400 effects in sentences imposing a high or low working memory load, induced by the disruption of the main clause by a subordinate clause. The final word of the main clause was either congruent or incongruent. The N400 elicited by an incongruent word was much smaller (and disappeared in high load sentences) for older participants (i.e., between 50 and 66 years) than for younger adults (i.e., 19 to 23 years). Sentence-level working memory processes, thus, were demonstrated to be influenced by an age-related reduction of working memory capacity. This conclusion was strenghtened by a reanalysis of the data according to individual working memory capacity. In this analysis, young individuals with low working memory capacity also showed a decreased congruency effect in the N400.

To sum up, a number of studies provided evidence for a modulation of ERP effects related to language by working memory manipulations. Factors that constrain the amount of working memory capacity available, such as individual working memory capacity, age, concurrent working memory load or syntactic complexity, differentially influence sentence processing at specific levels of representation. Early first-pass parsing processes appear to be independent of working memory resources. On the other hand, later aspects of syntactic processing, as reflected in the LAN and the P600 component, and semantic processes appear to be constrained by the amount of memory resources available.

3.3.5 ERP Components Related to Syntactic Complexity

Most ERP effects described so far were elicited by anomalous linguistic input. In recent years, ERPs have also been employed to investigate processing mechanisms in well-formed sentences that vary in processing difficulty. One such example, the elicitation of a P345/P600 in garden-path sentences, has been introduced in the description of the late positivity (see Section 3.3.3). As already noted, this effect has been associated with processes of syntactic reanalysis and restructuring. The amplitude of the late positivity is generally assumed to reflect the difficulty of reanalysis.

A more general function in phrase structure building has been ascribed to the processes reflected in the P600 by Kaan and colleagues (2000) who observed a P600 effect in grammatically well-formed, non-garden path sentences. In a visual word-by-word reading paradigm, participants read sentences such as [31a-c]. At the verb of the embedded wh-question (i.e., 'imitated'), a positivity between 500 and 900 ms was observed over central and posterior electrode sites. The amplitude of this P600 effect was greatest in the 'which-N' condition ([31b]), intermediate in the 'who' condition ([31a]) and smallest in 'whether'-questions. No other effects were reported for these sentences.

[31] a. Emily wondered who the performer in the concert had IMITATED for the audience's amusement.

[31] b. Emily wondered which pop star the performer in the concert had IMITATED for the audience's amusement.

[31] c. Emily wondered whether the performer in the concert had IMITATED a pop star for the audience's amusement.

The late positivity observed by Kaan and colleagues (2000) was interpreted as indexing the difficulty of integration processes or the amount of resources that have to be spent for integration. The authors argued that in wh-questions like [31a,b], both the moved object NP (i.e., 'who' or 'which pop star') and the subject NP ('the performer') have already been processed and have to be integrated with the verb. This is more difficult than the integration processes elicited by the verb in a whether-question because in whether-questions, there is only a subject NP to be integrated with the verb. The difference in the amplitude (and also in the topographical distribution) of the positivity between who- and which-questions has been explained by referring to a theoretically postulated difference between those two structures (e.g., Pesetsky, 1987; Cinque, 1992). Kaan and colleagues stated that when presented in isolation, "... 'which-N' questions trigger the inferencing of a set of entities in the discourse, whereas 'who' questions do not. " (2000, p. 173). Due to the greater number of discourse operations in which-questions, processing resources were assumed to be more taxed at the sentence position displaying the amplitude difference in the P600, resulting in an increased positivity.

The concepts of integration and integration difficulty used here are based on the Syntactic Prediction Locality Theory (Gibson, 1998) which was introduced in Chapter 2. Under the account proposed by Kaan and collaborators (2000), the P600 is taken to reflect a parsing process that is more general than syntactic reanalysis. It is important to note that with respect to SPLT, these data appear to suggest that only the integration cost component (see [20]) elicits processing costs detectable in ERPs. There are no effects that are reported here which would support the assumption that structural memory costs (see [21]) are also reflected in brain responses. More specifically, it appears that this amplitude difference is reflecting differences in the complexity or difficulty of integration processes between the two structures (cf. [20,(1)]). The second aspect of SPLT's integration cost component, which is assumed to be distance-based (see [20,(2)]), is not supported by the Kaan et al. (2000) results.

However, Kaan et al.'s (2000) finding of a P600 at the verb might also be due to the fact that prediction of the object gap position, which is located after the verb, is licensed by the processing of the verb. Under this assumption, the positivity would reflect the establishment of a link between the moved object and its canonical position in the phrase structure. Such an interpretation is suggested, e.g., by behavioral data from verb-final languages. In German, processing effects attributed to gap identification have been observed before the verb was encountered, namely at an NP preceding the assumed gap site (e.g., Muckel & Pechmann, 2000). An account of parsing that allows the predictive licensing of trace positions has been proposed, for example, by Crocker (1994). As ERP data relevant for this question are only available for English, it can apparently not be determined whether the processing cost reflected in the late positivity is elicited by the verb or by the structural gap position that can be posited after the verb in a predictive way.

Several other groups of researchers have investigated the processing of derived structures similar to those investigated by Kaan and colleagues (2000). Although most of the studies also involved ungrammatical sentence conditions, they allow conclusions regarding the ERP correlates of processing costs in grammatically correct sentences with non-canonical argument order. For example, Kluender and Kutas (1993a,b) investigated the processing of wh-questions, as compared to yes/no-questions. These authors assumed that when a wh-filler is processed, it has to be stored in working memory until it can be linked with its gap. The first study (Kluender & Kutas, 1993a) was designed to identify brain responses associated with the storage of a filler in working memory and with the assignment of the filler to its gap position. It was found that a left anterior negativity between 300 and 500 ms was observable at the word directly following the filler. The LAN was seen for object-initial questions containing a matrix wh-filler (i.e., 'Who have YOU ...') as compared to yes/no-questions (i.e., 'Have YOU ...') or, in the case of embedded questions, for object wh-fillers relative to that- and if-questions (cf. [32]). No LAN was observed for subject wh-questions. Interestingly, only ERPs at positions following the filler were reported but no ERPs elicited by the filler itself.

In the second study (i.e., Kluender & Kutas, 1993b), ERPs elicited by the subordinating question words were also reported. It turned out that 'who', as compared to 'if' and 'that' (in a sentence like 'Do you think THAT/IF/WHO ...') elicited an N400-like effect which was maximal over right posterior electrode sites. A corresponding effect was reported by McKinnon and Osterhout (1996). As the sentences in which this N400 effect was elicited were grammatical and semantically interpretable, this N400 was attributed to the fact that 'who' is potentially referential in nature while this is not the case for 'that' and 'if'. Kluender and Kutas (1993b) also observed LAN effects in wh-questions at the word following the wh-filler. In both studies, LAN effects were attributed to the memory load associated with storing the dislocated object in working memory.

[32] a. What$_a$ did he suppose that HE could coerce her INTO $\_\_\__a$ this time?
(wh-that)

[32] b. ?What$_a$ did he suppose if HE could coerce her INTO $\_\_\__a$ this time?
(wh-if)

[32] c. *What$_a$ did he wonder who$_b$ HE could coerce $\_\_\__b$ INTO $\_\_\__a$ this time?
(wh-wh, object)

LAN effects were also observed at positions directly following a postulated gap in object wh-questions. This second LAN effect was interpreted as reflecting the retrieval of the direct object filler from working memory. Left anterior negativities, which were previously exclusively associated with syntactic anomaly detection, thus were assumed to unspecifically index parsing operations that involve working memory processes. However, given the extremely complex sentence material that was used in these studies (see, e.g., [32a-c] from Kluender & Kutas, 1993a, with the critical positions printed in upper case), one is tempted to conclude that the participants might have had problems in parsing the sentences[3]. This interpretation receives some support from the fact that unlike in the Kaan et al. (2000) study, no ERP effects were reported for verbs in embedded sentences in which the verb directly preceded an object gap. An alternative account for the differences between the findings reported by Kluender and Kutas (1993a,b) on the one hand and Kaan et al. (2000) on the other, would be to follow the interpretation that the local LAN effects reflect working memory processes. As suggested in the context of AFH (e.g., Frazier, 1987a), the dislocated filler is maintained in working memory actively. Thus, in sentences like those investigated by Kaan et al., no information has to be retrieved from memory because it is already available. However, due to the complexity of the sentences used by Kluender and Kutas (1993a), the participants did not succeed in maintaining the dislocated element in working memory. When encountering the gap, they might have had to actively retrieve the information associated with the filler, thus eliciting a local difference in the ERPs at this position.

ERPs elicited during processing subject- and object-initial relative clauses like [33a,b] were investigated by King and Kutas (1995). ERPs elicited at individual word positions in this study mainly reflect differences in word category at the different positions of the sentences (due to the fact that in English, subject-initial and object-initial clauses do not have the same constituent order; cf. Münte et al., 1997)[4].

[33] a. The reporter$_i$ who$_i$ $\_\_{i}$ harshly attacked the senator admitted the error.
(subject)

[33] b. The reporter$_i$ who$_i$ THE SENATOR harshly attacked $\_\_{i}$ admitted the error.
(object)

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[3]This assumption can not be tested against the behavioral performance because no performance data were reported for the probe detection task carried out in these experiments. However, it might be of interest that in a pre-test for the ERP study in Kluender and Kutas (1993b), acceptability judgments for wh-questions were in a range of between around 15 and 55.

[4]When considering this study, as well as the behavioral on-line studies conducted in English that were reported in previous chapters, it becomes obvious that such on-line studies are faced with a potential problem in English due to the SVO nature of this language. In direct comparisons of subject- and object-initial sentences at each position of the sentence, different categories of words have to be compared. This problem, which is not present in German, is a potential confound in on-line studies. Accordingly, effects reported in studies subject to this confound have to be interpreted in light of the fact that these effects might be boosted by word category effects.

In addition to such local ERP effects, King and Kutas (1995) also reported multi-word ERPs which span extended regions of the sentences. A sustained frontal negativity for object as compared to subject relatives was observable bilaterally over the early relative clause region (i.e., at the words printed in upper case in [33b]; see also H. M. Müller et al., 1997, for supportive evidence from an auditory experiment). This region spans the adverb and the verb in subject relatives while it covers the second NP, which constitutes the relative clause subject, in object relatives. King and Kutas (1995) suggested that the sustained negativity observed here was due to maintenance of the second NP in working memory until the verb was encountered. This, however, is rather unlikely as there is no obvious reason why integration of the subject NP into the phrase structure should be delayed. More likely, this negativity might reflect the maintenance of the object filler in memory as proposed in the context of the Active Filler Hypothesis (Frazier, 1987a, see also Section 1.4) or, according to SPLT, the maintenance of a syntactic prediction which is more complex in object than in subject relatives.

No comparable sustained negativity was reported in the studies of Kluender and Kutas (1993a,b). This, however, might be due to the fact that multi-word ERPs were not analyzed by these authors. The presence of a negativity at the word following the wh-filler might indicate that a more sustained effect was present over the embedded question. Some of the figures displayed in these studies (e.g., Figures 1 and 3 in Kluender & Kutas, 1993a) suggest that indeed the negativity might continue over a longer time range as the waveforms in the object wh-condition did not return to the level of the control conditions at the end of the displayed time range.

Kaan and colleagues (2000), as well as McKinnon and Osterhout (1996), calculated multi-word ERPs in order to compare questions with wh-movement to questions without wh-movement. Both analyses spanned the region between the moved constituent and its gap position. When compared to whether-questions, in both studies there was no sustained negativity (and also no local LAN) found for wh-questions. This result is comparable to the reading time data reported by Schlesewsky, Fanselow & Kliegl (manuscript, cf. Table 2). These authors reported that reading times for two adverbials following the question word in whether-questions were longer than reading times in subject wh-questions but faster than those measured in object wh-questions (cf. [17]). Analogously, multi-word ERPs to subject- and object-initial clauses differed reliably (King & Kutas, 1995) but multi-word ERPs to whether and wh-questions (McKinnon & Osterhout, 1996; Kaan et al., 2000) did not.

By investigating multi-word potentials to wh-questions in English and German, Kluender and colleagues (1998) observed a frontally distributed slow negativity for object-first questions as compared to subject-first questions (e.g., [34]). In line with the interpretation given by King and Kutas (1995) for their findings in relative clause sentences, this sustained negativity was taken to reflect an increased load on working memory. It differed in topography from a local LAN effect which was elicited in the same experiment by a syntactic violation. While the local LAN effect was clearly left-lateralized, the slow negativity was more broadly distributed over frontal electrode sites.

[34] a. Who$_i$ did he realize [$\_\_i$ should accustom them to the procedure before the experiment]? *(subject)*

[34] b. Who$_i$ did he realize [that he should accustom $\_\_i$ to the procedure before the experiment]? *(object)*

A somewhat different approach to investigating integration difficulty in sentences containing dislocated constituents was taken by Rösler and colleagues (1998). These authors observed that scrambling full object NPs before the verb within the German 'Mittelfeld' (like in [35b] and [35c]) also elicited a left anterior negativity as compared to declarative sentences presented in their canonical ordering (i.e., [35a]). The LAN effect was found on the determiner of the scrambled NP. It was followed by a posteriorly distributed positivity on the corresponding noun.

[35] a. Dann hat DER Vater dem Sohn den Schnuller gegeben. *(S-IO-DO)*
then has the$_{NOM}$ father to the son the pacifier given

[35] b. Dann hat DEM Sohn der Vater den Schnuller gegeben. *(IO-S-DO)*
then has to the$_{DAT}$ son the father the pacifier given

[35] c. Dann hat DEN Schnuller der Vater dem Sohn gegeben. *(DO-IO-S)*
then has the$_{ACC}$ pacifier the father to the son given

In general, the operation of scrambling in German does not render sentences ungrammatical. Rösler et al. (1998) argued that although the functional roles are indicated overtly by the determiners, scrambled object arguments cannot be assigned their functional role immediately. Rather, role assignment has to be postponed and the NP has to be stored in working memory. However, the authors realized the unclear relation between the transient LAN and the sustained working memory load assumed. Indeed, the LAN was observed between 300 and 450 ms after the onset of the determiner, a point in time at which the noun to be stored was not available yet. Rösler et al. (1998) concluded that the LAN effect, instead of reflecting storage processes, is a "manifestation of some preparatory processing step which enables storage of the forthcoming noun" (p. 171). An alternative interpretation of the LAN in scrambling has been given by Friederici, Schlesewsky, and colleagues (Friederici et al., in press, see also Schlesewsky, Friederici & Frisch, manuscript). These authors suggested that the LAN in this context might be an indication of the detection of a local syntactic anomaly as sentences with fronted full object NPs in German are not grammatically licensed (at least when encountered out of context).

Taken together, the previously discussed data suggest that processing difficulty induced by grammatical movement operations is reflected in ERPs. However, the data available and the interpretations arrived upon, at present, are very heterogenuous. While the indication that the late positivity might be associated with difficulty of integration can in principle be accomodated with the function that is classically attributed to this component (i.e., reanalysis processes), the relationship of transient LAN effects and working memory processes like storage and retrieval is not so clear. The interpretation of sustained negativities as indicating processes of syntactic working memory, on the other hand, appears to be plausible. In the next subsection, a short overview of slow potentials associated with working memory processes will be given.

3.3.6 ERP Effects Related to Working Memory and Language

In the previous subsection, ERP studies have been introduced that investigated slow potential shifts elicited while processing a sentence. Some studies (i.e., King & Kutas, 1995; H. M. Müller et al., 1997; Münte et al., 1997; Kluender et al., 1998) reported ERP effects that extended over more than one word within the critical sentences. In the cases cited above, these effects were sustained negativities with frontal or left-frontal distribution. Due to the temporal extension of these effects, they have generally been associated with increased load in working memory. Similar results in sentence-level ERPs have been reported by Münte, Schiltz and Kutas (1998) for sentences that had an increased semantic load because the temporal order of events expressed did not mirror the sequential order in which they were perceived. The authors implied that in such sentences, the first part of the sentence had to be maintained in working memory until it could be integrated in the correct temporal order. Vos and co-workers (Vos et al., 2001a) demonstrated an anterior negativity when participants maintained a high additional load in working memory (i.e., three words) as compared to a low working memory load (i.e., one word). In this experiment, the words to be maintained in memory during sentence processing were presented before the onset of the sentences. The load-related negativity was present from the beginning of the sentence and increased across the sentence.

The reason for interpreting slow potential shifts over sentences as reflecting working memory processes is two-fold. First, it is very suggestive that such long-lasting effects reflect maintenance of information in working memory because this process, by definition, is extended in time. Second, similar effects have been observed in ERP studies especially designed to examine working memory mechanisms. For example, Ruchkin and colleagues (1990) investigated short-term storage of verbal material (i.e., letters) in working memory over a duration of 2500 ms. A transient positivity (P3b) between 500 and 750 ms after the onset of the memory set increased in amplitude with the number of items to be encoded (i.e., one, three, or six letters) both in a memory and in a visual search task. In addition, a long-duration negativity appearing within the delay interval, which was strongest over the left-anterior scalp (i.e., electrode F3), increased in amplitude with increasing memory load. Over posterior electrodes, a positivity was observed that also increased with load.

A relation between frontal negativities and verbal working memory load has been found in several other studies. For example, a sustained negativity was reported by the same authors from an experiment involving the maintenance of words and pseudowords (Ruchkin et al., 1999). The left-lateralized negativity has been associated with verbal rehearsal mechanisms (Ruchkin et al., 1997), an interpretation that appears to be consistent with the findings of brain activation in left inferior-frontal brain areas during articulatory rehearsal (e.g., Paulesu et al., 1993; Smith et al., 1996).

However, it should be noted that frontal negative slow waves modulated by working memory load have also been observed in non-verbal working memory tasks (e.g., Mecklinger & Pfeifer, 1996; Löw et al., 1999). The frontal negativity has been found to be left-lateralized independent of the content to be maintained in working memory (Bosch, 1998). This finding might be taken to suggest that this brain wave reflects a modality-unspecific process involved in the maintenance of information.

3.3.7 Concluding Remarks: ERPs and Language Processing

The reviewed studies (and several more that could not be considered here) suggest that ERPs are a tool that is very well suited for studying the processes of sentence comprehension as they unfold in time. Early work has identified components that are related to the detection of semantic and syntactic anomalies, giving much insight regarding when and how different types of information become available during the course of sentence processing.

More recent work has also followed the line of behavioral research in psycholinguistics that is concerned with the mechanisms of processing syntactic complexity. In this venture, studies have been designed that investigated the processing of grammatically well-formed and unambiguous sentences. Psycholinguistic models of parsing allow to make predictions regarding the positions in sentences where effects of processing difficulty should be observed. The multi-dimensional nature of the ERP component as dependent variable (i.e., polarity, latency, and distribution) and the high temporal resolution allow to associate the processing costs observable at certain positions in sentences with specific cognitive processes more reliably than is possible using purely behavioral measures. The data available so far support the assumption that both syntactic integration processes and working memory processes contribute to the processing difficulty observed in object-initial sentence constructions. This conclusion suggests a psycholinguistic model of syntactic complexity along the lines of theories like the (Gibson, 1998, see Section 2.3.3).

3.4 Neuroimaging Investigations of Sentence Processing

In this section, two methods used in neuroimaging studies of cognition (i.e., PET and fMRI) will be introduced. Furthermore, important results regarding the brain bases of sentence processing that were obtained with these methods will be reviewed. The description of the PET and fMRI methodologies will give the reader only a superficial introduction to these techniques. At the beginning of the sections, the reader will be referred to literature that gives a more detailed introduction.

3.4.1 Positron Emission Tomography (PET)

The description of the PET technology is based mainly on chapters in the textbooks of Schmidt and Thews (1995), Orrison and colleagues (1995), and Toga and Mazziotta (2000). If there is increased neuronal activity in a region of the brain, the consumption of oxygen in this region increases due to increased metabolism. To satisfy the increased need of oxygen, arterioles are enlarged which leads to an increase in the local influx of blood (e.g., Schmidt & Thews, 1995). The PET technique measures regional cerebral blood flow (rCBF) by injecting weak radioactive contrast agents (such as $H_2^{15}O$) which attach, e.g., to oxygen or glucose transported in the blood. When the positrons that are set free by these radioisotopes collide with electrons, two photons are emitted in exactly opposite directions. These can be detected by photodetectors arranged around the head in the PET scanner. The PET scanner counts an event if two photons are deteceted at opposite detector positions at the same time.

By using other radiopharmaceuticals, other metabolic processes such as glucose utilization can be measured. The markers have a relatively short half-life (e.g., 123 seconds for $H_2^{15}O$; cf. Raichle, 2000). After the radioactive marker has been injected, some time has to pass before the labeled compound has distributed sufficiently. Then an experimental run starts during which the participant performs the cognitive task and the scanner measures the distribution of the radioactive decay. Using short-lived tracers such as $H_2^{15}O$, functional measurements can be repeated up to 10 or more times with intervening intervals of 10 to 15 minutes.

The distribution of the radioisotopes within the brain can be inferred on the basis of the density of the detected signal in different regions. Activation is especially high in regions that are consistently activated throughout an experimental run. In order to associate the identified regions of increased activity with individual neuroanatomy, functional data are often overlayed with high-resolution anatomical images (e.g., MR images).

Apart from being invasive, the PET technique has some more drawbacks. The temporal resolution lies in the order of minutes. It is worsened by the fact that different experimental conditions have to be presented in a block-wise manner. This is so because the photon counts measured by the PET scanner are acquired over several minutes and can not be resolved in time. Blocked designs, however, are very uncommon in behavioral or ERP experiments of cognitive processes. The serious disadvantage that is introduced by blocked designs is that strategic effects, for example habituation to a task due to repetition, can not be excluded. Thus, the temporal course of the neural response to a single event can not be characterised. Another limitation is the relatively low intrinisic spatial resolution of around 5 or more mm. Furthermore, PET does not provide a direct measure of neural activity in the brain but only an indirect measure based on subsequent blood flow increase.

When working with blocked designs, the neuroanatomical correlates of specific cognitive processes are identified by subtraction of rCBF images (as was, for example, demonstrated in the pioneering studies of Petersen and colleagues, 1988, 1989). Ideally, the two experimental conditions have to be designed in a way that they differ in just the one process of interest (but see, for a critique of the pure insertion hypothesis, e.g., Friston et al., 1996).

3.4.2 Functional Magnetic Resonance Imgaging (fMRI)

The present description of the fMRI method is based on a book by Brown and Semelka (1999), as well as on chapters in the textbooks by Orrison and colleagues (1995), Moonen and Bandettini (2000) and Toga and Mazziotta (2000). Within the MR scanner, the individual is situated in a steady magnetic field of (in general) between one and four Tesla strength. This field changes the orientation of protons in the blood from random (resulting in a net magnetization of zero) into an ordered state (i.e., parallel and anti-parallel to the external magnetic field), thereby producing a net longitudinal magnetization. Due to the spin energy of the protons, they precess around the longitudinal vector of this magnetic field.

Short-lasting high frequency radio pulses (i.e., rf pulses) are induced which change this equilibrium temporarily. As a model, this process can be described as follows. The orientation of the protons is changed, often by an angle of 90°, resulting in a change in the direction of the net magnetization perpendicular to the longitudinal field. Precession of the net magnetization within the transverse plane induces a voltage in a receiver coil placed around the head of the individual in the scanner. When the rf pulse is turned off, the protons start to realign themselves and return into the original equilibrium. This process is characterized by two parameters. The relaxation along the longitudinal axis (i.e., relaxation time T1) specifies the time during which the voltage induced in the receiver coil decays as more of the protons give up their absorbed energy. The relaxation along the transverse axis (i.e., T2) describes the dephasing in the transverse plain, due to an exchange of energy between the protons. This relaxation time is faster than T1. Relaxation times are a function of the local environment (i.e., the tissue) in which a specific proton is located. Segregation of different tissue types in anatomical MR imaging can be achieved on the basis of relaxation times T1 and T2.

Related to the relaxation time parameters are the repetition time (TR), with which the interval between the application of two rf pulses is characterized, and the echo time (TE) which determines the delay between the application of the rf pulse and the measurement of the MR signal. The setting of these two timing parameters can influence the weighting of the two relaxation time parameters and thus influence the signal strength of different tissues.

An important principle of MR imaging is the coding of locations along the axes in three-dimensional space. Within a measured slice, this is achieved by introducing gradients (i.e., linear changes in the field) into the steady magnetic field. In the readout process, the location of a given voxel (i.e., volume element) is then coded by frequency. As the gradient introduces a known field difference between the different positions, the resulting frequency differences in the signal can be used to identify the measured positions. The composite MR signal has to be decomposed in frequency using Fourier analysis in order to obtain the original signal from a given location. In a similar fashion, a short duration gradient pulse along a perpendicular axis induces a spacially dependent phase change, which can then be used to produce a 2D image. The third dimension can be introduced by sequentially measuring several slices from different locations along this axis. In order to assure that an rf pulse excites only protons within a given slice, another gradient is introduced and frequency-selective rf pulses are applied. Depending on several parameters, the spatial resolution of a three-dimensional anatomical MR image can be in the order of one millimeter or less.

A further issue is the choice of specific pulse sequences, i.e., the hardware instructions of when or how to turn on which gradient or pulse and when to read out the signal (cf. Sanders, 1995; Brown & Semelka, 1999). There is a wide variety of different pulse sequences available (e.g., Spin Echo, Gradient Echo, Echo Planar Imaging, etc.). The selected sequence determines the image contrast, which then depends, among other factors, on tissue type and local field properties.

In addition to anatomical imaging, the MR technique can also be used to measure brain activation induced by experimental manipulation (i.e., functional MRI; cf. Sanders & Orrison, 1995; Moonen & Bandettini, 2000; Raichle, 2000). In contrast to PET, functional MR imaging can be performed without the use of contrast agents. The local magnetic properties of blood hemoglobin serve that function in fMRI. While oxygenated hemoglobin (which is delivered in large amounts when metabolism increases in stimulated tissue) has only a small magnetic moment, deoxygenated hemoglobin (which is reduced in concentration in activated areas) is paramagnetic. That is, deoxygenated hemoglobin, which has iron in the molecule, behaves like a small magnet. Such changes in magnetic susceptibility influence the homogenity of the magnetic field in localized regions of the brain and thereby the strength of the MR signal. This effect is generally referred to as BOLD effect (i.e., blood oxygenation level dependent effect; cf. Ogawa et al., 1990).

Despite having a better temporal resolution than PET, the fMRI technique still has a relatively low temporal resolution. The hemodynamic response to a short event is delayed by one or two seconds and reaches its maximum between four and six seconds after the onset of the event (see Figure 3.2 for a comparison of the spatial and temporal resolution of the different techniques). However, the spatial resolution of fMRI is superior to PET, going down to less than five millimeters (see Menon & Kim, 1999, for the spatial and temporal limits of this technique).

Probably the most important advantage of fMRI in comparison to PET is the possibility of employing single-trial or event-related designs (e.g., Buckner, 1998). Using this approach, events of different types (i.e., of different experimental conditions) can be presented in random order and then, for analysis, be averaged in a condition-specific way. The departure from blocked paradigms also enables to model the hemodynamic response evoked by the different types of events. A further improvement in performing cognitive experiments using fMRI has been achieved by demonstrating that (due to linear summation of the hemodynamic response) events can follow each other separated only by relatively short inter-trial intervals (e.g., Pollmann et al., 1998; Miezin et al., 2000).

3.4.3 Analysis of Neuroimaging Data

The analysis of data acquired in neuroimaging experiments includes a number of preprocessing steps which are followed by the actual statistical analysis using the general linear model. By and large, the different processing steps are the same in both imaging modalities. The steps of analysis described here are also applied in the analysis of the fMRI experiment presented in this thesis.

In a first step, functional data are corrected for motion artifacts and, in the case of fMRI, for the temporal delay introduced by the sequential acquisition of the different images (i.e., slicetime correction). As only one 2D image can be acquired at a time, the last image acquired in a given time step can be separated from the first image of the same time step by up to two or three seconds (dependent on the repetition time). Slicetime correction interpolates the time course of the raw data to correct for this effect. The last stage of preprocessing is a baseline correction which removes low-frequency drifts from the time series by high-pass filtering.

After pre-processing, the raw data are introduced into the general linear model and are convoluted with a design matrix that specifies the onsets of the different events as condition-specific regressors (e.g., Friston et al., 1995; Josephs et al., 1997). The beta-coefficients obtained in this processing step for every single voxel are used to contrast the different conditions that were specified by applying statistical tests such as, for example, a t-test at every voxel in the brain volume (e.g., Bosch, 2000). The result of this last step of the statistical analysis is a statistical parametric map (i.e., SPM) which generally contains a z-value for every voxel. It is important to realize that the results of neuroimaging studies generally do not reflect the absolute amount of activation in different brain areas associated with specific cognitive processes. Rather, what the statistical parametric maps display is the result of a statistical test between two experimental conditions or between a stimulation condition and a resting baseline. In order to reliably identify brain regions that exhibit differences in activation, a significance threshold is applied. For example, the frequently-used threshold of $p < .001$ is achieved by thresholding z-maps at $z = 3.09$.

At some stage of the analysis (i.e., either before or after applying the general linear model), functional data are coregistered with a high-resolution structural MR dataset of the participant. In order to allow for group statistics, the data are also transformed from the participant's individual geometry into a standardized space which is, in general, defined by the stereotachtic atlas of Talairach and Tournoux (1988; cf. also Kruggel & Lohmann, 1997).

More detailed overviews over the analysis of brain imaging data can be found, for example, in the volume edited by Frackowiak and co-workers (1997) or in a technical report describing the analysis software developed at the Max Planck Institute (Lohmann et al., 2000).

3.4.4 Neuroimaging of Sentence Processing

The earliest brain imaging studies that investigated sentence processing contrasted experimental conditions that differed considerably more than the relatively subtle differences in structural complexity between, for example, subject and object relatives. This approach reflects the necessity to map, as a first step, the brain areas generally involved in the processing of sentences and text. While earlier work had started out to investigate how the brain processes single words (e.g., Petersen et al., 1988, 1989), this area of research was relatively new. The first studies (i.e., Lechevalier et al., 1989; Mazoyer et al., 1993; Bottini et al., 1994; Bavelier et al., 1997, R.-A. Müller, 1997) investigated activation patterns elicited by the comprehension of sentences or short text passages, as compared to resting baselines or non-language control conditions. They provided insight into the extended network of cortical areas involved in language processing, especially temporal areas (i.e., Wernicke's area and superior, middle, and inferior temporal gyrus), inferior parietal regions (especially the angular gyrus) and portions of the left inferior frontal gyrus (i.e., BA 44 and 45, also referred to as Broca's area; cf. Section 3.2). The results demonstrated that rather than being associated with few language centers as proposed in the classical neurological model, sentence processing is associated with activation in extended regions of perisylvian cortex. This activation, generally, is dominant in the left hemisphere. One important advance is the recognition that in addition to frontal and posterior temporal areas, anterior temporal areas are also critically involved in sentence processing (e.g., Mazoyer et al., 1993; Bavelier et al., 1997). This finding can be connected to the suggestion of Dronkers and colleagues (1994, 2000) that brain regions along the anterior superior temporal gyrus (STG) or sulcus (STS) might be involved in syntactic processes. This conclusion was arrived at by investigating the neuroanatomical localization of lesions in aphasic patients exhibiting disorders of morphosyntactic comprehension. On the basis of the early neuroimaging studies of sentence processing, a clear association between the identified regions and specific language functions or levels of linguistic representation could not yet be derived.

In the last few years, a number of imaging studies have been published that tried to isolate specific aspects of language processing by more finer-grained study designs. One approach that was taken was to investigate the processing of syntactic and semantic anomalies, similar to the way it was done in ERP studies (see above). The results, however, are diverse. In an fMRI study, Meyer and co-workers (2000) observed that superior temporal regions of the left hemisphere (i.e., the planum polare, the gyrus of Heschl, and the planum temporale) were stronger activated by auditorily presented sentences containing syntactic violations than by correct sentences. Activation of inferior frontal areas was not influenced by the presence of a violation. If, however, participants had to mentally repair the sentences (in addition to the grammaticality judgment task they performed), right inferior frontal cortex was activated more strongly.

Moro and colleagues (2001) reported a PET study of visual sentence processing. These authors reported that two syntactic violations (i.e., a word order violation and a subject-verb agreement violation) did lead to increased activations in the left anterior portion of the insula and in the right homologue of Broca's area (i.e., BA 44/45) when participants made acceptability judgements on the sentences. Interestingly, Nichelli and colleagues (1995) also reported activation in the right inferior frontal gyrus (BA 44) when participants monitored for grammatical violations which were embedded in short text segments.

Ni and colleagues (2000) reported brain activation elicited by correct sentences and by sentences containing grammatical (e.g., *"Trees can grew.") or semantic (e.g., ♯"Trees can eat.") errors in an anomaly detection task. Correct sentences elicited activations in a considerable subset of perisylvian brain areas. Syntactic and semantic anomalies elicited activation increases that largely overlapped. These included the inferior frontal gyrus bilaterally (i.e., BA 44, 45, and 47), the middle frontal gyrus bilaterally (BA 46/9) and superior and middle temporal gyri bilaterally. A direct contrast between the two anomaly conditions revealed few sites where activation was stronger for the semantic violation condition. No regions specifically activated by syntactic violations could be identified.

A similar study, in which participants had to judge the sense of spoken sentences, was conducted by Kuperberg and co-workers (2000). Unexpectedly, contrasting syntactic, semantic, and pragmatic violations with correct sentences yielded reliable activation differences only in left inferior temporal and fusiform gyri. No activations were observed in inferior frontal regions. Again, no area was found where the syntactic violation elicited greater activity than the semantic violation.

A slightly different approach was taken by Friederici, Meyer and von Cramon (2000) who manipulated the presence of semantic and syntactic information in a different way. In addition to normal sentences in active or passive voice, participants also listened to word lists (i.e., stimuli that contained semantics but no syntax), to pseudoword lists (i.e., neither of both), and to sentences consisting of pseudowords but with legal function words and correct inflectional morphology (i.e., syntax but no semantics). The participants' task was to indicate after each sentence whether the stimulus heard contained a syntactic structure or content words. These authors observed that processing of normal speech did not activate frontal regions reliably. A region at the junction between the inferior frontal and the precentral sulci was activated in all three conditions that deviated from normal sentences. Normal and syntactic prose sentences activated the planum polare of the anterior temporal lobe, whereas the deep frontal operculum was selectively activated for syntactic prose sentences. These effects were observed bilaterally.

Dapretto and Bookheimer (1999) reported an fMRI study in which they investigated which brain regions were activated when participants directed their attention towards semantic or syntactic aspects of sentences. The results suggest that pars opercularis (i.e., BA 44) of the IFG is critically involved in the processing of syntactic information. When semantic information was required to perform the behavioral task, on the other hand, increased activation was observed in pars orbitalis which is located more anteriorly and inferiorly.

Finally, a number of studies were published that intended to isolate the neuroanatomical correlates of syntactic complexity. These studies are characterized by the attempt to directly contrast brain activation responses elicited by sentences of varying structural complexity. This approach is in close analogy to the behavioral experiments reviewed in Chapter 1 and the ERP investigations described in Section 3.3.5.

In a series of PET studies, Caplan and collaborators (Stromswold et al., 1996; Caplan et al., 1998, 1999, 2000) investigated the processing of sentences with subject relative clauses and object relative clauses (cf. [36]).

[36] a. The child spilled the juice that$_i$ _$_i$ stained the rug.
(subject)
[36] b. The juice that$_i$ the child spilled _$_i$ stained the rug.
(object)

In a first experiment, eight male participants read right-branching subject relative clause sentences like [36a] and sentences like [36b] which contained center-embedded object relatives (Stromswold et al., 1996). The sentences were presented visually in a blocked design. Half of the sentences were semantically not acceptable. The participants' task was to judge the plausibility of the sentences. The authors reported a focal activation in the left pars opercularis (i.e., BA 44 or Broca's area) for object-relatives as opposed to subject relatives[5]. This finding was replicated using female participants (i.e., Caplan et al., 1998) and, using cleft subject and cleft object sentences, also in the auditory domain (Caplan et al., 1999). The coordinates of the local maxima obtained in the different studies, although all argued to be be situated within Broca's area, varied considerably between studies (cf. Figure 3.7).

Caplan and collaborators attributed the activation increase in left IFG regions to the differences in structural complexity between the two sentence conditions. A "variety of factors that would make one sentence more syntactically complex would engage operations that are principally located in Broca's area" (Stromswold et al., 1996, p. 470). The authors suggested several possible explanations that could account for the activation difference. It was suggested that the processing of center-embedded sentences, as opposed to right-branching sentences, might induce different parsing strategies. One such candidate is the involvement of greater load in working memory due to maintenance of the disrupted main clause (Interruption Hypothesis; cf. Miller & Isard, 1964; see also Chapter 1). Note, however, that several behavioral studies (discussed in Chapter 1) demonstrated that sentences with one center-embedding are not necessarily more difficult to process than sentences with right-branching relatives. Furthermore, the finding of Caplan et al. (1999) that the same pattern of activation differences appeared in object-initial as opposed to subject-initial sentences that did not differ in the place of embedding (i.e., cleft sentences; cf. Caplan et al., 1999) suggests that the activation difference is

[5]Note that the maximum z-value within this region was z = 2.7. The threshold for significant activations was set to z = 2.4 which represents a p-value of about p = .015.

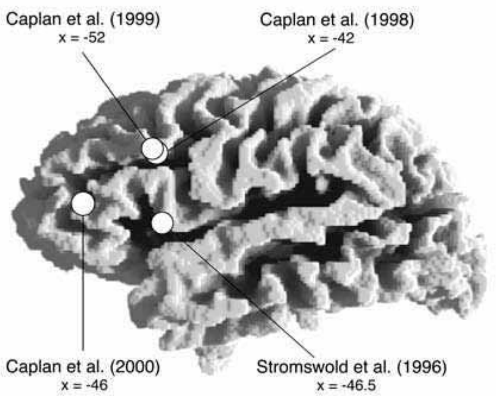

Figure 3.7: *Maxima of increased activations for object relatives as compared to subject relatives (Stromswold et al., 1996; Caplan et al., 1998; Caplan et al., 1999; Caplan et al., 2000). Coordinates of local activation maxima were projected onto the lateral surface of a white-matter segmented brain. The actual depth of these points is indicated by the x-coordinates which represent the medial (x = 0) to lateral axis.*

more likely caused by the more complex movement transformation underlying object relatives (cf. Chapter 1).

Several behavioral studies, reviewed also in Chapter 1, have established a link between the distance of grammatical movement operations and the difficulty of processing a sentence. Thus, the increased activation in center-embedded object relatives might be due to the necessity of maintaining the object filler in working memory for a prolonged duration. At least in the studies that contrasted center-embedded object relatives with right-branching subject relatives, the length of the filler-gap distance was confounded with the interruption of the main clause. Both aspects of processing, the maintenance of the object filler and the interruption of the main clause, are thought to increase working memory load during sentence processing.

In a subsequent study, in which participants had to read the sentences under conditions of articulatory rehearsal (intended to prevent them from rehearsing the sentences in phonological working memory), Caplan et al. (2000) again observed left IFG activation (cf. Figure 3.7). This result was taken to suggest that the activation reported previously was not due to rehearsal in verbal working memory during task performance. This finding is in line with the conclusions drawn on the basis of earlier neuropsychological studies that were mentioned in Section 2.2 (e.g., Baddeley et al., 1987).

Supportive results were obtained in an fMRI study reported by Just et al. (1996). These authors used three different types of sentences (i.e., sentences consisting of two simple active clauses conjoined by 'and', sentences with a center-embedded subject relative clause, and sentences with an embedded object relative clause). They reported that the number of activated voxels, both within inferior frontal and superior temporal brain regions, increased with the complexity of the sentences. This was true for the left hemisphere and, to a lesser degree, also for the right hemisphere. There were no coordinates reported that would allow an exact comparison of the regions of maximal activation with those reported by Caplan and colleagues. The authors argued that the amount activated brain volume is related to the amount of cognitive resources required for the performance of the task.

An increased activation of left IFG regions (i.e., BA 44 and 45) when processing syntactially complex (i.e., center-embedded) sentences in Japanese, as compared to less complex left-branching sentences, was reported by Inui and colleagues (1998). In this fMRI study, there was also an activation increase in premotor areas (BA 9) of the left hemisphere.

Stowe and colleagues (1998) investigated the passive reading of visually presented simple, complex and syntactically ambiguous sentences, as well as the reading of word lists, in Dutch using PET. These authors reported that rCBF was greater for sentences than for word lists in anterior superior temporal cortex of the left and, to a lesser degree, the right hemisphere. As activation in this region did not vary with syntactic complexity, it appeared to be involved in sentence processing in general (as has also been proposed by others; e.g., Mazoyer et al., 1993; Dronkers et al., 1994; Bavelier et al., 1997; Friederici et al., 2000; Meyer et al., 2000) but not specifically in processes required when processing complex structures. The expected pattern of results for the manipulation of syntactic complexity (i.e., word lists $<$ simple sentences $<$ complex sentences $<$ ambiguous sentences) was obtained exclusively in left superior and middle temporal gyri (i.e., BA 22 and 21). In contrast to the commonly assumed association of syntactic processing with left inferior frontal cortex, left IFG regions did not exhibit such a pattern of activation.

The only effect that was observed in the fronto-opercular region was in the left anterior insula underneath BA 44 and 45. Here, both complex sentences and word lists exhibited greater activation than simple sentences. The authors concluded that this brain region is likely to support working memory mechanisms that are required both for sentence processing and when storing lexical representations of single words (see also Stowe, 2000). It should be noted, however, that the participants did not have to perform a task in this study. It might thus be that they engaged in syntactic processing in word lists in the attempt to reorder the words in a way that would allow to establish a structural analysis. This is not implausible because the word lists that were used contained both content and function words. The activation observed in this condition, thus, might reflect similar processes as the repair task in the study reported by Meyer and colleagues (2000). In any case, it is not clear why participants should store words presented in word lists if they are not needed for a subsequent behavioral task.

Taken together, the studies that contrasted object-first and subject-first structures suggest that Brodman areas 44 and 45 appear to be involved in parsing structurally complex sentences. However, the exact nature of the parsing processes housed in this area is not clear, so far. ERP studies (see

Section 3.3.5) have demonstrated that over the course of a sentence, differences in the activation pattern of the brain can be elicited at more than one position in a sentence. The relatively low temporal resolution of PET and fMRI, worsened by the frequent use of blocked designs, does not allow to relate individual areas that are activated to specific positions in the sentence. The experiments, however, suggest that the fronto-opercular region is either involved in phrase structure building processes or in working memory processes associated with maintaining syntactic information available.

Some light might be shed on this question by the neuroimaging studies of syntactic violations which should identify brain regions associated with phrase structure building. However, the results of these studies are very heterogenous and appear also to be influenced by the modality in which sentences were presented. Some studies did not observe activation differences in left IFG regions at all (i.e., Kuperberg et al., 2000), others observed fronto-opercular activations only when participants were intentionally engaged in sentence restructuring (Meyer et al., 2000). Ni and colleagues (Ni et al., 2000) observed IFG activation, but this activity was not specific for the syntactic violation condition. Two studies showed activation increases to syntactic violations within right BA 44 (Nichelli et al., 1995; Moro et al., 2001). Within the left frontal operculum, Moro and colleagues reported activation differences associated with syntactic violations. The location of this effect, however, was even more medially than the insular activation reported by Stowe and colleagues (1998).

With regard to the syntactic working memory hypothesis, no evidence from brain imaging is available that would support or falsify this assumption. Caplan and colleagues (2000) demonstrated that BA 44 activation can not be suppressed if the articulatory loop of the verbal working memory system is blocked. However, the possibility remains that a central resource, as postulated by Just and Carpenter in their Capacity Theory of Comprehension (1992) or as assumed for interpretive sentence processing by Caplan and Waters (1999), is required for temporarily maintaining information in an activated state during on-line sentence processing. As Just and colleagues (1996) suggested, the activation increases for syntactically complex sentences might reflect the increased consumption of cognitive resources associated with such parsing operations. However, the association between left IFG activations and syntactic working memory has not yet been established empirically.

Importantly, there have also been reports of activation increases when processing complex sentences in superior temporal brain regions (Just et al., 1996; Stowe et al., 1998). The nature of the functional relation between these areas and inferior frontal regions has not yet been established. One obvious explanation might refer to the nature of the task required from the participants in the different experiments. While in the studies reported by Caplan and colleagues, participants made plausibility judgments, a sentence comprehension task had to be performed in the Just et al. study. It might thus be that performance of the comprehension task lad to the involvement of temporal brain regions. However, in the Stowe et al. study which also demonstrated activation differences in the superior temporal lobe, participants were not engaged in a behavioral task. Thus, it appears that there is no clear relationship between behavioral task and superior temporal acitvation differences.

3.5 A Neurocognitive Model of Sentence Processing

As an extension to early structure-driven models of parsing (e.g., Frazier & Fodor, 1978; Frazier, 1987a), Friederici (1999) proposed a model of (auditory) sentence processing in which the different stages of the parsing process (see Section 1.1) are attributed to specific brain regions (Figure 3.8). This model is based on the ERP and neuroimaging data reviewed above, as well as on patient data and studies that are concerned with other aspects of language processing such as auditory word recognition or sentential prosody.

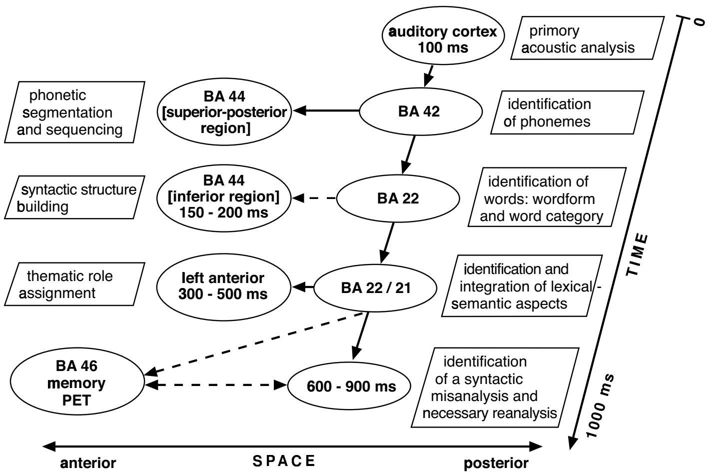

Figure 3.8: *Neurocognitive model of language comprehension as proposed by Friederici (1999).*

Within this model, postlexical sentence processing, i.e., the build-up of a structural analysis of a sentence, proceeds on the basis of word category information. This information is provided by superior temporal brain regions very fast, i.e., within 150 ms after the onset of the word (or, in case of ambiguity, after it can be unequivocally identified). Syntactic structure building is carried out by left inferior frontal regions (i.e., BA 44). The early detection of word category violations, indexed by the ELAN component in the ERP, suggests that this initial first pass parse takes place between 150 and 200 ms after word onset. Activation and integration of lexical-semantic knowledge associated with the given word is achieved by superior and middle temporal areas between 300 and 500 ms. In case the lexical-semantic information can not be integrated into the prior sentence or discourse context, an

N400 is elicited. In the same time domain, thematic roles are assigned on the basis of verb-argument structure information that is now available. ERP results (i.e., the LAN) suggest that this process has to be attributed to left anterior regions. If lexico-semantic information and the initial phrase structure can not be integrated into the current representation of the sentence, processes of reanalysis and repair are initiated that are reflected in the P600 component of the ERP. These mechanisms probably involve a widely distributed network of brain regions.

The neurocognitive model of parsing describes the flow of information given a sentence can be processed smoothly. In case that the parser detects an anomaly at some level of this process, brain regions critically involved in processing at this level will be activated and elicit specific ERP indicators associated with certain violations as described above. In case that processing can not proceed as smoothly, for example because some argument NP or other constituent is encountered in a position in surface structure where it can not be processed immediately, additional mechanisms such as temporary maintenance in working memory are required.

3.6 Summary

The research summarized in this chapter demonstrates that modern neurocognitive methods can be employed successfully to investigate how the brain processes language. Methodological aspects of ERPs, PET and fMRI were introduced and important findings regarding the processing of sentences that were obtained with these techniques were reviewed.

A number of studies that were outlined in the previous two chapters have addressed questions regarding the processing of structurally complex sentences. On the basis of ERP results, it can be concluded that the nature of processing difficulty in object-initial sentences is indeed two-fold, as was proposed by Gibson (1998) in the context of the Syntactic Prediction Locality Theory. Local effects of computational parsing processes and sustained effects of maintenance in working memory can be observed using ERPs. However, there are no data available at the moment that allow to determine the interplay between these two aspects of on-line parsing in well-formed sentences. An attempt at isolating local and global aspects of parsing within the same sentences will be made in the ERP experiments reported in this thesis.

Several attempts have been made at determining the brain regions that support the processing of syntactically complex sentences. Consistent evidence has been obtained that regions of the left inferior frontal gyrus are involved in this task. These results support classical models of brain and language. Superior temporal regions and right hemisphere homologues have been observed to be activated by complex sentences less frequently. The data at hand do not allow to decide which processes exactly are related to activation in which brain region.

Chapter 4

Aims of the Study

The present study tries to link several lines of research that share the same goal, namely to describe the cognitive and neuroanatomical mechanisms underlying the processing of syntactically complex sentences. From behavioral studies in psycholinguistics (see Chapter 1), it is known that parsing a complex sentence, and more specifically the long-distance dependencies between moved constituents and the corresponding gap positions, is costly in terms of cognitive resources. The processing difficulty exhibited by complex sentences has been explained in different ways.

Some researchers assumed that the processing difficulty of complex sentences is due to an increased computational complexity at circumscribed positions in the sentence. Under this view (here referred to as computational load models; see Section 1.3), local processes of sentence comprehension differ between simple and complex sentences in the amount of processing resources required to achieve a valid analysis of the input. For example, the complexity of the phrase structure representation that is built up at a specific position in the sentence or the complexity of the operations that are required to syntactically integrate a verb and an NP argument might differ between two sentences at specific positions of the sentences for various reasons.

Other researchers assumed that sustained working memory processes associated with maintaining syntactic information in working memory leads to an increase in processing difficulty. These approaches have been subsumed under the term memory resource models in Section 1.3. Both, the more local and the more global view, are supported by data from behavioral on-line studies and from ERPs. Furthermore, both aspects of processing difficulty can be modeled by relevant theories of sentence comprehension. Especially three theoretical approaches that have been introduced do allow to model the two-fold nature of processing difficulty. The Active Filler Hypothesis (Frazier, 1987; see Section 1.4.2] assumes that syntactic information of the moved filler is maintained in memory for some time while structural integration continues. Locally increased processing load at circumscribed positions in the sentence might, according to AFH, be caused by mechanisms associated with the localization of gaps (e.g., filled gap effects) or with gap filling. The Capacity Theory of Comprehension (Just & Carpenter, 1992; cf. Section 2.3.1) assumes a language specific working memory resource that supports both storage and computation. The focus of this theory is the competition of these two aspects of language processing for the limited amount of resources available. Like AFH, Gibson's Syntactic Prediction Locality Theory (1998, see Section 2.3.3) also encorporates two potential sources of processing difficulty, integration cost and structural memory cost. This approach provides a complexity metric that allows to make quantitative predictions for specific positions in different sentences. In contrast, the separate-resources model proposed by Caplan and Waters (1999) does not make an explicit attempt at modeling these two aspects of on-line sentence processing. However, it also does not exlcude the possibility of storage and computation as contributing to processing difficulty in sentence comprehension.

On the basis of the data and models discussed in the previous chapters, the following theoretical starting point was adopted for the present study. In line with the SPLT approach, it is recognized that during sentence processing, both global processes of maintenance in working memory and local computational processes of parsing are involved and, importantly, are likely to be active at the same time. Thus, dependent on the architecture of the underlying cognitive resources, competition between these two aspects of parsing might occur. However, the present research does not critically rely on the assumption of unitary or distinct underlying resources. Unlike in the SPLT approach, semantic and pragmatic aspects of incremental word-by-word integration will not be relevant in the present experiments.

As was suggested in the Active Filler Hypothesis, it is assumed that the parser will encounter processing difficulty if elements have been moved into a non-canonical position. The assumption that the filler is maintained in working memory until it can be linked with the relevant gap position is central to the present work. It is in line with the theoretical notions underlying previous ERP studies (e.g., Kluender & Kutas, 1993a; Rösler et al., 1998; see also Section 3.3.5), as well as with previous behavioral studies (e.g., Fanselow et al., 1999) and theoretical approaches in psycholinguistics (cf. Crocker, 1994; cf. also Section 1.4.2). While the filler is stored in working memory, parsing of new input continues. It is assumed that the difficulty of ongoing processing can vary dependent upon the nature of the material that is perceived. Once the gap is located and the filler-gap dependency can be established, the cognitive cost of this process should be reflected in on-line measures.

This characterization of how the parser handles non-canonical configurations of arguments integrates previous theoretical and empirical work. However, there remain several important questions that are not conclusively answered yet.

1. Is it indeed working memory that is involved when an embedded object-extraction is processed? Many researchers have claimed that working memory load is greater when object-initial structures are processed. Some theories suggest that establishing the linkage between a moved filler and its gap relies on working memory resources. Data from individual differences and

from studies that investigate parsing under conditions of concurrent memory load support this assumption. However, there is no direct evidence for an involvement of working memory processes when sentence complexity is varied. Especially, little is known about the exact time-course of such working memory processes during sentence processing and of their relation to theoretically predicted gap positions. In the present thesis, this question shall be answered by investigating ERPs elicited by sentence structures that differ specifically in the length of their filler-gap distance. The manipulation of filler-gap distance is assumed to influence the duration over which syntactic information has to be maintained in working memory. The working memory load, in the present studies, is not artificially introduced by adding an external working memory load. By analyzing multi-word ERPs that span the distance between the moved element and its gap site, working memory processes shall be made observable (see Section 3.3.4).

2. Both in the behavioral and in the ERP literature, local as well as sustained effects have been found when contrasting simple with complex sentences. Definitely, both components of parsing, local and sustained mechanisms, are indispensible for successful sentence comprehension. As already pointed out, some theories of parsing can well accomodate both findings. It remains to be demonstrated using methods with high temporal resolution over the complete sentence, whether maintenance and computation during sentence processing can be dissociated and, if so, how they interact. Most previous ERP studies (e.g., Kluender & Kutas, 1993a; King & Kutas, 1995; McKinnon & Osterhout, 1996; Kaan, Harris, Gibson & Holcomb, 2000) have focused mainly on one of these two aspects. Furthermore, a considerable part of the studies reported sofar has relied on syntactic violations to observe local mechanisms of syntax. In the ERP experiments to be reported here, multi-word ERPs that can identify clause-level effects and ERPs elicited at specific positions in the sentences will be examined. More precisely, ERPs at the moved element and the assumed gap site will be considered. In studies following a similar approach in English (e.g., King & Kutas, 1995), serious confounds due to category differences between the different conditions were present (cf. Footnote 4, Chapter 3).

3. What is the relationship between storage and computational aspects of parsing, on the one hand, and individual working memory capacity, on the other? Is the distinction between local parsing processes and more global aspects of structural maintenance compatible with single-resource models (e.g., Just & Carpenter, 1992) or with seperate resource models as proposed, for example, by Caplan and Waters (1999)? As an approach to this question, individual differences in working memory were investigated together with the aspects described in the previous two points. So far, there are no reports of studies investigating the relationship between multi-word ERPs and individual working memory capacity. The only study that considered a related as-

pect is the experiment of King and Kutas (1995) who analyzed fast and slow comprehenders separately.

4. Finally, can the brain regions supporting maintenance in working memory and syntactic computations in sentence processing be identified? If so, can this distinction contribute to a better understanding of the pattern of results observed in previous studies (see Section 3.4.4)? To answer this question, a functional MRI experiment will be reported.

In the experiments of this thesis, the processing of German wh-questions similar to those used in the experiments of Fanselow, Schlesewsky and colleagues (Fanselow et al., 1999; Schlesewsky, Fanselow & Kliegl, manuscript; cf. Section 1.4.2) was investigated. As sentence examples [37a] and [37b] indicate, both subject and object questions feature a wh-movement. However, just like in the English relative clauses discussed above, the two conditions differ with respect to the distance between the moved consituent and its original position (i.e., its gap).

In general, these sentences consisted of a matrix clause in which a wh-question was embedded. Different from the relative clauses discussed above, the present constructions (e.g., [37a,b]) were all right-branching and not center-embedded, thus avoiding a potential confound between processes of maintenance effects within the embedded clause and memory load induced by the interruption of the main clause (cf. Section 1.3). Furthermore, the wh-questions used in the present study were all masculine and, therefore, overtly case marked. I.e., the functional role of the moved constituent was always overtly indicated and therefore immediately available. Possible processing effects that might be found, thus, can not be attributed to strategies of ambiguity resolution.

[37] a. Karl fragt sich, wer$_i$ $\__i$ den Doktor verständigt hat.
Karl asks himself, who$_{NOM}$ the doctor$_{ACC}$ called has
(= Karl asks himself, who has called the doctor.)
(subject-initial)

[37] b. Karl fragt sich, wen$_i$ der Doktor $\__i$ verständigt hat.
Karl asks himself, who$_{ACC}$ the doctor$_{NOM}$ called has
(= Karl asks himself, who the doctor has called.)
(object-initial)

Event-related brain potentials and event-related functional magnetic resonance imaging were used to investigate the processing of these sentences. The excellent temporal resolution of the ERP method offered the possibility of monitoring sustained clause-level and local parsing effects within the same sentences. The time course, polarity and scalp distribution information that is delivered by this method can give clues regarding the nature of the effects observed. Event-related fMRI has better good spatial resolution and a relatively good temporal resolution, though clearly not as good as ERPs. In combination with the ERP data obtained from the same paradigm, insights might be gained into the role that brain regions involved in sentence processing play in phrase structure builing and in working memory processes of syntax.

The first experiment to be reported is an ERP study in which two potential sources of processing difficulty were varied in order to determine their contribution to the processing costs of object-initial sentences. Argument order (i.e., subject-first vs. object-first; cf. [37a] vs. [37b]) was manipulated in order to induce differences in the length of the wh-movement and differences in local processing difficulty due to the need to integrate verbal arguments into the phrase structure that are encountered in non-canonical order.

Furthermore, the length of the filler gap distance in object wh-questions (i.e., the length over which the filler had to be maintained in working memory) was also varied by inserting either a short prepositional phrase (i.e., [38a]) or a prolonged prepositional phrase (i.e., [38b]) between the dislocated object filler (i.e., 'wen') and the second noun phrase of the sentence (i.e., 'der Doktor'). In addition, ob-questions (i.e., 'whether'-questions) that did not contain a wh-movement were also included in the experiment. Furthermore, the between subjects-factor working memory capacity was considered by comparing individuals with low vs. high working memory capacity as determined using the reading span task (cf. Daneman & Carpenter, 1980). Local ERPs averaged at specific positions in the sentences and across-sentence multi-word ERPs were analyzed in order to identify both sustained effects and local effects of parsing difficulty.

[38] a. Karl fragt sich, wen_i *am Dienstag* der Doktor $\_\_{}_i$ verständigt hat.
Karl asks himself, who_{ACC} on tuesday the $doctor_{NOM}$ called has
(= Karl asks himself, who the doctor has called on tuesday.)
(short object)

[38] b. Karl fragt sich, wen_i *am Dienstag nachmittag nach dem Unfall* der Doktor $\_\_{}_i$ verständigt hat.
Karl asks himself, who_{ACC} on tuesday afternoon after the accident the $doctor_{NOM}$ called has
(= Karl asks himself, who the doctor has called on tuesday afternoon after the accident.)
(long object)

It turned out that the design of the first ERP experiment had to be changed in order to be applicable in the second imaging modality to be used. In order to perform equivalent analyses in an fMRI study, a subset of the sentence material was changed and the duration of the experiment had to be reduced. The second experiment is a replication of the first experiment using ERPs and the modified design. Thereby, Experiment 2 allowed to make an important comparison that could not be made in the first experiment but turned out to be critical in the fMRI experiment.

The third experiment to be reported is a study using functional MR imaging with the same two within subjects factors as in the ERP studies, namely subject- vs. object-first and short vs. long filler-gap distance. The fMRI experiment was intended to isolate brain regions associated with local computational processes and regions contributing to sustained memory-related processes. However, given the temporal resolution of the fMRI methodology which was already discussed above (cf. Section 3.4.2), this method is more suited to identify brain areas involved in global processes of parsing, rather than very fast computational processes. Thus, it was expected that the main results of Experiment 3 would be related to working memory processes during sentence processing.

The results will be discussed in the light of previous data and theories in each of the experimental chapters. The discussion of the results of Experiment 2 will be shorter than that of the other two experiments. This is so because Experiment 2 had the main purpose of providing a replication of the results of the first experiment in a design suitable for an fMRI study, thus linking Experiments 1 and 3. In the last chapter of the thesis, the results and the main points of the theoretical discussions will be repeated and integrated.

Chapter 5

Experiment 1: An ERP Study

As already outlined in the previous chapter, the first ERP study investigated the processing of German subject and object wh-questions with varying filler-gap distance in the object wh-questions. In this study, argument order (i.e., subject-first vs. object-first wh-questions) and the length of the distance over which the moved wh-filler had to be maintained in working memory before it could be linked to its gap position were varied as within-subjects factors. Subject questions were also included with short and long prepositional phrases. In addition to the four sentence conditions resulting from these two factors, whether-questions that did not contain a wh-movement operation were also included into the design. This was done in order to make the data comparable to previous studies in which wh-questions were contrasted with whether-questions (e.g., Kluender & Kutas, 1993a; McKinnon & Osterhout, 1996; Kaan, Harris, Gibson & Holcomb, 2000). Especially, this experiment is the first ERP study that investigated multi-word ERPs in subject wh-questions, object wh-questions and whether-questions. Previous studies contrasted either subject with object wh-questions (i.e., Kluender, Cowles, Walenski, Münte, Szenkuti & Wieringa, 1998) or one type of wh-question with whether-questions (i.e., McKinnon & Osterhout, 1996; Kaan, Harris, Gibson & Holcomb, 2000). Whether-questions were also included in a short and a long version.

The inclusion of whether-questions allowed to test one specific prediction of the SPLT approach. According to SPLT (cf. Section 2.3.3), the syntactic prediction that the parser makes at the beginning of the subordinate question is more costly for whether-questions than for subject wh-questions. While after processing a clause-initial nominatively marked wh-filler, only a verb has to be predicted, both a subject and a verb are predicted when processing the clause-initial 'ob'. In contrast, the syntactic prediction for object wh-questions is even more complex, as an object trace has to be predicted in addition to the subejct and the verb. Thus, according to SPLT, whether-questions should elicit more working memory costs than subject wh-questions but less costs than object questions. According to the Active Filler Hypothesis (cf. Section 1.4.2), on the other hand, whether-questions should be the least costly structure because there is no filler encountered in clause initial position which would have to be held in memory.

We assume that working memory is involved in establishing the syntactic chain between the filler and its gap. Unintegrated structural information of the disloacted element has to be maintained in memory until the gap position becomes available. These working memory operations should be detectable in multi-word ERPs (cf. Section 3.3.6). The difficulty of local parsing processes should be reflected in single-word or phrase-level ERPs (in the future these are referred to as 'local ERPs'). There are two positions in object wh-questions which are especially likely to exhibit local ERP effects associated with processing difficulty. Upon encountering an accusatively-marked wh-filler (i.e., an object) in clause-initial position, ERPs might either reflect working memory processes (as was suggested, e.g., by Kluender & Kutas, 1993a). Alternatively, the violation of the preference for subject-first structures might be violated by the object wh-filler, in analogy to the results reported by Friederici and collegues (1998) for object-first relatives in German. The first approach predicts a LAN effect at this position, the latter approach predicts a late positive ERP effect. However, with respect to the latter prediction, it was argued that pragmatic preferences play a smaller role in constituent questions than in relative clauses (Schlesewsky et al., 2000; cf. also Section 1.4.2). Furthermore, a corpus-analysis reported by the same authors yielded that the frequency relation of subject-initial to object-initial wh-questions is around 60 to 40 percent (of NP-initial structures) while the same relation for noun-phrase initial structures in general yields an asymmetry of around 90 to 10 percent for subject vs. object-first structures. The likelihood of ERP effects due to a possible violation of structural preferences, thus, is very small in wh-questions.

The second position in the sentence where local ERP effects are likely to occur is the area around the object-NP gap. Here, local processing difficulty might either be due to retrieving the stored wh-filler from working memory (cf. Kluender & Kutas, 1993a), thus probably eliciting a LAN effect, or might be caused by increased integration difficulty, resulting in a late positivity as suggested by Kaan and collaborators (2000). Note that at the position of the second noun phrase, where a first integration between of the subject and the object should take place because the object gap becomes available (cf. Section 1.4.2), SPLT (Gibson, 1998) does make identical predictions for both subject and object wh-questions. As was already outlined above in Section 2.3.3, the difficulty of syntactic integration processes at a certain position is influenced by the locality of the integration, i.e., by the distance between the two elements to be integrated. Interestingly, in an SOV language like German, fronting of the object does not change the number of pre-verbal NPs (like it does in English). Therefore, SPLT predicts that processing a German sentence with non-canonical argument order, like [37b], should not differ in the local integration costs from a canonical structure like [37a] (see Section 2.3.3). This prediction, however, is not very suggestive because the verbal arguments are encountered out of their preferred order, making integration processes difficult.

In addition to the within-subjects factors of sentence type and sentence length, individual working memory capacity was investigated as a between-subjects factor. This allowed to directly test the relationship between ERP components that were previously claimed to reflect working memory processes during parsing and individual differences in working memory resources. Importantly, this approach made it possible to relate the obtained ERP results to models of working memory usage during sentence processing. The present experiment was conducted in the visual modality. Participants read the sentences and afterwards performed a comprehension task in order to assure that the sentences were understood correctly.

5.1 Predictions

On the basis of the theoretical assumptions outlined in the previous chapters, the following predictions were derived:

1. ERPs elicited by object wh-questions should show a reflection of the greater working memory demand induced by maintaining the dislocated object filler available until it can be linked with its gap. In analogy to other ERP investigations of slow potentials elicited by syntactic complexity manipulations (King & Kutas, 1995; H. M. Müller et al., 1997; Münte et al., 1997; Kluender et al., 1998) or retention processes during verbal working memory tasks (e.g., Ruchkin et al., 1990, cf. also Chapter 3.3.6), we expected a frontally distributed negativity for object wh-questions relative to subject wh-questions in multi-word ERPs between the filler and the gap. Furthermore, we expected that whether-questions also should elicit a negativity. This effect, however, was assumed to be weaker than the one elicited by object wh-questions (see above).

2. A length-dependency of memory-related ERP effects was predicted. It was assumed that ERP effects related to working memory should be stronger if information has to be maintained in memory for a longer duration. I.e., stronger effects were predicted for questions with a long filler-gap distance as opposed to questions with a short filler gap distance. Such a finding would provide strong functional evidence for the syntactic working memory hypothesis.

3. Differential effects for individuals with high working memory capacity as opposed to those with low capacity were expected. If, as is commonly held, low-capacity individuals generally have fewer resources available, this group would have to spend a greater percentage of their overall resources for maintaining the structural information in working memory. Accordingly, low-capacity individuals should show stronger ERP effects reflecting the greater effort required for maintaining the wh-filler in memory. Furthermore, it was expected that this group should make more errors in the comprehension task because the limited capacity available for processing and storage was assumed to be exceeded more often in these participants.

4. In addition to the slow potential effects predicted for multi-word ERPs, a reflection of the syntactic integration of the moved constituent into the phrase structure should be observable at the point where the dependency between the filler and the corresponding gap can be established. The earliest point at which the gap position in German object wh-questions can be predicted is the subject noun phrase (see Section 1.4.2). As has been discussed in Section 3.3.5 (see also above), the P600 is an ERP component that has been shown to reflect increased integration difficulty. Accordingly, we expected a positivity in local ERPs for object as compared to subject wh-questions at the second noun phrase position. As we assume that the filler is maintained actively in working memory (cf. AFH; Frazier, 1987a), we do not predict a LAN effect at this position. This effect was associated to retrieval of linguistic information from memory (Kluender & Kutas, 1993a).

   We did not expect to find ERP differences between subject and object questions at the position of the question word because, as already argued above, there is no strong structural preference for either of the two structures. However, one might expect a difference between wether-questions and wh-questions because the latter have an NP-argument in clause-initial position and the former does not. However, previous studies (see 3.3.5) did not yield clear results in comparable sentences.

5.2 Methods

5.2.1 Material

40 sets of six indirect questions of the types displayed in Table 5.1 were constructed. The complete list of items is given in Appendix B. All sentences were made up (a) of a matrix clause and (b) of a subordinate question. The matrix clause always consisted of a first name and the verbal phrase 'fragt sich' (i.e., 'asks himself'). The embedded wh-questions contained a subject, an object, and a transitive verb in past participle (e.g., 'called') followed by the auxiliary verb 'hat'. Either the subject or the object were moved to clause initial position in the form of the masculine nominative or accusative interrogative pronoun (i.e., the wh-filler). As already described above, the distance between the wh-filler and the second noun phrase was varied by inserting either two words (short sentence conditions) or six words (long sentence conditions) as prepositional phrases after the wh-filler. The prepositional phrases used for the distance manipulation are printed in italic font in Table 5.1. All wh-questions were constructed according to the schema displayed in [39a]. Whether-questions followed the structure given in [39b].

[39] a. [[Matrix clause], [[wh-filler] [*PP(s)*] [2nd NP] [Verb] [hat/AUX]]].

b. [[Matrix clause], [[ob/whether] [*PP(s)*] [NP] [Verb] [hat/AUX]]].

In order to keep the whether-items identical in length to the wh-questions, they were constructed with only one noun phrase, i.e., the subject, and an intransitive verb (e.g., 'cried'). Whether-questions also were included in versions with short or long prepositional phrase.

Condition	**Example**
short subject wh	Thomas fragt sich, wer *am Mittwoch* den Doktor verständigt hat. Thomas asks himself, who$_{NOM}$ on Wednesday the$_{ACC}$ doctor called has
short object wh	Thomas fragt sich, wen *am Mittwoch* der Doktor verständigt hat. Thomas asks himself, who$_{ACC}$ on Wednesday the$_{NOM}$ doctor called has
short whether	Thomas fragt sich, ob *am Mittwoch* der Doktor geweint hat. Thomas asks himself, whether on Wednesday the$_{NOM}$ doctor cried has
long subject wh	Thomas fragt sich, wer *am Mittwoch nachmittag nach dem Unfall* den Doktor verständigt hat. Thomas asks himself, who$_{NOM}$ on Wednesday afternoon after the accident the$_{ACC}$ doctor called has
long object wh	Thomas fragt sich, wen *am Mittwoch nachmittag nach dem Unfall* der Doktor verständigt hat. Thomas asks himself, who$_{ACC}$ on Wednesday afternoon after the accident the$_{NOM}$ doctor called has
long whether	Thomas fragt sich, ob *am Mittwoch nachmittag nach dem Unfall* der Doktor geweint hat. Thomas asks himself, whether on Wednesday afternoon after the accident the$_{NOM}$ doctor cried has

Table 5.1: Sample set of sentence material with word-by-word translations to English.

For the behavioral comprehension task, probe assertions were constructed that restated some facts of the corresponding question item (e.g., 'The doctor was called after the accident.', or 'The doctor called somebody on Wednesday.'). In half of these assertions some critical information, like the prepositional phrases, the noun phrase, the verb, or thematic role assignment, was exchanged in order to form incorrect probes.

5.2.2 Experimental Procedure

Participants were seated in a dimly lit room at a distance of 80 to 90 cm from a computer screen. Before the experiment, a short training block was administered. Each trial started with a fixation cross that was visible for 300 ms, followed by a blank screen for another 300 ms. Experimental sentences were presented visually in a serial phrase-wise mode including punctuation. Each sentence presentation consisted of a series of either seven (short conditions) or ten (long conditions) frames. The frames were presented for either 600 ms for simple words or 700 ms for noun phrases, prepositional phrases, and the verb of the embedded question. Each trial was started by the participant in order to allow as much time for eye blinks and other movements as necessary. After each sentence, a blank screen was shown for 800 ms and then the complete probe assertion was presented on the screen. The delay of 800 ms served to separate ERPs related to sentence processing from those elicited by cognitive and motor aspects of task performance. The participant's task was to judge whether or not the probe assertion was correct in relation to the critical item. Behavioral responses were registered from the onset of the probe assertion. The main purpose of the comprehension task was to control for correct processing of the stimuli.

In addition to the 240 experimental items, another 320 sentences (complex conjuncts of two main clauses and one sub-clause) were included as fillers. The experiment was run in two sessions with seven blocks of 40 items. Due to the self-initiated item presentation, block lengths varied slightly. However, they were not longer than ten minutes.

The sequence of items and fillers was pseudo-randomized in a way that assured that (a) no more than three experimental items or fillers could be presented in a row, (b) at least nine items were intervening between two different items from the same set (i.e., set of six items like in Table 5.1), and (c) no more than four successive items with correct or incorrect probe assertions could be presented in a row. The six sentence conditions as well as correct and incorrect probes were distributed evenly across blocks. Furthermore, it was assured that the different types of incorrect probe assertions (i.e., dependent upon the sentence constituent that was exchanged) were also distributed evenly across the experimental blocks. Two lists containing different orders of the items were constructed to which the participants were randomly assigned. Independently, response-to-key assignment was balanced between the participants. For half of the participants, the yes button was assigned to the right hand, for the other half it was assigned to the left hand.

5.2.3 Participants

Altogether, 24 paid volunteers participated in the experiment. During off-line analysis, data from two participants had to be excluded on the basis of high rates of eye-movement artifacts and errors. For these two datasets, less than 50 % of the measured trials were available for the calculation of ERPs (see Section 5.2.5 below for the exact criteria for excluding participants). The data reported are from the remaining 22 participants (mean age 23.9 years; 20 to 28 years; 12 females). All participants were students at the University of Leipzig, right-handed as determined on the basis of the Edinburgh handedness inventory (Oldfield, 1971), and native speakers of German. Furthermore they had normal or corrected to normal vision and were without history of neurological or psychiatric diseases.

A German translation of the Daneman and Carpenter (1980) reading span task (cf. Steinhauer, 1995) was used to group the participants into a high-span group with reading span scores greater or equal to 4.0 (n = 10) and a low-span group with scores of 3.0 and less (n = 9).

5.2.4 ERP Recording Procedures

A continuous electroencephalogram was recorded from 51 AgAgCl-type scalp electrodes selected from the extended 10-20 system (cf. Figure 3.4), referenced to the left mastoid electrode. For detection of eye movements and blink artifacts, bipolar electrooculogram (EOG) was recorded from two electrodes placed to the outer canthi of the left and the right eye and two electrodes placed above and below the right eye. Impedances of all electrodes were kept below 2 kΩ. Signals were amplified with a lowpass filter of 30 Hz and sampled at a frequency of 250 Hz.

5.2.5 Data Analysis

Trials with EOG artifacts were identified by automatical and manual screening. The mean number of trials with artifacts was 2.8 % in local ERPs and 7.47 % and 9.08 % in short and long multi-word ERPs, respectively. The difference in artifact-contaminated trials between local and multi-word ERPs was due to the increased time window in which rejections could occur in multi-word ERPs (i.e., due to the length of the calculated average ERP).

As all EEG data sets showed a slow shift to negative, a detrending algorithm was used to correct for a common linear component. In time windows of 20 s, a linear trend was estimated by minimizing absolute errors. This linear component was subsequently subtracted from the original signal. In Section 5.3.2.2 a comparison between effects in the original signal and the detrended signal is reported that demonstrates that detrending did not affect relative differences between sentence conditions.

After pre-processing, local average ERPs in time windows of -200 to 1000 ms relative to the onset of a word or phrase were calculated at different positions within the embedded questions. Multi-word average ERPs starting with the question words and spanning the complete embedded question (i.e., -200 to 3700 ms in short questions and -200 to 5600 ms in long questions) were calculated. Averages were re-referenced to the mean activity of both mastoid reference electrodes.

Trials containing artifacts in these time windows and incorrectly answered trials were excluded from averaging. The minimum number of averaged trials per participant was 22. Two participants were excluded from the analysis because they had less than 20 trials left for averaging in at least one condition (see also Secion 5.2.3 above). For purposes of visualization, ERP waves were smoothed using an additional low-pass filter with a cutoff frequency of 7 Hz.

For statistical analyses, four regions of interest (i.e., ROIs) encompassing five lateral electrodes each (left anterior: AF3, F3, F5, FC3, FC5; right anterior: AF4, F4, F6, FC4, FC6; left posterior: CP3, CP5, P3, P5, PO3; right posterior: CP4, CP6, P4, P6, PO4; cf. Figure 3.4) were introduced into analyses of variance (ANOVAs) with the two two-level factors 'hemisphere' (left vs. right) and 'scalp extension' (anterior vs. posterior). Effects with central distribution were analyzed on midline electrodes with four ROIs (i.e., FPZ/AFZ; FZ/FCZ; CZ/CPZ; PZ/POZ) and the within subjects factor 'region'. All measured electrodes were used for displaying the scalp distribution of ERP effects by calculating interpolated topographic potential maps (Perrin et al., 1987).

ANOVAs were calculated with the within-subjects factors 'sentence length' (short vs. long) and 'sentence type' (subject-wh vs. object-wh vs. whether). Time-windows for statistical analyses will be reported with the individual analyses in the results section. Corrected p-values (Huynh & Feldt, 1976) will be reported automatically together with original degrees of freedom in case of ANOVAs with more than one degree of freedom in the numerator. Reliable effects in behavioral or ERP data were analyzed in a second analysis with the additional between-subjects factor 'reading span group'. If main effects of the three-staged factor 'sentence type' were significant, planned comparisons were calculated with an adjusted significance threshold set to $\alpha_{planned} = .033$ (determined on the basis of a modified Bonferoni-correction; e.g., Keppel, 1991).

Behavioral data were aggregated by participant and condition before descriptive and inference statistics were calculated. Reaction times departing by more than two and a half standard deviations from each participants mean were excluded from further analyses (e.g., Ratcliff, 1993). Reaction times and error rates were analyzed in ANOVAs with the within-subjects factors 'sentence type' and 'sentence length'.

5.3 Results

5.3.1 Behavioral Performance

Answers to long questions were significantly slower than those to short questions ($F_{1,21} = 13.31$; p = .001; cf. Table 5.2 for the relevant behavioral data). Descriptively, response times were longest for whether-questions and fastest for subject wh-questions. However, neither the main effect of sentence type nor the interaction of sentence type with sentence length became significant. The number of errors was smaller in whether- than in wh-questions ($F_{2,42} = 14.16$; $p < .0001$). A marginally significant interaction between sentence length and sentence type ($F_{2,42} = 2.58$; p = .09) suggested that only in long wh-questions, more errors were made in the object condition than in subject wh-questions ($F_{1,21}$ = 4.04; p = .05).

Sentence Type	RT (in ms)	Errors (in %)
short subject wh	1845.07 (±68.17)	21.7 (±2.04)
short object wh	1896.48 (±72.06)	21.25 (±2.96)
short whether	1900.01 (±57.60)	9.43 (±1.64)
long subject wh	1972.96 (±94.24)	18.64 (±1.93)
long object wh	1979.99 (±83.10)	23.52 (±2.68)
long whether	2010.77 (±66.50)	12.16 (±2.44)
overall	1934.21 (±30.28)	17.69 (±1.66)

Table 5.2: Reaction times and error rates (n = 22). Standard errors are given in brackets.

Participants with low reading span made more errors than those from the high span group ($F_{1,17}$ = 3.65; p = .07; cf. Table 5.3). No interactions involving span group reached significance in the error rates (all F < 1). Furthermore, reaction times did not differ reliably between high span and low span individuals (F < 1).

	Low Span Group (n = 9)		High Span Group (n = 10)	
Sentence Type	*RT (in ms)*	*Errors (in %)*	*RT (in ms)*	*Errors (in %)*
short subject wh	1861.26 (±87.16)	25.0 (±3.29)	1819.5 (±114.14)	19.25 (±2.96)
short object wh	1954.98 (±93.31)	26.94 (±4.44)	1794.47 (±92.03)	18.75 (±4.76)
short whether	1922.31 (±83.57)	11.67 (±2.73)	1918.79 (±87.99)	7.0 (±1.43)
long subject wh	2002.12 (±102.59)	20.83 (±3.28)	1888.93 (±114.65)	17.0 (±2.29)
long object wh	2026.12 (±100.01)	29.17 (±4.39)	1943.66 (±121.72)	21.5 (±3.54)
long whether	2025.94 (±90.15)	16.11 (±4.93)	2049.36 (±90.22)	8.25 (±2.04)
overall	1965.46 (±37.41)	21.62 (±3.03)	1906.45 (±42.2)	15.29 (±1.99)

Table 5.3: Reaction times and error rates for individuals with high and low reading span. Standard errors are given in brackets.

5.3.2 Event-Related Potentials

The section reporting electrophysiological results is grouped into three subsections corresponding to the ERPs examined. First, potentials elicited by the question word at the initial position of the subordinate questions are reported. Following this, analyses of multi-word ERPs starting from the onset of the question word are described for long and short questions. Effects of span group are also discussed. In the third subsection, local ERPs elicited at the second noun phrase of the embedded questions will be reported.

Presentation of ERP results will focus on late or 'endogenous' components of the ERP elicited by language stimuli. Early components of the event-related potential like the N100 and the P200, which are elicited by every word onset in the sentence and which are generally assumed to reflect sensory aspects of language processing (e.g., Neville et al., 1992; Osterhout & Holcomb, 1992; Mecklinger et al., 1995), will only be mentioned briefly in the next subsection.

5.3.2.1 Local ERPs to Question Words

The P200 component differed between wh-questions and whether-questions (as can be seen in Figure 5.1 for centro-parietal electrodes Cz and Pz). The slightly greater amplitude of the P200 component in wh-questions is most probably due to the greater number of letters in these conditions (i.e., 'wer' or 'wen') as compared to the question word 'ob'.

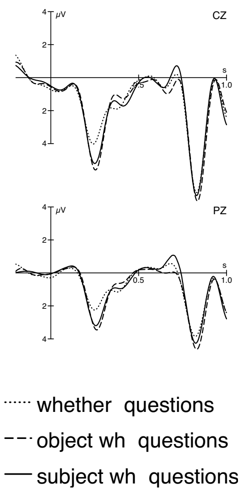

Figure 5.1: *Local ERPs elicited by subject (solid line) and object (dashed line) wh-questions as well as whether-questions (dotted line) at the subordinating question word (collapsed across sentence length). Displayed are one central (Cz) and one parietal (Pz) midline electrode. The complete array of electrodes is displayed in Appendix A, Figure 8.1.*

Apart from this early sensory effect, no effects of sentence type were present at the question words. Visual inspection revealed that ERPs to object wh-questions were slightly more positive going than those to subject wh-questions between 600 and 750 ms. This positivity was analyzed in separate ANOVAs with lateral and midline ROIs. In both analyses, neither the main effects of sentence type or sentence length nor any interaction of sentence type with topographical factors or sentence length was reliable even in time windows as small as 50 ms (all $F < 1.5$).

As there was no effect of sentence length, ERPs displayed in Figure 5.1 were collapsed across sentence length. The complete set of electrodes is displayed in Figure 8.1 of Appendix A.

5.3.2.2 Multi-Word ERPs to Embedded Questions

Long question conditions. Due to the different number of words of the embedded questions in short and long conditions, multi-word ERPs elicited by short and long questions were analyzed separately. Long object wh-questions elicited a sustained negativity relative to long subject wh-questions (cf. Figure 5.2). Visual inspection of the grand average ERPs yielded that this negativity started at about 400 ms after the onset of the first prepositional phrase (i.e., 'am Dienstag') and ceased at most electrodes at around 900 ms after the onset of the last phrase of the prepositional phrases (i.e., 'dem Unfall'). A laterality ANOVA (see Section 5.2.5) using exactly this time window (i.e., 1,000 to 3,400 ms after the onset of the question word) showed a significant main effect of sentence type ($F_{2,42}$ = 4.46; $p < .05$). Planned comparisons revealed that the main effect of sentence type was due to (a) significantly more negative potentials in the object condition as compared to the subject wh-questions ($F_{1,21}$ = 6.64; $p < .033$; see Figure 5.2), and (b) the fact that the multi-word ERP elicited by the long whether-question was between the two wh-questions, but closer to the object question, thus also differing significantly from subject wh-questions ($F_{1,21}$ = 5.71; $p < .033$; see Figure 5.3). As the comparison of the topographical potential maps in Figures 5.2 and 5.3 displays, the negativity for whether-questions was smaller and less focused than that for object wh-questions.

To demonstrate that the application of the detrending algorithm did not influence the effects observed in this experiment, ERPs to long subject and object wh-questions, and their difference wave, as calculated from the detrended signal (see Figure 5.4 C and D) were compared with the corresponding ERPs calculated from the original EEG signal before detrending (Figures 5.4 A and B). Analysis of variance of the difference waves using the same time window as in the previous analysis showed that detrending did not introduce reliable differences between the two effects (all $F < 1.2$).

The topographical potential map of the difference between object and subject wh-questions in the analyzed time window (cf., Figure 5.2A) reveals that the sustained negativity was maximal at left-anterior electrode positions. This observation is supported by the finding of a significant interaction of sentence type with hemisphere and scalp extension ($F_{2,42}$ = 3.69; $p < .05$). The interaction can be followed up to show a main effect of sentence type over left-anterior electrode sites ($F_{2,42}$ = 5.13; $p < .05$) that is due to a reliable difference between subject and object wh-questions in this ROI as revealed by planned comparisons ($F_{1,21}$ = 7.11; $p < .033$). In this ROI, ERPs to whether-questions did not differ from ERPs elicited by subject wh-questions ($F_{1,21}$ = 2.1; $p > .15$).

In order to describe the time-course of the sustained left-anterior negativity in more detail, six time windows corresponding to the phrases or words presented during the embedded questions (i.e., from the wh-filler to the second NP) were extracted from the multi-word ERP and analyzed separately

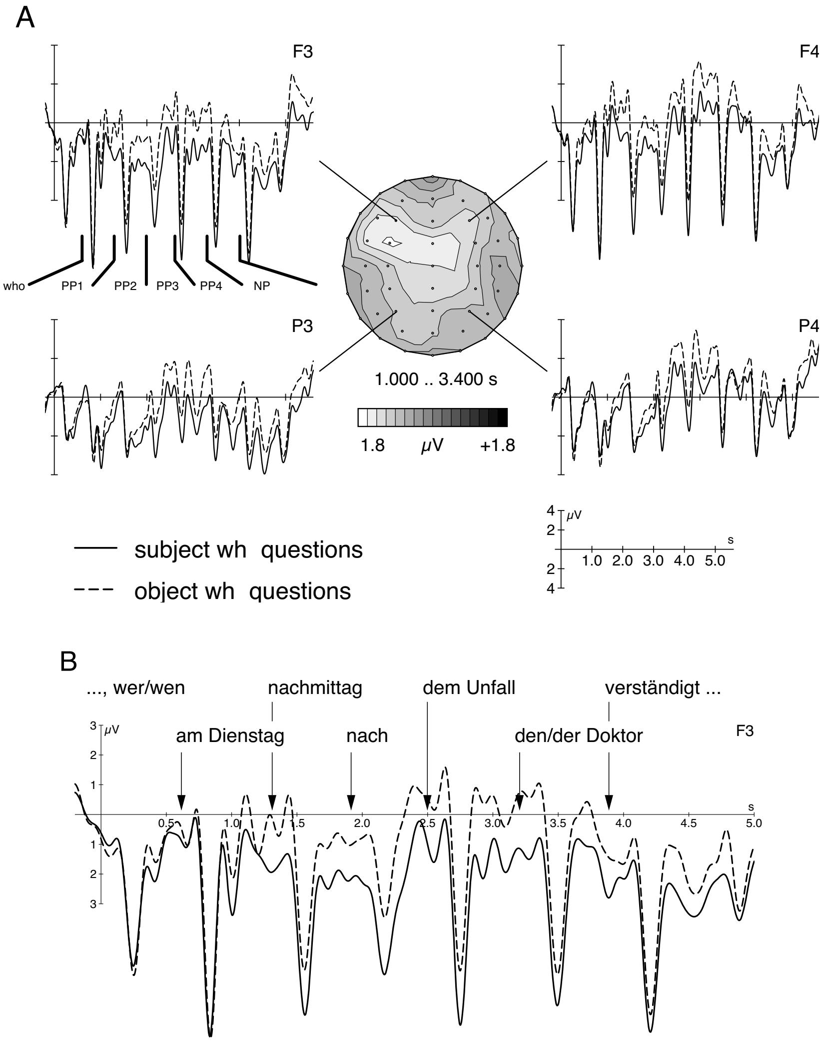

Figure 5.2: *Multi-word ERPs averaged from the onset of the interrogative pronoun for long subject (solid line) and long object (dashed line) wh-questions for one selected electrode from each ROI and as a scalp topographical potential map representing the difference between object and subject wh-questions (A). In the difference maps, bright grey reflects negative-going ERPs for object questions. (B) illustrates the onset of words and phrases relative to the multi-word ERP at left-anterior electrode F3. The complete array of electrodes is displayed in Figure 8.2 of Appendix A.*

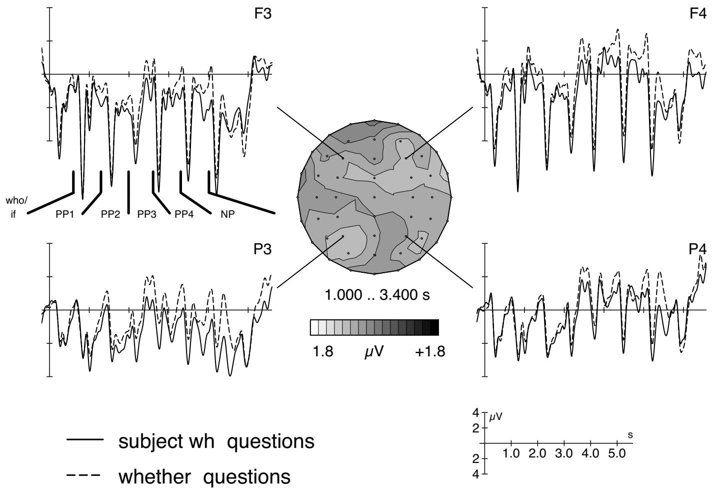

Figure 5.3: *Multi-word ERPs averaged from the onset of the interrogative pronoun for long subject wh-questions (solid line) and long whether-questions (dashed line) for one selected electrode from each ROI. The topographical potential map displays the difference between whether and subject wh-questions. The complete array of electrodes is displayed in Appendix A, Figure 8.3.*

for subject and object wh-questions. Each time window started at 400 ms after the onset of the corresponding phrase or word and lasted for 350 ms for single words or for 450 ms for phrases (in correspondence with the 100 ms difference in presentation duration; cf. Table 5.4 for the exact time windows covered). These time windows were defined such that sensory P200 components were not entered into the averages.

From the topographical maps displayed in Figure 5.5 it is evident that the sustained negativity became more and more pronounced until the last of the prepositional phrases was reached. At the second noun phrase position, however, the broadly distributed negativity changes abruptly its topography and only a small focus over left anterior electrodes remains. This time course is confirmed by a significant interaction of the factors time window and sentence type ($F_{5,105} = 4.00$; $p < .005$). The third row of Table 5.4 gives the results for the main effect of sentence type, analyzed in each time window separately. These statistics confirm the time-course of the negativity as displayed in Figure 5.5. Furthermore, the factor time window also entered a four-way interaction with hemisphere, scalp extension and sentence type ($F_{5,105} = 2.95$; $p < .05$), indicating that the identified time course of the negativity was present most clearly over left-anterior electrodes (cf. Table 5.4).

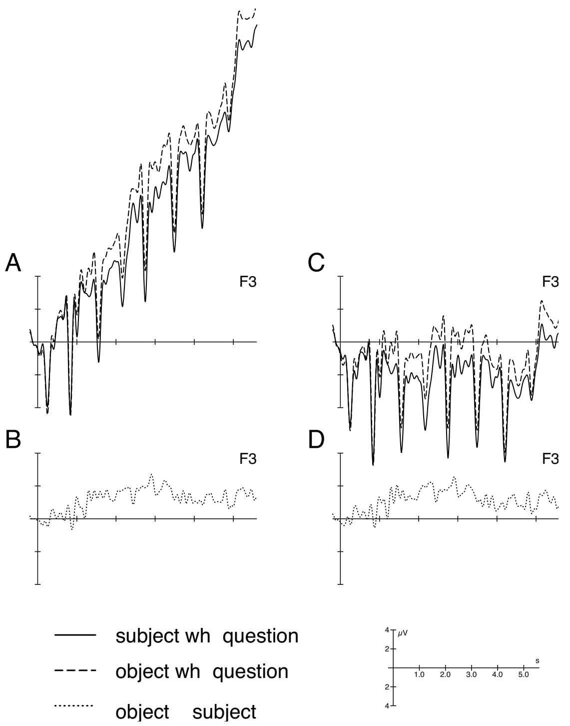

Figure 5.4: *Multi-word ERPs for subject and object wh-questions and corresponding difference waves calculated from the original EEG signal before detrending (A,B) and after detrending (C,D).*

Short question conditions. Short question conditions were analyzed in a time window that was defined in analogy to the one used for long questions. It lasted from 400 ms after the onset of the prepositional phrase to 900 ms after its onset, resulting in an effective time window of 1000 to 1500 ms relative to the onset of the question word. No significant differences between subject and object wh-questions and whether-questions were obtained in this time window. Furthermore, no interactions involving the factor sentence type became significant.

As, however, visual inspections of the ERPs to short subject and object wh-questions suggested a small negativity at left anterior electrodes for short object as compared to subject questions at the prepositional phrase (indicated by an arrow in Figure 5.6)[1], an additional ANOVA was calculated with a smaller time window (i.e., 700 to 800 ms after onset of the PP). At this position in the sentence, the participants could not be aware of the length of the filler-gap distance of the current sentence. For this

[1]ERPs for short whether-questions, together with short subject wh-questions, are shown in Figure 8.5 of Appendix A.

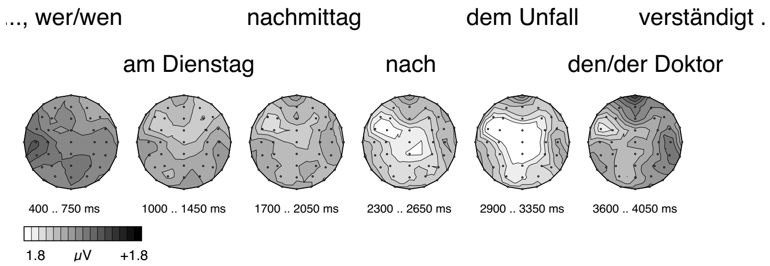

Figure 5.5: *Multi-word ERP difference between object and subject wh-questions displayed as topographical potential maps for the time windows specified in Table 5.4.*

	Time Windows					
	wer/wen who	am Dienstag on Tuesday	nachmittag afternoon	nach after	dem Unfall the accident	den/der Mann the man
milliseconds	400-750	1000-1450	1700-2050	2300-2650	2900-3350	3600-4050
main effect	-	#	-	*	**	-
left anterior ROI	-	#	#	*	**	-

Table 5.4: Time window analysis of the sustained negativity between long object and long subject wh-questions. Row three displays statistical results for the main effect of sentence type and the bottom row shows the effects of sentence type in the left anterior region of interest. '-' stands for not significant ($F < 1.5$), '#' equals $p < .1$, '*' is $p < .05$, and '**' signifies $p < .01$.

reason, short and long wh-questions were both entered into this analysis. There was no main effect of sentence length or interaction between sentence type and sentence length in this analysis ($F < 1$), supporting the assumption that at this point, participants were not aware of the length condition of the present sentence. However, a marginally significant main effect of sentence type ($F_{2,42} = 2.66$; $p < .1$) could be resolved to demonstrate a reliable negativity for long and short object wh-questions, as compared to subject wh-questions ($F_{1,21} = 4.22$; $p = .05$) that was strongest over anterior electrode sites, as revealed by an interaction of scalp extension (i.e., anterior vs. posterior) and sentence type ($F_{1,21} = 9.04$; $p < .01$).

Effects of span group on multi-word ERPs. The dependency of the sustained negativity in long wh-questions upon individual working memory capacity was investigated by repeating the above analyses with the additional between-subjects factor span group. In the long time window, these analyses revealed two interactions of sentence type and span group with topographical factors. First, a reliable three-way interaction with hemisphere ($F_{2,34} = 3.96$; $p < .05$) could be resolved to show a

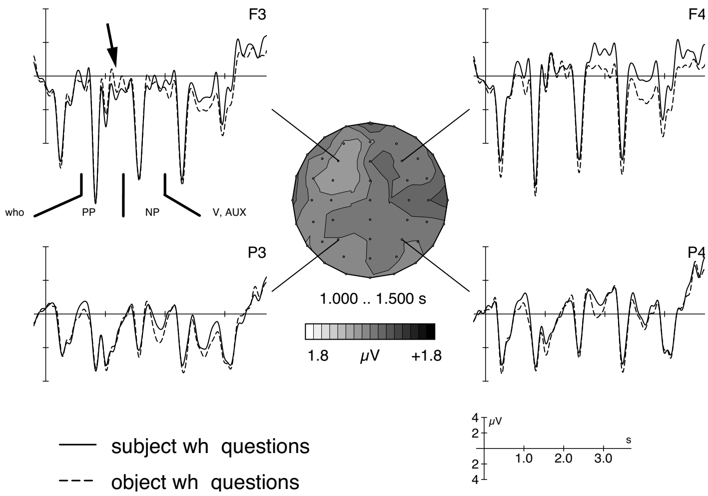

Figure 5.6: *Multi-word ERPs averaged from the onset of the interrogative pronoun for short subject (solid line) and short object (dashed line) wh-questions for one selected electrode from each ROI and as a scalp topographical potential map. The complete array of electrodes is displayed in Figure 8.4, Appendix A (cf. also Footnote 1).*

significant interaction of hemisphere with sentence type in the low span group ($F_{2,18}$ = 5.17; $p < .05$) but not in the high span group ($F < 1$). This result reflects a lateralization of the sentence type effect to the left hemisphere ($F_{2,18}$ = 4.01; $p < .05$; $F < 1$ for the right hemisphere) in the low span group only (cf. Figure 5.7). Planned comparisons revealed that over the left hemisphere, ERPs to object wh-questions were significantly more negative than ERPs to subject wh-questions in this group ($F_{1,9}$ = 6.53; $p < .033$).

The second interaction involved the factors scalp extension, sentence type, and span group ($F_{2,34}$ = 4.17; $p < .05$). This effect was caused by a marginally significant extension by sentence type interaction ($F_{2,16}$ = 3.14; $p = .07$) in the high span group. Although Figure 5.7 reveals that the negativity for long object as compared to subject wh-questions manifests itself primarily over anterior electrode sites in the high span group, this interaction could not be further resolved.

Furthermore, there was no four-way interaction observed between span-group, hemisphere, scalp extension, and sentence type. Nevertheless, the previous results justify the conclusion that participants with low working memory capacity displayed a greater and more broadly distributed sustained negativity with a maximum over left central and parietal electrodes while the negativity displayed by high-span subjects was more focused to anterior electrode sites bilaterally with a slight dominance of the left hemisphere. Statistically, the time course of the sustained negativity did not differ between

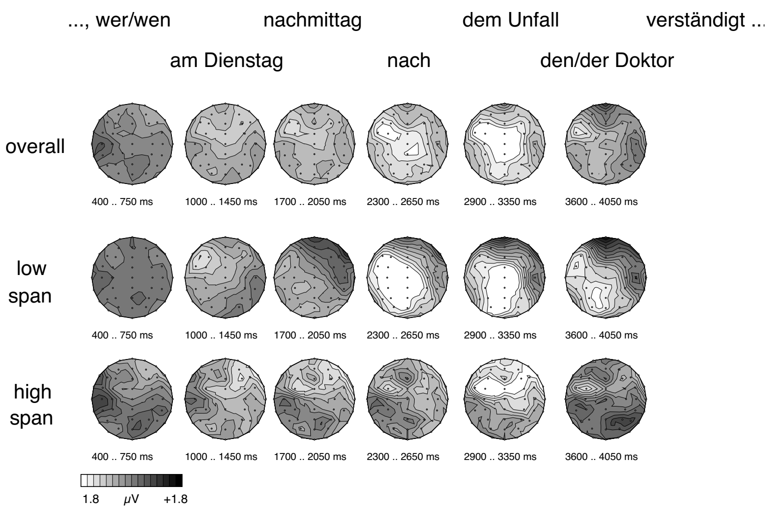

Figure 5.7: *Topographical potential distributions corresponding to the time windows displayed in Table 5.4 for the complete sample (see Fig. 5.5) as well as for individuals with low (n = 9) and high (n = 10) working memory capacity.*

the two groups. However, visual inspection of the difference maps shown in Figure 5.7 suggests that the sustained negativity was present earlier in the low span group than in the high span group.

5.3.2.3 ERPs elicited by the Second Noun Phrase

Visual inspection of multi-word ERPs elicited by short wh-question suggests that object wh-questions elicited more positive-going ERPs than subject questions at the second noun phrase position (cf. electrodes P3 and P4 in Figure 5.6). This effect was examined with local ERPs averaged from the onset of the second noun phrase. At this position a positivity for object wh-questions as opposed to subject wh-questions was observed in the time window between 400 and 700 ms which peaked between 500 and 550 ms (cf. Figure 5.8). This effect was maximal over midline electrodes. ERP waveforms elicited by whether-questions were situated between the two wh-questions (cf. Figure 5.9).

An ANOVA with four midline ROIs yielded a reliable main effect of sentence type ($F_{2,42} = 4.33$; $p < .05$) with a significant difference, according to planned comparisons, between subject and object wh-questions ($F_{1,21} = 6.39$; $p < .033$; cf. Figure 5.8A). Whether-questions did not differ from subject wh-questions ($F < 1$) but tended to be less positive-going than object questions ($F_{1,21} = 3.76$; $p = .07$; cf. Figure 5.9). The amplitude of the positivity for object wh-questions did not differ statistically between the four ROIs (all interactions involving region of interest were $F < 2$).

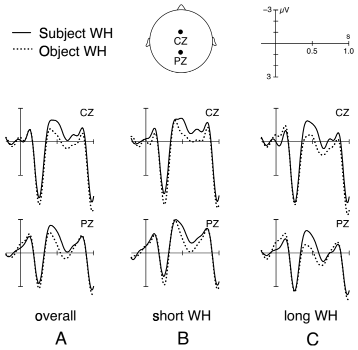

Figure 5.8: *Local ERPs elicited by subject (solid line) and object (dotted line) wh-questions at the second noun phrase position at electrodes Cz and Pz, collapsed across short and long sentence conditions (A) as well as separately for short (B) and long (C) wh-questions.*

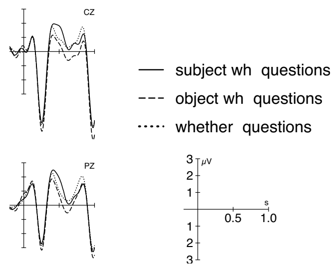

Figure 5.9: *Local ERPs to subject, object and whether questions at the second noun phrase position (collapsed across sentence length). See Figure 8.6 of Appendix A for the complete set of electrodes.*

The interaction between sentence type and sentence length was not significant ($F < .5$), suggesting that the positivity for object wh-questions was present both in short (Figure 5.8B) and long (Figure 5.8C) wh-questions. This result justified the strategy of averaging local ERPs although there was a sustained negativity present in long sentence conditions on the previous word which was used as baseline. Figure 5.8A displays the local ERPs collapsed over long and short sentence conditions. A main effect of sentence length ($F_{1,21} = 8.17$; $p < .01$) reflects the fact that across sentence types, ERPs elicited by long questions were more positive-going than those elicited by short questions (Figure 5.10). There were no differences between individuals with high and low reading span with respect to the positivity elicited at the second noun phrase position (all $F < 1.5$).

5.3.2.4 Summary

To summarize, the following pattern of effects observed: While local ERPs to the question words did not differ between sentence types, wh-movement of the object NP into clause-initial position induced a sustained left-anterior negativity as compared to wh-movement of the subject in long wh-questions. Short object wh-questions elicited a very short-lived negativity that lasted for about 100 ms. The

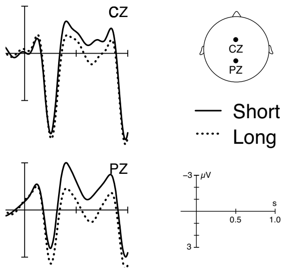

Figure 5.10: *Local ERPs elicited by short (solid line) and long (dotted line) questions at the second noun phrase position (collapsed across sentence types).*

sustained negativity for long object questions started at the first prepositional phrase in the sentence, i.e. at the position after the wh-filler, and lasted until the subject noun phrase was encountered. The negativity became more and more pronounced with increasing distance from the filler. As there was no comparable sustained negativity found for short object wh-questions, it can be concluded that the sustained negativity is directly related to the distance over which the wh-filler has to be maintained in working memory. Furthermore, as expected in prediction 3, the negativity was stronger, more broadly distributed and appeared earlier in the course of the embedded question in individuals with low working memory capacity than in high capacity individuals.

These ERP results were supported by the behavioral data which demonstrated (a) that slightly more errors were made for long object wh-questions than for long wh-subject questions and (b) that individuals with low working memory capacity made more errors than those with high working memory capacity.

At the second noun phrase position, a local positivity between 400 and 700 ms was elicited for object as opposed to subject wh-questions, independent of the distance between the filler and the gap. The positivity observed at the second noun phrase position had a greater amplitude in long questions (when collapsed over sentence types) than in short questions.

ERPs to whether-questions also were more negative-going than those elicited by subject wh-questions. However, this negativity was small in amplitude and there was no consistent topographical distribution like it was observed for object wh-questions in the long time window. At the second noun phrase position, ERPs to whether-questions did not differ reliably from those elicited by subject wh-questions.

5.4 Discussion

5.4.1 Behavioral Results

The behavioral data did not exhibit strong effects of sentence type, apart from the fact that short questions were answered faster than long questions, whether-questions elicited less errorsthan wh-questions, and slightly more errors were made in long object questions than in short subject questions. This result is probably due to two factors. First, the items were long and difficult to answer, as indicated by the long reaction times and by the high number of errors. Most probably, participants did have enough time to restructure the items before responding, thus minimizing behavioral differences between the different conditions in the off-line measures. The delay of 800 ms between the offset of the item and the onset of the probe assertions might have been used for such processes of restructuring. Second, participants were not instructed to give speeded responses. They were asked to focus more on giving correct answers. This instruction also might have contribute to minimizing behavioral differences in reaction times and error rates.

Nevertheless, the main effect of span group was in line with prediction three. It was expected that individuals with a low working memory capacity might exceed their total amount of working memory capacity more often in processing these sentences. In support of this prediction, reliably more errors were made in the low capacity group. This finding suggests that processing these complex sentences was highly demanding in terms of working memory capacity. However, on the basis of these behavioral off-line data, it can not be concluded whether the span-group difference was due to processes related to on-line sentence processing or to post-interpretive performance in the behavioral task. The fact that performance in all conditions was worse in these subjects might suggest that this effect is more due to the post-interpretive aspect of the experiment. However, the main purpose of registering behavioral responses in this experiment was to identify trials that were incorrectly answered in order to not include them into the analyses of ERPs.

5.4.2 Question Words

The fact that there were no differences between ERPs elicited by subject and object wh-fillers in clause-initial position did not come unexpected. As already pointed out in the first paragraphs of this section, there are no strong preferences for subject-initial constituent questions in the pragmatic or structural domain (cf. Schlesewsky, Fanselow, Kliegl & Krems, 2000). Previous data appear to be in line with this finding. Corresponding results have been obtained in self-paced reading studies where reading time increases for object questions at the wh-filler were only marginal (Fanselow, Kliegl & Schlesewsky, 1999).

Interestingly, although wh- and whether-questions differed at this position with respect to the presence or absence of a verbal argument, there were also no ERP differences between these conditions (other than a difference in the P200 amplitude that was obviously induced by the difference in the amount of sensory input). It appears, thus, that at the clause initial position itself, neither the fact that there is no argument at all in whether-questions nor the recognition of a non-canonical argument order in object questions does lead to an increase in processing costs as reflected in ERPs. Most importantly, the clause-initial object does not trigger the build-up of a more complex phrase structure representation right away, at least not as reflected in ERPs. This conclusion appears to be in line with previous data from grammatically correct questions with moved and unmoved complementizers (e.g., Kluender & Kutas, 1993a; Kaan, Harris, Gibson & Holcomb, 2000). In these studies, no effects were reported for the question words, suggesting that there were probably no differences found in the ERPs between the subordinating interrogative pronouns and other complementizers such as 'if', 'whether' or 'that'. In these studies, analyses were reported only for the words following the question words (i.e., Kluender & Kutas, 1993a) or for the verbs of the embedded clauses (i.e., Kaan et al., 2000).

However, there have also been reports of negativities for wh-fillers as opposed to non-moved complementizers such as 'if' or 'that' (Kluender & Kutas, 1993b). This effect was interpreted as a modulation in the amplitude of the N400 component due to increased lexico-semantic differences associated with the wh-filler, which was assumed to be referential in nature (Kluender & Kutas, 1993b). However, this effect could not be replicated in the present experiment. A possible explanation for the difference between these data and the present results might be to assume the triggering of additional processes when encountering ambiguous wh-fillers like the English ones used by Kluender and Kutas (1993a).

In contrast to wh-interrogative pronouns, case-unambiguous object relative pronouns in German relative clause sentences have been demonstrated to elicit a positivity between 500 and 900 ms at the embedded clause boundary (Friederici et al., 1998). This positivity was argued to reflect a violation of the subject-preference in German by the object relative pronoun. As already argued above, this preference is much less pronounced in wh-questions. Thus, the present data are not contradicting previous results obtained from the investigation of case-unambiguous relative clauses.

5.4.3 Filler-Gap Dependency

The sustained left-anterior negativity which we selectively observed for long object wh-questions appeared to vary with the distance over which the filler was moved. This result can be taken as support of predictions 1 and 2. Prediction 1, as such, can only be partly supported because the sustained negativity was only observed in long object wh-questions but not in short wh-questions. However, this result is qualified by the finding of a dependency of the negativity upon the length of the filler-gap distance. As expected in prediction 2, the sustained negativity was stronger when the filler-gap distance was greater. Thus, the present data provide strong support for the working memory hypothesis.

The present data are also in line with previous behavioral studies which demonstrated increased reading times for unambiguously marked object wh-questions (Fanselow et al., 1999; Schlesewsky, Fanselow & Kliegl, manuscript). In addition, they extend previous ERP data by delineating the time course of working memory involvement during sentence processing in a more fine-grained way and without being confounded with local effects due to differences in word category. On the basis of the present results, the sustained negativity can be unambiguously associated with the bridging of the filler-gap distance because it was observed exactly between these two constituents of the phrase structure (see below). Further support for the interpretation of the sustained negativity as a reflection of working memory costs comes from the topographical similarity of this ERP component with frontal slow wave potentials reported in ERP studies of verbal working memory. For example, Ruchkin and co-workers (1990) reported a frontally negative ERP wave for the retention interval of a verbal memory task that increased with load. This negativity was also lateralized to the left hemisphere.

The cognitive resources supporting the working memory process which is reflected in the sustained negativity were demonstrated to be dependent upon the participants' working capacity. The successful processing of object wh-questions obviously was more effortful for individuals with low working memory capacity, as indicated by amplitude, scalp distribution and temporal aspects of the sustained negativity. This finding supports prediction 3. Importantly, the group difference was not present at all positions of the sentence, suggesting that it is only a specific aspect of processing object wh-questions which is more taxing for low-capacity individuals.

As was discussed in Chapter 1, the filler needs to be linked to its gap during sentence processing in order to allow, for example, the assignment of a functional role to the moved element. The appearance of the sustained left-anterior negativity between the filler and its gap position strongly supports the assumption that working memory mechanisms are critically involved in this process of forming a syntactic chain between the moved element and its original position. In order to establish this chain, the object wh-filler (or some of its syntactic features) has to be maintained in working memory until it can be linked to the gap. The fact that this aspect of parsing is much more demanding for individuals with a low working memory capacity strongly suggests that working memory resources are required for this aspect of parsing. In short object wh-questions, on the other hand, the filler-gap distance was so short that there was no need to spend a comparable amount of resources in order to make the linking of filler and gap possible.

The focus over left-anterior electrodes is very similar to the distribution of local ERP effects elicited by syntactic violations (i.e., ELAN or LAN effects). This analogy might be taken to suggest that the working memory processes observed in the present study and the detection of syntactic anomaly involve brain regions that are overlapping or, at least, located very close to each other. Although it is not claimed here that the sustained negativity belongs to the family of transient left anterior negativities discussed in Section 3.3.3, the similarity in scalp topography might be taken to suggest that the working memory process observed here is syntactic in nature. However, it has to be pointed out that left anterior negative slow waves have been observed in classical verbal working memory tasks (e.g., Ruchkin, Johnson, Canoune & Ritter, 1990) as well as in different other working memory paradigms (cf. Section 3.3.6). Nevertheless, it is unlikely that the sustained negativity reflects an increased load on the articulatory rehearsal system of the multi-component working memory model as both subject and object wh-questions have the same number of words. There is no evidence that would suggest a greater involvement of verbal working memory in syntactically more complex sentences during on-line parsing (see Section 2.2 and Caplan et al., 2000). Furthermore, it is unlikely that the appearance of the sustained negativity was related to performance in the behavioral task (in the sense of, e.g., a contingent negative variation; cf. Coles & Rugg, 1995) because it disappeared before the end of the sentence.

Instead, based on both scalp topography and psycholinguistic considerations, it is suggested here that the working memory mechanism reflected in the sustained left-anterior negativity is syntactic in nature and internal to the parsing mechanism, as it was proposed, e.g., by Caplan and Waters (1995, 1999). This conclusion is similar to the distinction between local LAN effects, elicited by (morpho)syntactic violations, and global LAN effects reflecting increased working memory load, which was recently proposed by Kluender and colleagues (1998). However, this terminological similarity should not be taken to indicate that the underlying neural generators of these components are identical. Only two out of four criteria used for defining ERP components, namely polarity and scalp topography, are identical in the two classes of effects. The temporal characteristics and the functional characteristics leading to the appearance of the two components are clearly distinct.

It is of special significance that the working memory component observed in this experiment could be elicited without adding concurrent load to the verbal working memory system while sentence processing is accomplished. This approach was taken in many other studies of working memory and language (e.g., King & Just, 1991; Vos et al., 2001a,b). In the present study, all effects reported were obtained from purely syntactic manipulations of the sentence structures processed. Interestingly, the distribution of the sustained negativity that indexes syntactic memory load in the present study was similar to a sustained negativity that was related to the amount of load present in an experiment reported by Vos et al. (Vos et al., 2001a). In the latter study, a negativity was reported for the high load condition (i.e., three words as opposed to one word) which was broadly distributed over frontal electrodes. This negativity was also stronger for individuals with low capacity (Vos et al., 2001a). The characteristics of the present effect differed, however, from a load-related negativity reported in an other study reported by Vos, Gunter, Schriefers, and Friederici (2001b). In this experiment, a local negativity was elicited that was broadly distributed for high-span readers while it was maximal at posterior scalp in the low span group. The strength of this load-related negativity was the same in both groups.

It is also important to note that the sustained negativity was not elicited by the fact that the prepositional phrases encountered between the question word and the noun phrase have been scrambled from within the verb phrase to their actual position on surface structure. As was argued elsewhere (Friederici, Schlesewsky, & Fiebach, in press; cf. also Rösler et al., 1998), scrambling operations elicit transient LAN effects, indicating that scrambled phrases induce local syntactic violations. Such an effect was not observed in local ERPs elicited by the prepositional phrases in this experiment (see Appendix 8.4, Figures 8.7 and 8.8 for the corresponding local ERPs for subject and object wh-questions elicited at the PPs in the long wh-questions).

Finally, it shall be noted that one aspect of evidence in favor of the working memory assumption proposed here could not be obtained in the present experiment. It would have been of interest to directly contrast ERPs elicited by long and short object wh-questions. However, this analysis was not possible in Experiment 1 because the two sentence conditions differed in their absolute length. In Experiment 2, this comparison will be possible by including the prolonged prepositional phrases in all sentence conditions (see next chapter).

5.4.4 Second Noun Phrase

At the second noun phrase position, no syntactic violation was present and there was no need for reanalysis processes like in temporarily ambiguous structures (cf. Section 3.3.3). Instead, a local difference in processing complexity was predicted at the second NP position based on behavioral findings suggesting that the gap position becomes available at this position. The observation of a sustained negativity between the filler and its gap suggested that at the clause initial wh-filler, formation of a syntactic chain between the filler and its gap had to be delayed in object questions, leading to an increased working memory load. When in object wh-questions the subject is encountered, the phrase structure representation can be projected into the verb phrase, thereby making the object trace available to the parser. At this position, the filler-gap dependency can be established. It follows that upon encountering the subject NP, both the subject and the object of the sentence (the latter in the form of the syntactic chain between the moved element and its gap) can be integrated into the mental representation of the phrase structure. In subject questions, in contrast, the subject filler was integrated immediately when it was encountered in clause-initial position. Accordingly, at the position of the second NP in subject questions, the object will be identified and integrated into the phrase structure.

A broadly distributed positivity was elicited for object as opposed to subject wh-questions at the second NP for both short and long object wh-questions. Although this ERP effect is very similar to the positive ERP components elicited by syntactic anomaly (e.g., Friederici et al., 1993; Osterhout & Holcomb, 1992), the present ERP component reaches its maximum slightly earlier than the classical P600 effects. In line with a recent interpretation of P600 effects in syntactically correct and unambiguous sentences which was put forward by Kaan and colleagues (2000), it can be assumed that the positivity observed here reflects the difficulty of local integration processes associated with this position in the sentence. More precisely, it is assumed that the positivity is due to the integration of the moved element, which is stored in working memory, with its gap position. However, it can not be definitively determined whether the positivity was elicited by the fact that linkage between the filler and its gap takes place at this position or whether it is due to the fact that in object wh-questions, two arguments (i.e., the subject and the object) can be integrated into the phrase structure at this position while in subject wh-questions, only the object needs to be integrated at the second NP (see above).

Interestingly, although the present finding of a late positivity at the second noun phrase is in line with the results reported by Kaan and colleagues (2000) regarding the difficulty of integration processes, it is not supporting the way integration costs are calculated for specific positions of the sentence in the SPLT framework (cf. Gibson, 1998). As already outlined in the introductory remarks of this chapter, SPLT assumes that linguistic integration costs increase when the number of discourse referents intervening between two elements to be integrated increases (i.e., distance-based integration costs; cf. [20]). In German, however, the distance is found between the wh-filler and the second NP in both subject and object wh-questions. Nevertheless, ERPs indicate that local parsing processes at the second NP are more costly in the object wh-condition.

Further support for the interpretation of the late positivity as reflecting integration difficulty comes from the finding that long questions, collapsed across sentence types, elicited more positive-going potentials than short questions. In this case, SPLT's locality assumption can be applied. Local parsing processes that integrate new input with previous arguments (like, e.g., an object NP with a previously processed subject NP) were proposed to be more difficult when the distance between the elements to be integrated is great (cf. SPLT; Gibson, 1998). This is the case in the long wh-questions of this study. In these sentences, more prepositional phrases separate the wh-filler and the second NP, thus making integration processes more difficult[2]. Consequently, a stronger late positiviy is observed at the second NP position. The present data, thus, provide evidence for the principle of locality as assumed in the context of SPLT. However, they also suggest that other aspects of syntactic processing can influence the difficulty of processes of integration.

It should be noted that the interpretation of this positive ERP component as reflecting the process of establishing the dependency between the filler and the corresponding gap position is in opposition to the interpretation given by Kluender and Kutas (1993a) for their data. These authors proposed that recovering the stored filler from memory is associated with a left anterior negativity. Note that this interpretation is not in line with the AFH as it implies (a) that the filler is not maintained actively available and (b) that filler-gap assignment takes place when the word following the gap position is processed, i.e., in a gap-as-second-resort way. The present finding of a positivity, in contrast, is confined to the position preceding the gap, supporting the notion of predictive gap localization (e.g., Muckel & Pechmann, manuscript).

Parsing processes indexed by the late positivite effect appear to be independent of the resources that support the syntactic working memory processes reflected by the sustained negativity. This can

[2]Note, however, that Gibson (1998) defined distance as the number of intervening discourse referents. It is not clear whether or not the prepositional phrases used in the present study fall under this definition.

be concluded because only the latter were influenced by the individual working memory capacity of the participants.

5.4.5 Whether-questions

The fact that whether-questions also elicited a sustained negativity relative to subject wh-questions can be accounted for by the fact that in these sentences, no subject NP is encountered for a considerable portion of the sentence. In terms of Syntactic Prediction Locality Theory (Gibson, 1998), the parser has to maintain the syntactic prediction of a subject and a verb that are minimally required to form a grammatical sentence when processing a whether-question. In subject wh-questions, in contrast, only a verb needs to be predicted in order to achieve the same goal. The small amplitude of the negativity suggests that maintaining this prediction in working memory is not very costly. Conversely, the finding of a greater negativity in object wh-questions suggests that processing these sentences is clearly more costly in terms of working memory load. According to SPLT, the only difference in the complexity of the syntactic prediction between object and whether-questions is the additional prediction of an object trace in object wh-questions. It is not likely, however, that this prediction can account fully for the difference between whether- and object-questions. An important additional factor contributing to the sustained negativity elicited by object questions is probably the maintenance of the moved element in working memory, as was suggested in the context of the Active Filler Hypothesis (e.g., Frazier, 1987a).

The lack of strong effects between whether-questions and wh-questions in multi-word ERPs is consistent with similar data reported by Kaan, Harris, Gibson and Holcomb (2000). However, the negativity for whether questions relative to subject wh-questions observed in the present study was reliable, suggesting that indeed more information (namely the prediction of a subject) had to be kept in working memory in these sentences. This conclusion is supported by Kluender and Kutas (1993a) who reported negative ERP effects with left anterior distribution for words following moved constituents as opposed to words following unmoved complementizers such as ’if’. The missing effect in the Kaan et al. (2000) study might be due to the fact that whether-questions were compared with object wh-questions which, in the present experiment, elicited an even stronger negativity but also did not differ significantly from whether-questions. However, Kluender and Kutas (1993a) also contrasted if-questions with object wh-questions and obtained local ERP differences. The fact that an ERP effect attributed to working memory processes is observable in their study might be related to the relatively complex sentence structures used in their study (see the discussion of these data in Section 3.3.5) .

At the position of the full NP, ERPs to whether-questions did not differ from those elicited by subject wh-questions. At this position, in subject and whether-questions only one NP had to be integrated into the phrase structure. In subject wh-questions, the object NP is processed and in whether-questions, the subject is encountered. Both are integrated without much effort because there is no additional load present in working memory. In contrast, it is assumed that in object wh-questions, both the newly perceived subject argument and the stored object filler have to be integrated (see above). The fact that there is no difference in local ERPs between subject and whether-questions supports the conclusion derived above that the positivity at the second NP position is reflecting the processing cost associated with integrating two arguments at the same time into the phrase structure.

5.4.6 Theoretical Implications

What implication does the finding of (a) a sustained left-anterior negativity in the region of the filler-gap dependency and (b) a late positivity at the second NP position in German object wh-questions have for models of parsing? First, it can be stated that the present ERP data contribute to the growing body of evidence that supports the psychological relevance of empty categories during sentence processing. The finding that the sustained negativity disappeared at the second NP and the fact that a late positivity was observed at this position were taken to indicate that the syntactic chain between the filler and the gap could actually be established already before the verb of the embedded questions was processed. Accordingly, the present data speak against the Direct Association Hypothesis (see Section 1.4.1) which postulates that a moved constituent is directly associated with the subcategorizing verb in sentences like the present wh-questions. In the case of the present sentences, direct association would predict that integration can take place only at a position in the sentence clearly beyond the assumed gap site. The present data, however, do not confirm this prediction.

Second, the basic assumption of active maintenance of the wh-filler, which was formulated explicitly in the Active Filler Hypothesis (Frazier, 1987a; Frazier & Flores D'Arcais, 1989; Clifton & Frazier, 1989), receives strong support from the present data. Syntactic memory costs can account for processing difficulty over extended regions of sentences. However, while AFH assumed the temporary maintenance of the filler in working memory in the context of ambiguity resolution, the present data demonstrate that these mechanisms are also needed when there is no temporary ambiguity to be resolved. It can be concluded that when a verbal argument is encountered in non-canonical position in the sentence, the build-up of the phrase structure representation is delayed until the subject of the sentence is encountered. The moved element is maintained in memory until its original position, i.e., the gap position, becomes available. With respect to wh-movement, the results of the first experiment suggest that the mechanism that allows the establishment of the filler-gap dependency (i.e., of the syntactic chain that relates filler and gap; cf. Rizzi, 1990; de Vincenzi, 1991) during parsing of sequential linguistic input is a working memory component of the language processing system.

Finally, it can be concluded that it is a valid assumption to differentiate between syntactic memory costs and syntactic integration costs as two aspects contributing to processing difficulty in syntactically complex sentences (Gibson, 1998). The high temporal resolution of the ERP method allowed to tear apart these two aspects of parsing, providing support for this basic assumption of SPLT. This assumption is implicitly present in many other models of sentence processing. Furthermore, the present data suggest that these two aspects of parsing, temporary maintenance and syntactic integration, draw upon independent cognitive resources.

The present data provide further support for the SPLT approach. On the one hand, the amplitude of the sustained negativity, which was strongest for object-initial questions, weaker for whether questions, and least strong in subject-first questions, confirms the SPLT assumption of syntactic predictions that vary in the amount of load on the system. However, the finding that there was no difference in the ERPs elicited by the subordinating question word suggests that the complexity difference of the syntactic prediction is not costly at the element that triggers the prediction. The memory cost is only observable at the elements following the question word. This result indicates that upon detection of the clause-initial object, the parser probably does not build up a more complex phrase structure immediately (as was discussed, e.g., by Friederici and colleagues, 1998, in the context of relative clauses).

On the other hand, the finding of a late positivity that is greater in amplitude for long questions than for short questions can be taken to support the notion of locality that is central to SPLT. More distant integrations (i.e., integrations over a greater number of intervening constituents) are assumed to be more costly and elicit a stronger ERP response.

The question of what exactly is maintained in syntactic working memory can not be answered on the basis of the existing data. From models such as the Active Filler Strategy (Frazier & Flores D'Arcais, 1989), the assumption can be derived that what is held in memory is the filler itself, or some of its syntactic features. SPLT (Gibson, 1998), however, postulates that on the basis of the available input a prediction is made about what constituents are minimally required to form a grammatical clause. Memory costs in this model are due to the maintenance of this prediction, which is more complex for object wh-questions than for subject wh-questions. Both approaches make very similar predictions with respect to working memory load for subject and object wh-questions. However, on the basis of the separate comparisons of object wh-questions and whether-questions with subject wh-questions, it appears that both aspects contribute to the processing difficulty observed in sentences with dislocated object arguments (see Section 5.4.5).

It is difficult to make claims as to whether the two aspects of processing difficulty (i.e., integration costs and memory costs) draw on the same pool of resources (as suggested by Just & Carpenter, 1992) or on separate resources dedicated to different aspects of working memory during sentence processing (e.g., Waters & Caplan, 1996; Caplan & Waters, 1999). However, it was observed that the two ERP components indicative of the two aspects of syntactic complexity (i.e., the local positivity reflecting integration difficulty and the sustained left-anterior negativity) responded differently to the working memory manipulations included in this study. While the sustained negativity was affected both by filler-gap distance and individual working memory capacity, the late positivity for object wh-questions was independent of these variables. This dissociation might be taken to suggest that syntactic working memory and syntactic integration processes draw upon different processing resources. As both the sustained negativity and the integrational positivity occurred during on-line processing of the sentences, both have to be attributed to working memory resources dedicated to the assignment of syntactic structure and to its use in deriving sentence meaning (i.e., to 'interpretive processing resources' as opposed to 'post-interpretive resources' which are involved in using the propositional content of sentences to accomplish behavioral tasks; cf. Caplan & Waters, 1999). The present dissociation with respect to individual working memory capacity might be taken to suggest a further subdivision within the domain of 'interpretive processing resources'. Local computational processes such as syntactic integrations, on the one hand, and more sustained storage or maintenance processes, on the other hand, might require different cognitive or neural resources dedicated to parsing.

5.5 Conclusion

The results of the present study demonstrated that the analysis of both local ERP effects and multi-word ERPs is important for understanding the cognitive mechanisms that contribute to a correct processing of sentences. With regard to psycholinguistic theory, the data suggest that the establishment of a filler-gap dependency is not merely a representational assumption but is a psychologically valid process that unfolds in time. Due to the sequential nature of the linguistic input, syntactic working memory resources play a critical role in the reconstruction of the filler-gap dependency during parsing. In Experiment 1, maintenance of the moved wh-filler in working memory over an increased distance was reflected by a sustained left-anterior negativity. Freeing memory from this load and integrating the dislocated element into the phrase structure representation was indexed by a different ERP component with positive polarity that was detected at the second NP position. The two mechanisms were independent as they (a) elicited ERP components with different time scales, topographies and polarities, and (b) were differentially affected by the length of the filler-gap distance as well as by individual differences in working memory capacity.

Chapter 6

Experiment 2: Replication and Extension of Experiment 1

Experiment 2 was motivated by three goals. First, it was intended to provide a replication of the main findings of Experiment 1 (i.e., of the sustained negativity and of the late positivity at the second noun phrase in object wh-questions). Second, it was designed in a way that allowed a direct comparison between short and long object wh-questions. As was discussed in the last chapter, the sentence stimuli used in Experiment 1 did not allow a direct comparison between these two conditions because they differed in the total number of words. However, this comparison is of great interest because it can show how the presence of a working memory load, induced by maintaining the wh-filler in memory, affects the processing of certain parts of the sentence. While the presence of the working memory load was is also manipulated in the comparison of long subject and object questions, this comparison is confounded with a difference in the order of verbal arguments. When directly contrasting short and long object wh-questions, both sentence conditions have a non-canonical order with a moved object in clause-initial position. Accordingly, effects observed in this analysis can not be attributed to changes in the argument order but have to be related to the presence of a concurrent syntactic working memory load due to the unintegrated filler.

Third, Experiment 2 was intended to serve as a pre-test for an fMRI experiment using the same linguistic manipulations as the first ERP experiment (i.e., subject vs. object wh-questions and short vs. long filler-gap distance in the object wh-questions). However, for a brain imaging study, two major changes had to be made in the design. On the one hand, it had to be assured that the amount of sensory input (i.e., the number and length of the words of a sentence) was equated across conditions. This is important because if the amount of sensory input differs, direct contrasts between two activation conditions might result in activation differences that are not related to parsing processes but to sensory processing. Accordingly, it had to be assured that the different sentence conditions did not differ in the number of words like it was the case in Experiment 1. Second, there is a maximum duration that a functional measurement in the MR scanner should not exceed in order to be acceptable for the participants and in order to keep the size of the functional data sets within a certain limit that can be handled by the analysis software. These two design constraints were not met in the first ERP experiment. For this reason, a shorter design with slightly different stimulus material in the short question conditions was chosen for Experiment 2 and, subsequently, for the fMRI study (i.e., Experiment 3). In addition, fewer participants were measured, like it is generally done in fMRI studies (i.e., 14 in Experiments 2 and 3; cf. for example Vitouch & Glück, 1997, for a discussion of sample sizes in neuroimaging research) and no span group comparisons were made. Furthermore, whether-questions were not included in this experiment.

6.1 Methods

6.1.1 Material

In this study, four critical sentence conditions were used, two long wh-questions (i.e., subject and object questions) and two short wh-questions. The long questions were identical to the ones used in Experiment 1 (compare Table 6.1 to Table 5.1 in Chapter 5). Short wh-questions, however, were modified such that they had the same overall length as long questions but that the wh-filler and the second NP were directly adjacent. This was achieved by presenting the same prolonged prepositional phrases as in the long questions, but now after the second noun phrase. The general schema of short wh-questions used in this study is displayed in [40]. Table 6.1 contains an example set of the items used in this experiment.

[40] [[Matrix clause], [[WH-filler] [2nd NP] [*PPs*] [Verb] [hat/AUX]]].

Because of the relatively high rate of errors that was made in the first experiment, the number of items per condition was increased to 48 (cf. Appendix B).

6.1.2 Experimental Procedure

The experimental procedure used in this experiment (i.e., presentation format and rate, comprehension task, etc.) was the same as that used in Experiment 1 (cf. Section 5.2.2). However, the present experiment differed in three important ways from the previous experiment. First, as already stated, 48 instead of 40 items were presented per condition. Second, no filler items were included in the study. As already indicated above, filler sentences were omitted in order to keep the length of the experiment within the time range that is acceptable for an fMRI study. Third, trials could not be started individually by the participants in this experiment. This was done in order to speed up the experiment and to ensure the correct timing for the analysis of the following fMRI study. The shortening of

Condition	Example
short subject wh	Thomas fragt sich, wer den Doktor *am Mittwoch nachmittag nach dem Unfall* verständigt hat. Thomas asks himself, who$_{NOM}$ the$_{ACC}$ doctor on Wednesday afternoon after the accident called has
short object wh	Thomas fragt sich, wen der Doktor *am Mittwoch nachmittag nach dem Unfall* verständigt hat. Thomas asks himself, who$_{ACC}$ the$_{NOM}$ doctor on Wednesday afternoon after the accident called has
long subject wh	Thomas fragt sich, wer *am Mittwoch nachmittag nach dem Unfall* den Doktor verständigt hat. Thomas asks himself, who$_{NOM}$ on Wednesday afternoon after the accident the$_{ACC}$ doctor called has
long object wh	Thomas fragt sich, wen *am Mittwoch nachmittag bei nach dem Unfall* der Doktor verständigt hat. Thomas asks himself, who$_{ACC}$ on Wednesday afternoon after the accident the$_{NOM}$ doctor called has

Table 6.1: Sample set of sentence material used in Experiment 2 with word-by-word translations to English.

the present experiment was achieved at the cost of an increased number of rejected trials due to blink artifacts (see below). Randomization of the stimulus sequence was done in analogy to the first experiment. Constraints involving filler items were omitted.

6.1.3 Participants

Fourteen paid volunteers (eight females; mean age 23 years; age range 20 to 30 years) participated in this study. All participants were undergraduate students of the University of Leipzig, had normal or corrected to normal vision, and were without history of neurological or psychiatric diseases. Furthermore, all participants were native speakers of German and consistent right-handers (as indicated by a laterality quotient of 100 according to the Edinburgh Handedness Inventory; Oldfield, 1971). The number of participants was reduced as compared to the previous experiment in order to use a sample size like it is typically used in functional neuroimaging studies (see above).

6.1.4 ERP Recording Procedures

The recording procedures of the present experiment were identical to those of Experiment 1 (see Section 5.2.4).

6.1.5 Data Analysis

Behavioral data were analyzed as described for Experiment 1 (see 5.2.5). Preprocessing and statistical analyses of ERPs were also performed in analogy to the previous experiment. Condition-specific trial averages of 5.6 seconds length were calculated for all conditions, time-locked to the onset of the embedded wh-questions. Across conditions, an average of 19.9 % of the trials (range 16.5 to 22.8 %) were rejected due to blink artifacts or eye movement artifacts. As already pointed out above, the increased number of eye movement and blink artifacts is most probably caused by the shorter time available between the trials in this study.

In addition to the long multi-word analyses, ERPs were also calculated that spanned only the region of the prepositional phrases in short and long object wh-questions. These ERPs had a duration of 2,900 ms. This analysis was performed in order to directly compare ERPs elicited by the prepositional phrases under conditions of syntactic working memory load (i.e., between the filler and the gap in long object wh-questions; cf. Experiment 1) with the same constituents in sentences where the argument order is the same (i.e., object-first) but where no comparable working memory load is expected because the gap has already been processed (i.e., in short object wh-questions). In the long object condition, on average 15 % of the trials were excluded from further analysis, and 14.6 % of the trials were excluded in the short object condition.

The sentence examples in Table 6.1 show that the word preceeding the first prepositional phrase differs between the two conditions. In short object questions, the PP is preceeded by the nominative NP (e.g., 'der Doktor') while in long object questions, the wh-filler 'wen' directly preceeds the PP. This difference might influence the multi-word ERPs calculated for the PPs because the baseline for this ERP (i.e., -200 to 0 ms before the onset of the first PP) is located here. However, an analysis of variance of the baseline amplitudes using the factors 'sentence length' (i.e., short object vs. long object wh-question), 'hemisphere' and 'scalp extension' (i.e., anterior vs. posterior) did not yield any effects involving sentence length that were greater than $F = .5$.

At the position of the second noun phrase, local ERPs were calculated. Due to blink artifacts and eye movement artifacts, 9.1 % of the trials (range from 6.7 % to 14.1 %) were excluded from further analyses. As in Experiment 1, ANOVAs at this position were calculated using a within-subjects factor 'region of interest' with four levels corresponding to four midline regions of interest.

6.2 Results

6.2.1 Behavioral Performance

The mean reaction time across the different conditions was 1,728 ms from the onset of the probe assertions. There were no significant differences in reaction times between short and long conditions ($F < 1$). Response times to object wh-questions were 46 ms than those elicited by subject wh-questions ($F_{1,13} = 6.39$; $p < .05$), independent of the length of the filler-gap distance ($F < 1$). The mean percentage of errors made was 11.9 %. The only effect that was obtained in the ANOVA of the error rates was a reliable main effect of sentence type with $F_{1,13} = 7.22$ and $p < .05$. This effect was due to the fact that more errors were made in object questions than in subject questions. Although there was a considerable difference in this effect between short questions (i.e., 2.2 % more errors in object than in subject questions) and long questions (5.2 % more errors in object questions), the interaction between filler-gap distance and sentence type did not reach significance ($F_{1,13} = 2.27$; $p = .16$).

6.2.2 Event-Related Potentials

6.2.2.1 Multi-Word ERPs to Embedded Questions

In the comparison of object wh-questions with subject wh-questions (cf. Figures 6.1A and 6.1B), a difference was observed in the ERPs elicited by long but not by short wh-questions in the time window in which the sustained negativity was observed in the first ERP experiment. ERPs to long object wh-questions were reliably more negative than those to long subject wh-questions between 1000 and 3400 ms after the onset of the wh-filler. Short wh-questions did not show a comparable effect in this time window. This finding is supported by a reliable interaction between sentence type (i.e., subject vs. object) and filler-gap distance ($F_{1,13} = 5.79$, $p < .05$) which could be resolved to show that there was a strong negativity present only in long object wh-questions ($F_{1,13} = 13.82$; $p < .005$). Short wh-questions did not differ statistically ($F < .5$) in this time window. A significant interaction of sentence type with scalp extension (i.e., anterior vs. posterior ROIs; $F_{1,13} = 9.21$; $p < .01$) indicated that this negativity was present most clearly over frontal electrode sites (cf. Figure 6.1B).

Analogous to Experiment 1, a time window analysis was calculated for the long subject and object wh-questions. The time windows were defined as described in Section 5.3.2.2 (cf. Table 5.4 for the exact definition of the time windows). In this analysis, the main effect of sentence type was replicated ($F_{1,13} = 13.1$; $p < .005$) as well as the interaction of scalp extension with sentence type ($F_{1,13} = 8.17$; $p < .05$). An interaction of time window, hemisphere, scalp extension, and sentence type also became significant ($F_{4,52} = 2.64$; $p < .05$; corrected degrees of freedom according to Huynh & Feldt, 1976).

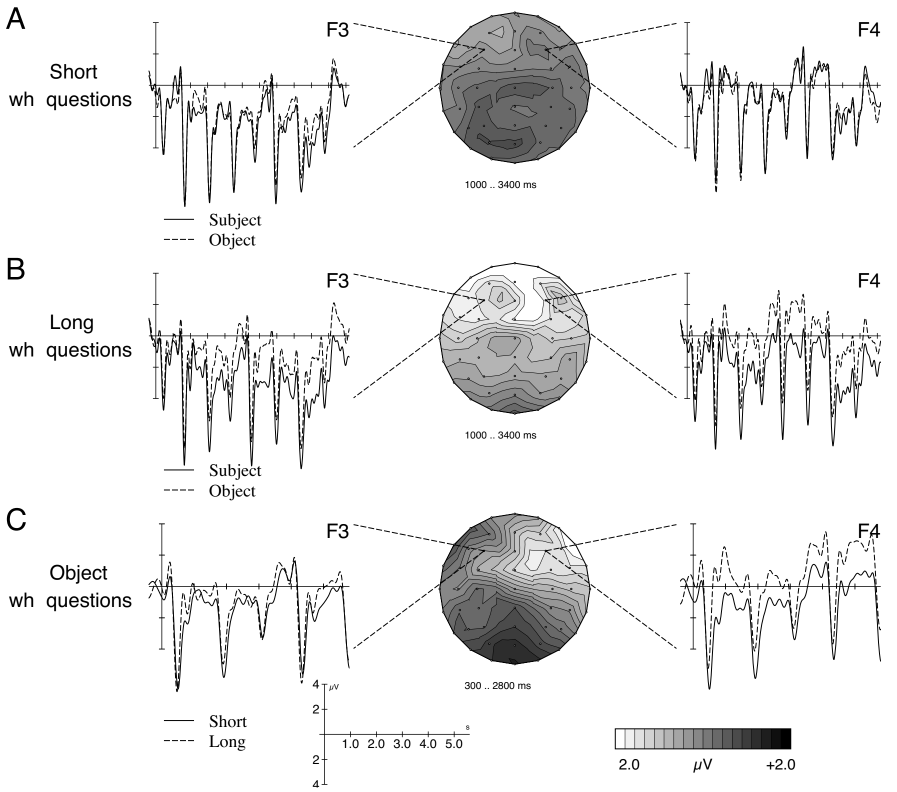

Figure 6.1: *Multi-word ERPs elicited by short subject and object wh-questions (A), long subject and object wh-questions (B), as well as ERPs elicited at the prepositional phrases for short and long object wh-questions (C).*

In order to resolve this interaction, an ANOVA was calculated within every time window. The most prominent finding was that, as in Experiment 1, there was no main effect of sentence type at the clause initial element ($F < .5$; compare to Section 5.3.2.1 and Table 5.4) while there were reliable effects of sentence type in all other time windows untile the second NP position was reached (i.e., all $F > 6$; see also Figure 6.2). These effects were caused by more negative-going ERPs in the long object wh-questions.

Furthermore, this analysis suggested that as in Experiment 1, the time course of the sustained negativity for object wh-questions was observable most clearly over anterior electrode sites. While the interaction of scalp extension with sentence type was only marginally significant in the first two time windows (i.e., 400 to 750 ms: $F_{1,13} = 4.49$, $p < .1$; 1000 to 1450 ms: $F_{1,13} = 4.64$, $p < .1$), it

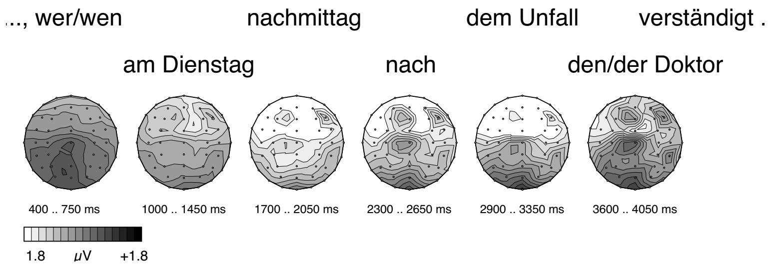

Figure 6.2: *Topographical scalp distributions of the negativity for long object wh-questions (as compared to long subject wh-questions) for time windows corresponding to the presented words and phrases.*

was strongest at the last NP of the prepositional phrases (i.e., between 2,900 and 3,350 ms; $F_{1,13}$ = 10.76; $p < .01$).

The only difference between the results of this experiment and the first ERP experiment was that in the present experiment, the sustained negativity for long object questions was distributed broadly over anterior electrode sites while it was lateralized to the left hemisphere in the previous data set.

6.2.2.2 Multi-Word ERPs at the Prepositional Phrases

In the direct comparison of ERPs at the PPs in short and long object wh-questions, long object questions elicited more negative-going potentials than short object questions, starting with the first PP and lasting over the region of the prepositional phrases (cf. Figure 6.1C). This negativity was strongest over right frontal electrodes. In a time window between 300 and 2800 ms, the main effect of filler-gap distance (i.e., short vs. long) was not significant ($F_{1,13} < 1$). However, the interaction of filler-gap distance with hemisphere ($F_{1,13}$ = 8.99; $p < .01$) revealed a reliable effect of filler-gap distance that was only present over the right hemisphere ($F_{1,13}$ = 5.43; $p < .05$). An interaction of scalp extension (i.e., anterior-posterior) with sentence length approached significance ($F_{1,13}$ = 4.12; p = .06), suggesting that the difference between long and short object questions was negative over frontal electrode sites but more positive-going over posterior electrodes. The three-way interaction of sentence type with hemisphere and scalp extension did not become significant ($F_{1,13}$ = 2.04; $p > .15$).

As already described in the methods section, a statistical analysis of the 200 ms that were used as baseline using the same factors revealed no significant main effects or interactions involving sentence type in the baseline (all $F < .5$). This finding showed that the effect observed in multi-word ERPs was not due to condition-specific differences in the baseline.

In a time-window analysis analogous to the one performed for the long multi-word ERPs, there was no reliable interaction between filler-gap distance and time window ($F < 1$). The only interaction

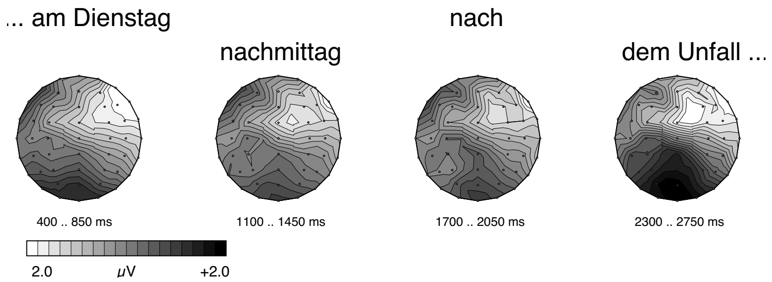

Figure 6.3: *Topographical scalp distributions of the negativity for long object wh-questions (as compared to short object wh-questions) for time windows corresponding to the constituents of the prolonged prepositional phrase.*

reaching significance that involved time window and filler-gap distance was with the factor hemisphere ($F_{3,39} = 3.11$; $p < .05$). This interaction could be resolved to show that in all but the third time window ($F_{1,13} = 2.41$; $p = 0.1448$) there was a significant lateralization to the right hemisphere for the sustained negativity to long object questions (all other $F > 4.5$; see also Figure 6.3).

6.2.2.3 Local ERPs at the Second Noun Phrase

At the position of the second noun phrase, the positivity for long object wh-questions, relative to long subject questions, which was observed in the first Experiment could be replicated (see Figure 6.4B). Interestingly, in this study there was no comparable positivity observable for short wh-question. Instead, there was a small negativity found at Cz and more anterior electrodes.

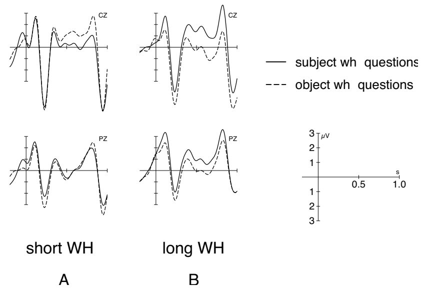

Figure 6.4: *Local ERPs elicited at the second noun phrase position for short (A) and long (B) subject and object wh-questions.*

The statistical analysis of ERPs elicited at this position in the sentence revealed a strong interaction between filler-gap distance and sentence type ($F_{1,13} = 26.14$; $p < 0.0005$) which was due to a reliable positive-going effect only in the long wh-questions ($F_{1,13} = 11.03$; $p < 0.01$). No reliable

ERP difference was obtained in short questions ($F_{1,13} = 2.36$; $p = 0.15$) at the second NP. No interactions with the factor region reached significance. Thus, the negativity that Figure 6.4A indicates for short object wh-questions did not become significant.

6.2.2.4 Summary

The behavioral data showed that longer reaction times were elicited and more errors were made when processing object wh-questions than when reading subject questions. The performance was slightly better in this study than in Experiment 1, indicated by faster reaction times and fewer errors. ERPs showed a sustained negativity with frontal focus for long object wh-questions as opposed to long subject wh-questions, thus replicating one of the main results of the first ERP experiment. In the direct comparison of multi-word ERPs between long and short object wh-questions in the region of the prepositional phrases, there was also a sustained negativity observable for long object questions. That is, ERPs elicited by the prepositional phrases were more negative-going when the dislocated object had to be maintained in working memory at the same time. This negativity, however, was strongest over right anterior electrode positions. As in Experiment 1, local ERPs at the second noun phrase showed a positivity for long object as compared to long subject wh-questions. Short object questions, in contrast, did not elicit a comparable ERP effect at this position.

6.3 Discussion

The present experiment had three main goals. First, it was conducted in order to replicate the main findings of Experiment 1, i.e., the sustained negativity for object wh-questions with a long filler-gap distance and the late positivity for object wh-questions at the second NP position. Second, it was designed to allow a direct comparison between long object questions and short object questions. These two points will be discussed in the following sections. The third goal was to ensure that a design similar to the one used in the first ERP study can be used for an fMRI experiment. The present results support this assumption. The behavioral data even demonstrated that the present design was slightly easier for the participants than the design of the first experiment. This might be caused by the fact that there were no distractor items present in this experiment. The participants thus could have developed strategies for performing the comprehension task, triggered by the exclusive presentation of wh-questions. However, the finding that the main results of Experiment 1 could be replicated contradicts the assumption that participants utilized different response strategies in the two experiments. Alternatively, the better performance might be due to the shorter duration of the experiment (i.e., between 40 and 45 minutes as opposed to two session of around 75 to 90 minutes). The greater number of errors in the first experiment thus might be caused by a certain lack of concentration towards the end of the experimental sessions.

6.3.1 Replication of Previous ERP effects

The sustained negativity and the positivity observed for long object as opposed to long subject wh-questions in Experiment 1 could be replicated in Experiment 2. This is especially important because due to requirements of experimental design for an fMRI study (which was subsequently conducted using the same experimental procedure), the present experiment was run without filler sentences. Despite the influence of the new design on the behavioral performance, the appearance of the critical ERP components was not influenced by the lack of filler items. With respect to the long wh-questions, the only difference between the two experiments was the distribution of the sustained negativity which was focused over left anterior electrode sites in the previous experiment and more bilaterally distributed over the anterior scalp in the present study.

A further discrepancy between the two data sets was the lack of a positivity at the second noun phrase in short object wh-questions in this experiment. This finding is most probably attributable to the change in the sentence structure of the short wh-questions. While in the short object wh-questions used in Experiment 1, a short prepositional phrase was intervening between the wh-filler and the second NP (cf. Table 5.1), the second NP directly followed the wh-filler in the present experiment. Accordingly, a possible account of the difference between the two experiments is to assume that the late positive effect is only observable when at least a transient involvement of working memory processes is required for maintaining the moved element activated. It is not clear whether the amplitude difference between object and subject questions is influenced by the distance between the filler and the gap (as proposed in SPLT; cf. Gibson, 1998) because there was no interaction of sentence type and filler-gap distance in Experiment 1 for this effect. In the last chapter, two accounts of the late positive ERP effect at the second NP were discussed. One possible cause of this positivity was that in object questions, two arguments had to be integrated into the phrase structure while in subject questions, only one argument, namely the object NP, had to be integrated at this position (see discussion in Section 5.4.4). The other assumption was that the appearance of the positive-going effect at the second NP might reflect the linkage of the filler to its gap, as soon as the gap site becomes available for this process. It turns out that none of the two explanations can hold as such because both explanations would predict an effect also for the short object questions in the second experiment. It appears that the late positivity is observable only when the moved element has to be maintained in working memory and then can be linked to its gap position. The involvement of working memory resources for maintaining the dislocate object was greatest in long object wh-questions, very small in the short object questions of Experiment 1, but almost non-existent in the short object condition of the second ERP study. In the latter sentences, the object gap became available almost immediately after identifying the wh-filler, i.e., at the following word.

6.3.2 Short vs. Long Object Questions

The sentence material used in this study was especially designed to also allow a direct comparison of multi-word ERPs elicited by object wh-questions with long and those with short filler-gap distance. This analysis was especially interesting because it allowed to compare ERPs elicited by the same constituents (i.e., the prolonged prepositional phrases) under conditions of a syntactic working memory load due to the simultaneous maintenance of the dislocated object in memory (i.e., in long object questions) and under conditions of no syntactic working memory load (i.e., in short object questions). A comparable contrast was obtained by comparing subject and object questions. However, this contrast is always confounded with the difference in the order of verbal arguments which is canonical in subject-first questions, but non-canonical in object-first questions. In the present comparison, the order of arguments did not differ. That is, in both conditions that were compared here, the object NP was encountered in clause initial position. While the moved element could not immediately be linked to its gap and thus had to be maintained in working memory in the long object questions, the gap was already located and filled when the first prepositional phrase was encountered in the short object wh-questions.

The ERPs elicited at this part of the sentences also exhibited a sustained negativity for the condition with the greater working memory load, i.e., for long object questions. This finding suggests that the sustained negativity was not due to an interaction between non-canonical order with increased filler-gap distance, as might be concluded from Experiment 1. However, it might be the case that distinct sub-components of the working memory mechanisms elicited by wh-movement influence the extension and distribution of the sustained negativity independently. It appears that the sustained negativity observed in the contrast of the two object questions is more focused than that observed in the comparison of long subject with long object questions. Furthermore, it was strongest over right frontal scalp while the subject-object difference was either left-lateralized (Experiment 1) or bilaterally distributed (Experiment 2).

6.4 Conclusion

Experiment 2 supports the results of Experiment 1 by providing replications of the effects reflecting syntactic working memory involvement and local processes associated with syntactic integration difficulty. This finding was important because it demonstrated that the present design could also be used for the following fMRI study.

The present study yielded two important new results that extend the theoretical implications of the present work. First, no late positivity was obtained at the second NP if the dislocated element and the second NP, which licenses the object gap, are directly adjacent. This result suggests that the difficulty of establishing the syntactic dependency between the filler and its gap is related to the distance between the filler and the gap position. Second, the present design allowed to calculate a direct contrast between short and long object wh-questions. This result gave additional support for the interpretation of the sustained negativity as being related to syntactic working memory processes. The fact that it was elicited in a comparison of two conditions with identical argument order (i.e., object before subject) was taken as further evidence for assuming that the sustained negativity is independent of local integration difficulty. The present data thus provide additional support for the interpretation of the sustained negativity as reflecting the maintenance of syntactic information in working memory.

Chapter 7

Experiment 3: An fMRI Study

The third experiment of this thesis is a functional magnetic resonance imaging (fMRI) study in which the processing of the same sentences as in Experiment 2 was investigated. The goal of this study was to identify the brain regions associated with the syntactically driven working memory processes identified in the previous two experiments. This goal is of special importance for the understanding of the neurocognition of syntactic processing because previous studies of syntactic complexity were not able to establish a clear-cut link between activation differences in inferior frontal brain regions (especially BA 44 of the left hemisphere; but see Section 3.4.4) and the underlying cognitive operations supported by these areas. Often, the functional description of the processes that were assumed to cause activation differences was quite vague. For example, Just and colleagues (1996) concluded that more resources are required to process more complex sentences. These authors stated that "the brain responds to increased comprehension demand" by recruiting "more neural tissue" (p. 116). Stromswold et al. (1996) suggested that the activation differences observed in their PET study might be due either to an increase in working memory load or that it might be "associated with a variety of syntactic processes" involved in the processing of more complex sentences (p. 470).

On the basis of the conclusions drawn from the two ERP experiments reported so far, the present study is an attempt at identifying brain regions associated with the cognitive processes involved in maintaing syntactic information in working memory (i.e., maintaining the dislocated object in working memory until the gap becomes available). Furthermore, brain areas associated with the processing difficulty of sentences that contain a non-canonical order of verbal arguments (i.e., object first wh-questions) as compared to sentences with a canonical word order shall be identified. From the description of the fMRI method in Section 3.4.2, it is clear that the temporal resolution of this method is worse than that of event-related brain potentials. Accordingly, it can be assumed that when investigating sentence processing with fMRI, it is easier to detect activation differences associated with sustained or global aspects of parsing present over broader regions of a sentence (like maintenance in working memory), than to detect transient changes in the complexity of local integration processes.

7.1 Methods

7.1.1 Material

The sentence material used in Experiment 3 was exactly the same as that used in Experiment 2 (see 6.1.1).

7.1.2 Experimental Procedure

The experimental procedure was identical to that used in the previous experiment (cf. 6.1.2) with regard to stimulus material, presentation rate, order of presentation, comprehension task, and response registration. Within the MR scanner, visual stimuli were projected onto a translucent screen located behind the head of the participant. The stimuli were viewed via glasses onto which mirrors were mounted.

7.1.3 Participants

Fourteen paid volunteers (six females; mean age 24.3 years; age range 19 to 31 years) participated in the fMRI experiment. As in the previous experiments, participants were undergraduate students of the University of Leipzig, had normal or corrected to normal vision, and were without history of neurological or psychiatric diseases. All participants were native speakers of German and consistent right-handers as indicated by a laterality quotient of 100 according to the Edinburgh Handedness Inventory (Oldfield, 1971).

7.1.4 fMRI Acquisition Procedures

Functional images were acquired in eight axial slices (cf. Figure 7.1) using a gradient-echo EPI sequence with an echo time of TE = 30 ms, a flip angle of 90 degrees, a repetition time of TR = 1 sec, and an acquisition bandwidth of 100 kHz. The matrix acquired was 64 x 64 with a FOV of 19.2 cm, resulting in an in-plane resolution of 3 mm x 3 mm. Slice thickness was 5 mm with an interslice gap of 2 mm. The upper border of the second slice was aligned to the AC-PC line[1] such that in all participants, the perisylvian region was covered.

Each trial had a length of 16 sec, thereby having an effective inter-trial interval between the end of one wh-questions and the beginning of the next of about 9 sec. The comprehension task was performed during the inter-trial interval. The functional measurement was a single-trial design (see Section 3.4.2) carried out in three runs of about 15 minutes length. Within each run, the different sentence conditions (i.e., event types) were presented in a pseudo-randomized order. Prior to the functional measurements, a T1-weighted MDEFT scan (cf. Ugurbil et al., 1993) was obtained (data

[1]The AC-PC line passes through the anterior commissure and the posterior commissure of the human brain.

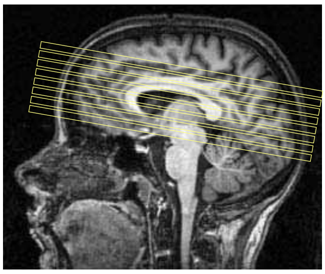

Figure 7.1: *Sagittal view of the brain, displaying the eight axial slices that were measured.*

matrix 256 x 256, TR = 1.3 s, TE = 10 ms) with a non slice-selective inversion pulse followed by a single excitation of each slice (Norris, 2000). These anatomical images were used for coregistration of the functional data sets with high resolution whole-head 3D MDEFT (Ugurbil et al., 1993; Lee et al., 1995) brain data sets (128 sagittal slices, 1.5 mm thickness, FOV 25.0 x 25.0 x 19.2 cm, data matrix of 256 x 256 voxels) which were acquired in separate sessions.

7.1.5 Data Analysis

Functional data were submitted to a number of preprocessing steps including a slicetime correction using sinc-interpolation, spatial smoothing with a Gaussian kernel of 4.9 mm FWHM, and a baseline correction using a high-pass filter of 1/45 Hz. All analysis were performed with the LIPSIA software package (Lohmann et al., 2000). Before the statistical analyses, functional data sets were coregistered with high-resolution 3D structural images and normalized to stereotactic space (Talairach & Tournoux, 1988). Normalized data sets were analyzed statistically in a fixed-effects general linear model on the basis of procedures from the SPM software package (Friston et al., 1995; Josephs et al., 1997). Functional data were analyzed in an event-related design using a fixed-effects model. The first 32 images obtained in each run and all incorrectly answered trials were excluded from the statistical analyses. The critical event was defined as the point in the sentence where the different conditions diverged, i.e. the question word that introduced the embedded wh-question. This word was presented four seconds after the onset of the trial. The hemodynamic response was modelled assuming a delay of four seconds. Observed data and the design matrix were convolved by a Gaussian kernel with 4 seconds FWHM. High-pass filtering was performed with a cutoff frequency of 1/45 Hz. The different conditions were compared by calculating direct contrasts between the sentence types. The resulting continuous statistical parametrical maps (i.e., SPM{Z}) were thresholded at z = 3.09 ($p < .001$; uncorrected). Only clusters of activation of at least 150 mm^3 will be reported.

7.2 Results

7.2.1 Behavioral Performance

The mean reaction time across the different conditions was 1,735 ms from the onset of the probe assertions. There were no significant differences in reaction times between any of the four conditions in both experiments. The mean percentage of errors made was 10.9 %. As in Experiment 2, a main effect of sentence type ($F_{1,13} = 12.76$; $p < .005$) was due to the fact that object wh-questions elicited 4 % more errors than subject wh-questions.

Also similar to Experiment 2, the interaction between sentence type and filler-gap distance was not reliable ($F < 1$). Nevertheless, descriptive analysis showed that the difference in error rates between subject and obkect questions was greater in long questions (i.e., 5.1 %) than in short questions (i.e., 2.8 %).

7.2.2 fMRI Data

At the general significance threshold of $z > 3.09$, no brain areas were consistently activated stronger for object as opposed to subject wh-questions. This result was obtained both for long and short wh-questions. In contrast, the direct contrast between object wh-questions with long filler-gap distance and object wh-questions with short filler-gap distance (i.e., the analysis that was assumed to isolate the working memory involvement associated with processing the dislocated object filler most clearly) resulted in reliable activation differences in inferior frontal and superior temporal areas of both hemispheres (cf. Figure 7.2 and Table 7.1).

Increased activation for long object wh-questions was obtained bilaterally in the superior portion of pars opercularis of the inferior frontal gyrus (BA 44), on the border to pars triangularis (BA 45; cf. Figure 7.2). In addition, the inferior portion of pars opercularis, extending into the deep frontal operculum, was also activated stronger for long object wh-questions. The activation difference in inferior pars opercularis, however, was only present in the left hemisphere. For the bilateral activation in superior BA 44, z-values were greater on the right than on the left hemisphere (cf. Table 7.1). However, an analysis of variance of the mean z-values in spherical regions of interest (3 mm radius) centered at the local maximum of this area did not reveal reliable differences between the two hemispheres ($F < 1$).

In the contrast between object wh-questions with long and short object wh-questions, pronounced activation differences were also found in areas along the superior temporal sulcus of both hemispheres (cf. Figure 7.2 and Table 7.1). Furthermore, a small and just reliable activation increase was found in the left thalamus (see Table 7.1). The size of this activated area was below the cluster threshold used so far. However, it is reported here because it can be assumed that subcortical areas activated in statistical contrasts might be smaller than cortical areas. No reliable activation increases in perisylvian

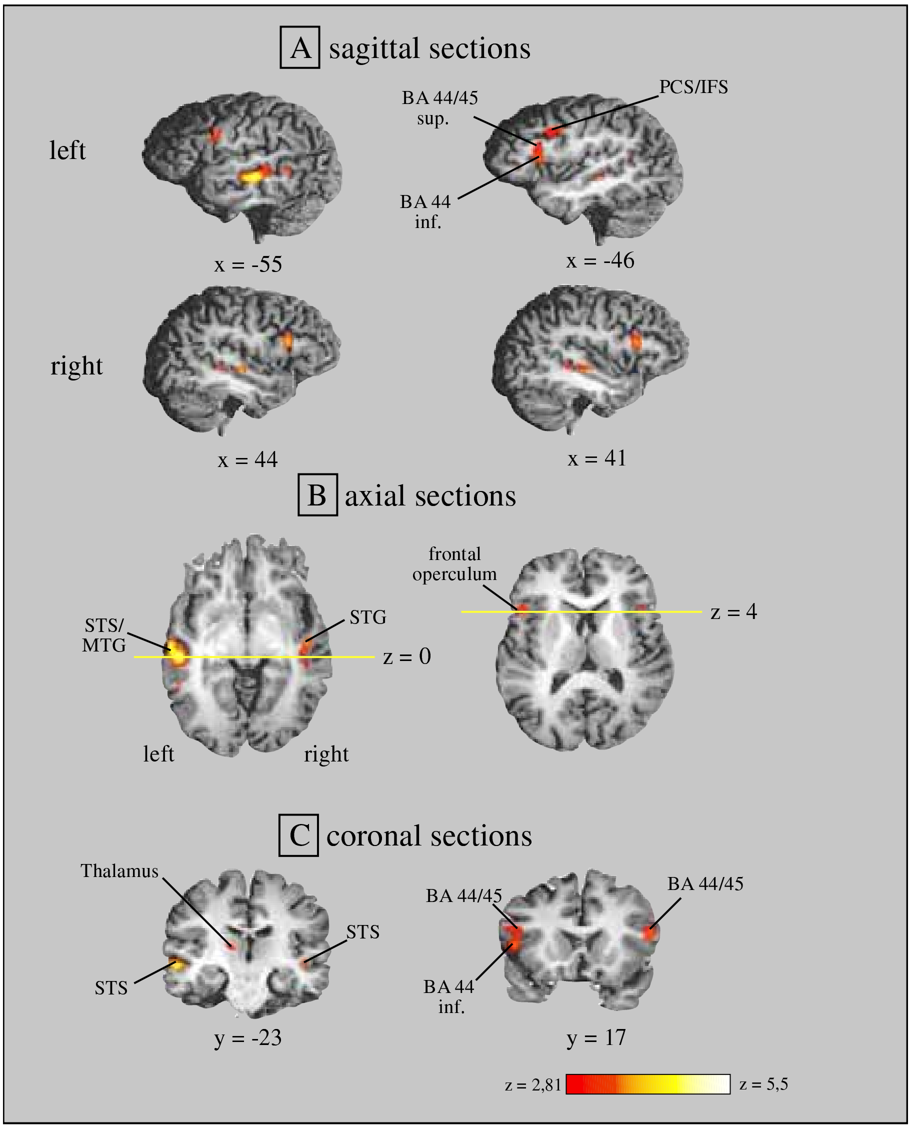

Figure 7.2: *Brain regions exhibiting increased activation for long object wh-questions as compared to short object wh-questions. Sagittal sections through the left and right hemisphere (A), as well as axial sections (B) and coronal sections (C) are shown. Note that for visual display, z-maps were thresholded at z = 2.81 (i.e., p < .0025, one-tailed).*

Brain Region	**BA**	**Hemi.**	**x**	**y**	**z**	$\mathbf{Z}_{max}$
Inferior frontal gyrus, pars opercularis and pars triangularis (superior portion)	44/45	L R	-44 43	21 20	11 8	3.44 4.06
Inferior frontal gyrus, pars opercularis (inferior portion)	44	L	-44	16	4	3.46
Junction of pre-central sulcus and inferior frontal sulcus	6/44	L	-53	6	26	3.64
Superior temporal sulcus (middle portion)	21/22	L	-53	-27	0	5.52
Superior temporal sulcus and gyrus (middle portion)	21/22	R	43	-18	-2	4.16
Thalamus		L	-17	-18	11	3.09

Table 7.1: Anatomical descriptions, Brodmann Areas, Talairach coordinates, and maximal z-values for brain regions activated stronger by long object than by short object wh-questions.

cortices were obtained when subject wh-questions with long and short filler-gap distance were directly contrasted (cf. Table 7.2).

Brain Region	**BA**	**Hemi.**	**x**	**y**	**z**	$\mathbf{Z}_{max}$
Parieto-occipital sulcus (inferior portion)	31	L R	-20 19	-53 -59	21 20	3.35 3.58
Parieto-occipital sulcus (superior portion)	7/19	L	-14	-66	41	3.46

Table 7.2: Anatomical descriptions, Talairach coordinates, and maximal z-values for brain regions activated stronger by long subject than by short subject wh-questions.

7.3 Discussion

The behavioral performance data, by and large, replicated the results of the second experiment. In the neuroimaging data, activation differences in left pars opercularis (i.e., in the classical area of Broca) co-ocurred with activity in superior temporal brain regions and also with activity in homologous frontal and temporal areas of the right hemisphere. This finding is different from the results of previous PET studies of syntactic complexity (i.e., Stromswold et al., 1996; Caplan et al., 1998, 1999).

In these studies, brain activation has been observed repeatedly in left inferior frontal regions but not in the temporal lobe and not in right hemispheric areas. On the other hand, the present result is consistent with an fMRI study of syntactic complexity reported by Just and colleagues (1996; see also Section 3.4.4) in which an increase in the number of activated voxels in inferior frontal and superior temporal brain areas bilaterally, but with a left hemispheric dominance, was demonstrated.

The similarity of the present results with those reported by Just et al. (1996) might either be due to the increased sensitivity of fMRI as opposed to PET, resulting in the identification of a more complex configuration of activated brain regions, or, alternatively, might be the result of similar task demands in the two studies. While in the PET studies reported by Caplan and colleagues plausibility judgments were required, sentence comprehension judgements on probe sentences presented after the critical sentences had to be made in the two fMRI studies. Thus, the tasks of the PET studies on the one hand and the two fMRI studies on the other hand clearly differed. However, it was argued in Section 3.4.4 that this explanation is probably not correct. For example, Stowe and colleagues (1998) also reported superior temporal activations in a passive reading task. It should be noted that in the plausibility judgment task used by Caplan and co-workers, half of the sentences contained in an experimental block were semantically implausible. This semantic manipulation might have influenced the summed activation and might, furthermore, even have interacted with activations associated with structural factors (this critique has been pointed out, for example, by Stowe, 2001).

7.3.1 Syntactic Working Memory or Syntactic Computation?

Unlike previous neuroimaging studies of syntactic complexity, the present study did not yield IFG activations when comparing object-initial sentences with subject-initial sentences. Instead, in the present study this and associated brain regions were most strongly activated when object-first sentences eliciting greater demands on syntactic working memory (i.e., with a long filler-gap distance) were contrasted with structurally very similar object-first sentences which caused lesser demands on working memory. This result is not contradictory to the previous findings. In fact, Caplan and colleagues (Stromswold et al., 1996; Caplan et al., 1998, 1999) discussed that their experimental design did not allow to attribute the reported activation effects unequivocally to either syntactic working memory processes or computational processes of parsing. Just and colleagues (1996) suggested that their fMRI effects were dependent upon the amount of resources required for processing more complex sentences, thereby not specifying whether these resources were required for sustained working memory processes or for more local parsing processes. The present data suggest that the more likely cause of the IFG activations reported in all these studies is an involvement of syntactic working memory processes.

This conclusion is supported by the syntactic analysis of object and subject relative clauses that was given above (cf. Section 1.3). On the basis of syntactic criteria that are frequently used to determine the structural complexity of a sentence (i.e., on the basis of the number of non-terminal phrase structure nodes in the tree diagrams displayed in Figure 1.1), it was demonstrated that subject-first and object-first relatives do not differ in the complexity of their phrase structures. The only difference between the two structures is the length of the filler-gap distance. On the basis of the ERP results of Experiments 1 and 2, it was concluded that an increased distance between the dislocated filler and its gap position leads to a greater demand on working memory over the course of the sentence. In the present experiment, this working memory load could be isolated while at the same time, the order of arguments was matched between the conditions to be contrasted. In contrast, in the studies reported by Caplan and colleagues (e.g., Stromswold et al., 1996; Caplan et al., 1998) the working memory demand induced by the longer filler-gap distance in object-relatives, as opposed to subject relatives, was probably over-estimated. In Section 3.4.4, it was argued that the working memory load induced by maintaining the dislocated element in memory was confounded with the interruption of the matrix clause in the sentence stimuli used by these researchers.

Furthermore, there was one additional factor that might possibly have contributed to previous activation effects. In English, relative pronouns are case-ambiguous. The resolution of this ambiguity is thought to be costly in terms of working memory (see Section 1.4.2). In the present study, the interrogative pronouns were overtly case-marked, removing influences of ambiguity resolution from brain activation effects observed. Therefore, the present study might give a more clear view on the bases of activation differences associated with parsing complexity. However, the lack of the subject/object ambiguity in the present sentences might even be responsible for the missing activation effects between subject-first and object-first structures in the present sentences.

In the analogous comparison to the one eliciting the activation differences just reported, a sustained frontal negativity was observed in the second ERP experiment. This negativity was stronger over right anterior electrodes than over the left anterior scalp (see Figure 6.3). A statistical analysis using regions of interests within the activated superior IFG areas, however, did not yield a lateralization effect in the activation differences between short and long object wh-questions.

In addition to the bilateral activity in the superior portion of pars opercularis, an activation increase was also observed in the inferior tip of the left pars opercularis. On the basis of the data currently available in the literature, this circumscribed area is assumed to be critically involved in processes of syntactic structure building (e.g., Friederici, 1999; see also the neurocognitive model of sentence processing described in Section 3.5). The present data do not speak against a functional association between parsing processes and left BA 44. In fact, it has been demonstrated convincingly that the pars opercularis of the inferior frontal gyrus (BA 44) and the deep portion of the left frontal operculum are activated if syntactic information is in the focus of information processing (e.g., Dapretto & Bookheimer, 1999; Friederici, Meyer & von Cramon, 2000). However, the data of the present fMRI study suggest that the pars opercularis is activated especially when on-line parsing has to rely more than it normally does on syntactic working memory resources. This aspect of parsing is generally viewed as one important contributor to processing difficulty in parsing (e.g., Gibson, 1998).

The results of the present fMRI study provide a possible explanation for the fact that pars opercularis is activated in some neuroimaging studies of syntactic processing and not in others (like, e.g., in the study conducted by Kuperberg et al., 2000, and in the grammaticality judgment task reported by Meyer et al., 2000). The present data suggest that pars opercularis is mainly involved when normal processing has to be temporarily supported by additional syntactic working memory resources. This is the case when, like in the sentences used in the present study, processed constituents can not be integrated immediately and have to be kept available temporarily. The establishment of a syntactic chain between a moved element and its gap position is a typical example of this situation. However, such working memory resources are not necessarily needed for local processes of phrase structure building. Detecting a syntactic violation, for example, does not pose a demand on working memory. On the other hand, Meyer and co-workers (2000) reported increased activation in fronto-opercular cortex (of the right hemisphere) when participants had to perform a sentence repair task on grammatically incorrect sentences. This task very likely requires a greater amount of working memory resources than the mere detection of an ungrammaticality.

In the literature, there is a controversy regarding the exact nature of the working memory processes involved during parsing. For example, Stowe and colleagues (Stowe et al., 1998; Stowe, 2000) proposed that left IFG supports verbal working memory capacities that are used for temporary storage of structural information, as well as of lexical items. The assumption that activations in left inferior frontal regions reflect aspects of verbal working memory as specified within the multi-component model of working memory (e.g., Baddeley & Logie, 1999) is not unplausible given the fact that neuroimaging studies of verbal working memory (e.g., Paulesu et al., 1993; Smith et al., 1996) consistently associated activation of BA 44 with articulatory rehearsal. However, the assumption that phonological working memory processes are the cause of inferior frontal activation differences during sentence processing is rendered unlikely by the fact that activation increases in left IFG are also present when sentences are processed under conditions of articulatory suppression (Caplan et al., 2000). Furthermore, as the number of words in the different sentence conditions did not differ, it is unlikely that activation increases could be due to an increased load in phonological back-up storage of the sentences (see also Section 2.2).

As already discussed above, it appears that in terms of the structural complexity of the phrase structure tree, subject and object relatives do not differ (cf. Section 1.3). On the basis of this analysis and on the basis of the present results, it has to be concluded that inferior frontal (and also superior temporal) activation differences reported in previous studies of syntactic complexity were most probably not caused by differences in the complexity of the phrase structure representation that had to be built up. Nor is it likely that these activation differences were induced by differences in the computational processes associated with local aspects of syntactic processing. Processing sentences with non-canonical word order, as such, did not lead to an increase in brain activity. However, given previous neuroimaging studies in English, as well the ERP findings reported above, it was an unexpected result that there were no significant activation differences in inferior frontal areas (as well as in other brain areas) in the contrast of subject with object wh-questions.

Some researchers suggested that certain aspects of parsing are carried out in other brain regions than the ones discussed so far (see, e.g., Section 3.4.4). Mechanisms contributing to syntactic structure building have been associated with anterior portions of the superior temporal lobe repeatedly. For example, Dronkers and co-workers (1994, 2000) reported that the brain regions of greatest overlap in agrammatic aphasics exhibiting problems in the processing of morpho-syntactic information was in the left anterior temporal lobe (i.e., anterior portion of BA 22). Meyer and colleagues (2000) reported that activation in the left planum polare of the anterior superior temporal gyrus, but not left IFG, was reliably increased when sentences contained syntactic violations of phrase structure rules or agreement constraints. Other researchers (see Section 3.4.4) also reported increased activation in anterior temporal lobe areas of the left hemisphere for sentences or text passages as opposed to word lists.

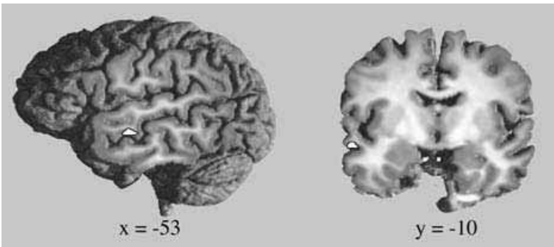

Figure 7.3: *Left anterior superior temporal activation increase for long object wh-questions as compared to long subject wh-questions (z-map thresholded at z = 1.96; p < .05 uncorrected).*

In the present study, a small activation increase in the anterior portion of the left superior temporal sulcus (aSTS, upper bank: x = -53, y = -10, z = -7; Z_{max} = 2.44) could be observed when the significance threshold was lowered to z = 1.96 (i.e., $p < .05$ uncorrected) for an explorative analysis. The anterior STS activation was small in size (see Figure 7.3), obviously because it was located at the lower border of the most inferior slice that was measured. The consideration of statistical z-maps calculated for each individual separately yielded that in the close neighbourhood of this activation focus (i.e., less than ten millimeters in any direction), eight of the participants displayed increased activation for long object as compared to long subject wh-questions (see Table 7.3). However, no external criterion could be identified which would predict why some participants exhibited left aSTS activations and others did not. The most plausible assumption is that the critical region was not covered with the present scanning procedure in all participants. In any case, the anterior superior temporal lobe region is a possible candidate area for the neural generator of the sustained negativity observed in the corresponding contrast in ERP experiments 1 and 2. However, this result is only very tenative in nature and has to be treated with great care as the lowered significance threshold does not provide enough protection against false positives.

Participant	**Sex**	**x**	**y**	**z**	$\mathbf{Z}_{max}$
01	f	-58	-16	0	2.2
03	m	-50	-16	-11	2.15
04	m	-55	-7	-4	2.91
06	m	-61	-2	-8	2.61
07	f	-59	-19	-2	3.33
08	m	-52	-7	-10	2.64
11	f	-60	-1	-12	3.24
14	m	-54	-7	-8	2.29

Table 7.3: Talairach coordinates and maximal z-values for anterior temporal activations greater than z = 1.96 (i.e., $p < .05$ uncorrected) in eight out of fourteen participants.

7.3.2 Relation to Neurolinguistic Studies

An association between left IFG and the processing of filler-gap relationships, as is suggested by the present results, is not a completely new assumption. Neurolinguistic studies with brain-damaged patients exhibiting agrammatic comprehension have led some researchers to suggest a specific deficit in the processing of sentences containing filler-gap dependencies (e.g., Hickok & Avrutin, 1996; Hildebrandt et al., 1987; Swinney & Zurif, 1995; Swinney et al., 1996; Zurif et al., 1993, but see Blumstein et al., 1998, and Thompson et al., 1999).

The most recent of these proposals is Grodzinsky's (2000) Trace Deletion Hypothesis which claims that Broca's area is selectively supporting the computation of the relation between transformationally moved constituents and their gap sites. With regard to Broca's aphasia, it is claimed that damage to Broca's area is associated with a missing mental representation of the trace or gap position in the phrase structure. However, the strong claim of a representational deficit associated with damage to the 'classical' area of Broca has been criticized on different grounds such as neuroanatomical considerations (cf. Dronkers, 2000; Friederici, 2000) and empirical findings from the neurolinguistic and neuroimaging literature (e.g., Caplan, 2000; Dick & Bates, 2000; Friederici, 2000; Frisch, 2000; Levelt, 2000). Hickok (2000) argued that evidence from neurolinguistics for an involvement of Broca's area in the processing of filler-gap dependencies is only indirect. As an alternative account, he suggested that frontal brain regions might be recruited in sentence comprehension "only under conditions of increased processing load and/or attentional demands" (p. 36). The present data provide more direct evidence from functional neuroimaging regarding a functional association between inferior frontal areas and the processing of filler-gap dependencies. However, they do not lend themselves to Grodzinsky's (2000) assumption of a representational deficit in Broca's aphasia. Given the assumption, derived from Experiments 1 and 2, that syntactic working memory resources are involved in establishing the dependency between a filler and its gap, the present results strongly suggest that such working memory resources are supported by posterior portions of the IFG (especially BA 44) bilaterally (see also Müller, 2000). With regard to the performance of agrammatic aphasics on sentences with transformationally moved constituents, it might thus be hypothesized that the impaired performance in such sentences is caused by a reduction of syntactic working memory resources (for a similar suggestion, see for example Friederici & Frazier, 1992).

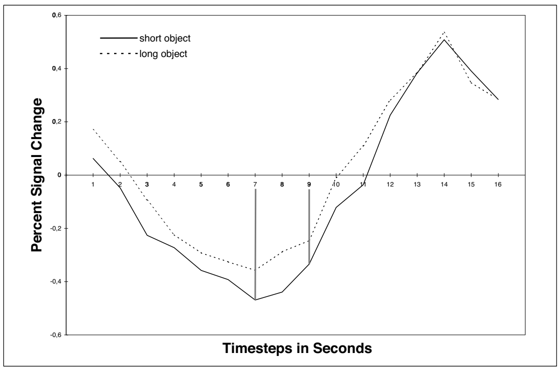

Figure 7.4: *Time lines of activation for long (dashed line) and short (solid line) object wh-questions, averaged across subjects. Time lines were calculated at the local maximum of the activation difference in the inferior portion of left pars opercularis (BA 44). As described in Section 7.1.5, the critical event was set at timestep four. Grey lines delimit the region of reliable difference between the two conditions.*

The present data allow to make a further clarification. Hickok (2000) suggested that frontal (and also parietal) brain regions support the employment of conscious processing strategies when sentence processing is difficult. Mapping the time-courses of brain activity elicited by long and short object questions at the local maximum of the activated area in left inferior BA 44 (see Figure 7.4) showed that activation within this region reached a late maximum which was temporally associated with the performance of the behavioral task[2]. However, in this late time window, no differences were observed

[2]This description of the data in Figure 7.4 considered the fact that due to the sluggish nature of the hemodynamic response, the changes in activity elicited by a certain event are delayed by four to six seconds. In the present study, a delay of four seconds was used for modeling the hemodynamic response function (cf. Section 7.1.5).

between short and long object wh-questions in the time courses. Instead, reliable condition-specific activation differences appeared earlier in the time course, i.e., about four seconds after the two sentences started to differ (as indicated by the two grey lines in Figure 7.4). Given the slow nature of the hemodynamic response (cf. Footnote 2), this activation difference can be attributed to mechanisms of sentence comprehension rather than to processes associated with the performance of the comprehension task. The activation difference was obviously induced by the structural differences between the two sentence conditions. Thus, the proposal that left pars opercularis is involved in conscious or strategic aspects of language processing is not contradicting the present results. Nevertheless, it has to be assumed that the activation effects observed in the present study are due to certain aspects of on-line processing, namely the reconstruction of filler-gap dependencies. These processes, however, are unlikely to be under strategic control.

7.4 Conclusion

Taken together, the results of the present fMRI study demonstrate that left and right pars opercularis (i.e., BA 44) and pars triangularis (BA 45) are involved in processes of syntactic working memory which are critical for the on-line establishment of filler-gap dependencies. These working memory processes are most probably responsible for maintaining unintegrated syntactic information available over restricted regions of a sentence. This conclusion is in line with the demonstration that subject and object relative clauses (which were most often investigated in related studies) do not differ in the complexity of their phrase structure but only in the length of the filler-gap distance (see Section 1.3). These data shed new light on previous brain imaging studies of syntactic complexity. While in these studies, no clear association between the underlying cognitive processes and the neural activity effects could be established, the present data suggest that syntactic working memory is the most likely cause of activation effects reported earlier. Furthermore, the present data suggest that inferior frontal areas of the left hemisphere are not working in isolation during sentence processing. Rather, they cooperate with right-hemispheric homologues and with superior temporal areas of both hemispheres. The present data provide tentative evidence regarding the localization of computational aspects of syntactic processing, induced by the non-canonical argument order in object wh-questions, in the left anterior superior temporal lobe. Although not incompatible with the previous literature, the latter suggestion is only tentative and statistically weak.

Chapter 8

Summary and General Discussion

In the first three chapters of this thesis, previous research on sentence processing and on the role of working memory during on-line parsing has been introduced. This review of the literature showed that the assumption of an involvement of working memory processes and resources in sentence processing has a long tradition in psycholinguistic research. Especially when investigating the processing of syntactically complex sentences such as, for example, sentences with embedded relative clauses, wh-questions or other structures derived by syntactic transformations, theoretical modelling has often involved working memory resources. There appeared to be two major questions. First, how do working memory processes contribute to sentence processing and how do they interact with local computational aspects of parsing such as the build-up of a phrase structure representation. Second, what is the nature of the cognitive (and neural) resources that support language processing in general and, more specifically, working memory processes during parsing. Although a lot of research has been conducted in this area (cf. Chapters 1, 2, and 3), these questions have not yet been answered conclusively.

The availability of ERPs as dependent measure which provides a very good temporal resolution and the advent of modern neuroimaging methods allowed to approach these questions anew, thus contributing to an understanding of the neurocognitive basis of sentence processing. However, the use of these methods also raised new problems. For example, the relatively low temporal resolution of neuroimaging techniques made it difficult to relate activated brain regions to specific sub-processes of sentence comprehension. ERP results, on the other hand, can generally not be directly related to specific brain regions. These problems call for refined psycholinguistic paradigms, in order to isolate very specific sub-processes of parsing, but also suggest that the parallel investigation of identical psycholinguistic paradigms with electrophysiological and hemodynamic methods is necessary. This approach has been pursued in the work that lead to the present thesis. In the last three chapters, two experiments using the ERP technique and an fMRI study have been described. In the following sections, the results of the three experiments will be repeated and summarized. Implications for psycholinguistic and neurocognitive models of sentence processing will be resumed and some suggestions will be made how the present series of experiments can be continued.

8.1 Summary of the Results

8.1.1 Performance Data

In the three experiments reported here, the behavioral data did not provide consistently strong effects of sentence type. This finding is most probably attributable to the instructions given to the participants. In all three experiments, participants were asked to concentrate more on giving a correct answer than on giving a fast response. It is likely that a speeded comprehension task would have yielded stronger differences between the different sentence conditions. However, in the context of the present experiments, the main intention of administering a behavioral task was to assure (a) that participants processed every sentence thoroughly and (b) that only correctly answered trials were used for the analysis of the electrophysiological and the fMRI data. This goal was met. A speeded task would probably have led to an increased number of errors, thereby decreasing the number of trials available for ERP or fMRI analyses.

Participants did not make more errors or respond more slowly in the fMRI experiment. Experiments 2 and 3 elicited very similar behavioral results. This was surprising because it is plausible to assume that performance in the fMRI experiment might be worse due to, e.g., scanner noise or the more complicated mode of stimulation via mirror glasses. It appears that the psycholinguistic paradigm used in the present experiments was indeed suitable for both experimental techniques. A clear performance difference was observed between Experiment 1, on the one hand, and Experiments 2 and 3, on the other. Participants had longer reaction times and made more errors in Experiment 1. As was already discussed in Chapter 6, the most likely cause of this difference is the longer duration of the testing sessions in the first experiment.

8.1.2 Working Memory Effects during Parsing

As expected on the basis of the theoretical work discussed in the first chapters, the two ERP experiments demonstrated that over specific regions of the sentence, differences in multi-word ERPs (i.e., in slow-wave ERP activity) between the conditions could be observed. These sustained effects were more negative going for object wh-questions and distributed over (left-)anterior electrode sites, suggesting that they were caused by a greater load in working memory. This ERP effect, which was observed in both ERP studies, was not found over the whole sentence. It was restricted to the region between the dislocated element (i.e., the object wh-filler) and the position of its gap. Furthermore, it was only observed when the filler-gap distance was long, and it was stronger for individuals with a low working memory capacity than for individuals with a high working memory capacity. Taken together, these results strongly suggest that the obtained slow-wave effects were related to working memory processes.

This finding led to the conclusion that when a moved element is identified and can not be integrated immediately because the corresponding gap site in the phrase structure representation is not yet available, the dislocated element (or some of its syntactic features) has to be maintained in working memory until it can be linked to its gap. The establishment of a syntactic chain between a filler and its gap, thus, relies on maintenance mechanisms of the working memory system.

This interpretation is in line with the assumption of the Active Filler Hypothesis (e.g., Frazier, 1987a; see also Section 1.4.2) that the filler is maintained actively in working memory until the gap is located. However, the present data suggest that AFH, which is a model of ambiguity resolution, can be extended to a more general account of memory costs in the processing of sentences with underlying transformational movement operations. It can be concluded that temporary maintenance of syntactic information in working memory is necessary when complex sentences are processed that contain verbal arguments in (non-canonical) positions that do not allow a direct establishment of the filler-gap dependency (cf. also Fanselow, Kliegl & Schlesewsky, 1999). When case-ambiguous wh-fillers are encountered, the same working memory mechanism is activated. In addition, the parser has to utilize strategic processes, like suggested in the AFH, to identify the correct gap site.

The results obtained in Experiments 1 and 2 are also in line with assumptions made by the Syntactic Prediction Locality Theory (cf. Gibson, 1998). In the context of this approach, it was suggested that working memory costs are associated with maintaining a syntactic prediction in working memory. This syntactic prediction specifies which synactic categories (e.g., predicate/verb, subject NP, and so on) are minimally required to make the current sentence fragment a grammatical sentence.

However, the present data do not allow to make a direct comparison between AFH and SPLT with regard to the contents of working memory that lead to the sustained negativity. While SPLT postulates that a syntactic prediction, as described above, is maintained in memory, AFH assumes that it is the maintenance of the dislocated element which causes the increased memory costs. The present data appear to be in line with both proposals. With regard to SPLT, the prediction for Experiment 1 was that subject wh-questions would impose the least memory burden, while whether-questions should cause an intermediate load and object wh-questions should elicit the greatest load. This pattern was observed in the amplitudes of the sustained negativity. While the syntactic predition triggered at the clause-initial element encompasses only a verb in the subject wh-questions, it contains a subject-NP and a verb in whether-questions and a subject-NP, a verb and the trace of the object-NP in the object wh-questions. The difference between the syntactic prediction for whether-questions and that for object wh-questions is the additional expectation of an object NP trace in object wh-questions. It is not very likely that the prediction of an additional object trace causes the strong differences, in amplitude and topography, between the two sentence conditions (when the respective contrasts with the subject condition are compared). This difference can probably better be accounted for by assuming, in analogy to AFH, that in object wh-questions some features of the wh-filler have to be maintained in working memory. Although the present experiments were not designed to compare AFH and SPLT, it appears that both aspects of parsing, maintaining a syntactic prediction and maintaining the dislocated element, contribute to the working memory load observed during the parsing of German wh-questions.

The sustained negativity for long object wh-questions, observed in the comparison with long subject wh-questions, is similar in the temporal extension over the sentence to the reading time effects observed in behavioral experiments reported by Fanselow, Kliegl and Schlesewsky (1999) and by Schlesewsky, Fanselow and Kliegl (manuscript). In these studies, increased reading times were observed over adverbials that were introduced between the object filler and the second noun phrase of embedded wh-questions (see also Section 1.4.2). By adding evidence from the polarity and scalp topography of the ERPs, the present data support the functional interpretation of these behavioral effects as reflecting syntactic working memory processes. Additional support comes from the direct comparison of short and long object wh-questions which was made in Experiment 2. In this analysis, it could be demonstrated that multi-word ERPs elicited by identical prepositional phrases in the two conditions were more negative-going when a syntactic load was present due to the maintenance of the wh-filler in working memory.

It can be concluded that the ERP studies reported in this thesis succeeded in mapping sustained working memory effects that are active during on-line sentence processing. Importantly, the method and paradigm employed here were sensitive enough to directly observe these working memory processes, without having to rely on more indirect approaches such as observing the effects of external load on certain aspects of parsing. The assumption that the slow wave effects observed here are related to working memory processes is strongly supported by the analysis of individual differences in working memory capacity. Most importantly, the present results allow to precisely associate the observed working memory mechanisms with specific regions of the sentences in question.

8.1.3 Local Parsing Processes

In addition to sustained slow-wave activity, local ERPs at single words or phrases were calculated in order to identify points in the sentence where computational parsing processes differed in complexity between the different sentence conditions. The first result was that there were no local ERP differences between the sentence conditions at the position of the question word. Thus, the different subordinating elements, i.e., the nominative and the accusative wh-filler and the word 'ob' ('whether') did not immediately trigger the build-up of phrase structure representations that strongly differ in complexity.

At the first prepositional phrase, which was presented in both short and long questions, a transient negativity was observed for short and long wh-questions alike. At this point in the sentences, the participants could not yet know whether they were processing a question with a short or a long filler-gap distance. This transient negativity obviously was the beginning of the sustained effect which was observed in long wh-questions. It was taken to index a very short-lived load on working memory. In the short questions, there was no need for a suistained maintenance of the moved object because the next word that was encountered made the gap site available. These data also indicate that the maintenance of the dislocated element does not pose a load on the system in the instance it is perceived in the clause-initial position. Only when the subsequent input indicates that the dislocated element can not integrated immediately, maintenance of this element in working memory becomes costly.

At the position of the second noun phrase, i.e., when the sustained negativity observed in long object questions disappeared, a late positivity was observed. It was concluded that this positive-going ERP effect reflects the increased difficulty of linking the filler, which was maintained in working memory, with its gap position. This had to be done in addition to the integration of the subject NP which was encountered at this position, causing a locally increased processing difficulty. However, this effect was only observed in sentences which required the temporary maintenance of the moved element in working memory, at least for a very short time. The positivity was observed in both short and long conditions in Experiment 1. However, in the short wh-questions of Experiment 2, no such positivity was elicited. This was the only condition of the two ERP experiments in which no element at all was inserted between the filler and the second NP. Thus, it has to be concluded that the local integration process observed at the second NP is dependent upon the distance over which the dislocated element was maintained in memory.

The locality principle as formulated in SPLT – i.e., the assumption that integration costs are greater when a greater distance, measured in the number of intervening discourse referents, has to be bridged – is not necessarily supported by the present data from German wh-questions. In subject and object wh-questions, i.e., in the sentences that showed the late positive ERP effect, there is no difference in the locality of integration processes at the second NP, as determined on the basis of intervening discourse referents. However, the findig of a length-dependency of the late positivity in Experiment 2 provides support to the general idea of locality in sentence processing. This conclusion is supported by the finding of Experiment 1 that independent of sentence type, the amplitude of the late positivity was greater in long questions than in short questions.

The ERP experiments reported in the present thesis identified differences in local parsing complexity at specific positions but not at others. Thus, it can be concluded that within a single paradigm, by exploiting the different methods of analyzing ERP data, both local and global aspects of parsing could be identified. Both these aspects of sentence processing critically contribute to the successful comprehension of sentences.

8.1.4 Resource Distribution during Parsing

Taken together, the findings from multi-word ERPs and the analyses of local ERP effects strongly suggest that global and local aspects of parsing can be active in parallel and have to cooperate in order to arrive at a correct interpretation of a sentence. Although this conclusion appears to be very obvious, the interplay between local and global parsing mechanisms has only rarely been included into theoretical models of parsing, and there are only few studies that explicitely investigated both aspects of sentence processing at the same time. The present results suggest that temporary maintenance of syntactic information and more local aspects of parsing draw upon distinct cognitive resources. This conlusion is supported by two findings from Experiment 1. First, while the sustained negativity was only present for long object wh-questions, the late positive component was independent of the length of the filler-gap distance. However, as discussed in the previous section, the latter effect disappeared when the moved object and the subject-NP were adjacent, as in the short questions in Experiment 2. Second, providing even stronger evidence, the sustained negativity was clearly dependent upon individual working memory capacity while the late positivity was not influenced by this factor.

It appears, thus, that while the actual computational processes of sentence processing can be performed by a part of the parsing mechanism that is available to all individuals to the same degree, independent of their performance in the reading span task, a distinct aspect of the available working memory resources has to be involved when syntactic information needs to be stored for later processing. The working memory capacity measure that was used to determine the amount of resources available, i.e., the reading span task (Daneman & Carpenter, 1980), obviously is only sensitive to the latter aspect of sentence processing. It can be questioned whether it is reasonable at all to refer to the former of the two resources, i.e., the one supporting the actual compuational processes of parsing, as a working memory resource.

With respect to current models of working memory and language, the present data do not clearly favor either of the two dominant theories in the literature. On the one hand, they contradict the Capacity Theory of Comprehension (Just & Carpenter, 1992) by demonstrating that not all aspects of sentence processing are dependent upon individual working memory capacity. On the other hand, the dissociation with respect to individual working memory capacity that was observed here does also not directly fit to the distinction proposed by Caplan and Waters (1999). These authors suggested that 'interpretive processes' of on-line sentence interpretation are independent of individual capacity while 'post-interpretive' processing correlates with individual working memory capacity. In the ERP experiments reported here, two aspects of on-line parsing, temporary maintenance and local establishment of a filler-gap dependency, have been identified which were differentially influenced by the participants' working memory capacity. One of these processes was clearly dependent upon the amount of working memory capacity available. The data, thus, suggest that within the domain of interpretive processing, there might be a further subdivision into cognitive resources supporting local integrational processes and working memory resources drawn upon when syntactic information has to be maintained temporarily. This assumption is very close to the distinction of linguistic integration costs and structural memory costs which was recently proposed in the context of the Syntactic Prediction Locality Theory (Gibson, 1998).

8.1.5 Neuroanatomical Correlates

The neuroanatomical correlates of the working memory processes identified in the ERP experiments were investigated in Experiment 3, an fMRI study. As the temporal resolution of fMRI makes it hard to isolate transient processes of only a few hundreds of milliseconds duration, the focus of this experiment was primarily on identifying the neuroanatomical correlates of the sustained effects of maintenance observed in the previous studies. The most important result of this study was the finding of a bilateral network of inferior frontal (i.e., BA 44 and 44/45) and superior temporal brain areas that were activated more strongly for long object wh-questions, as compared to short object wh-questions. Thus, the clearest effects were observed in a contrast in which, in Experiment 2, a right-lateralized sustained frontal negativity was observed which was interpreted as reflecting the syntactic working memory load caused by temporarily maintaining the dislocated object in memory. As it was argued in the theoretical part of this work that previous activation effects in similar experiments using PET or fMRI techniques were most likely attributable to differences in working memory load between the conditions (see Section 3.4.4), this result was not unexpected. However, the finding that object-first structures, when compared to subject-first questions, did not lead to an activation increase in any perisylvian area was surprising and was in clear contrast to the previous studies reported in the literature.

On the basis of the present data, it has to be concluded that the frontal and temporal areas identified in this study were activated by working memory processes elicited during the on-line establishment of filler-gap dependencies. Although the results of this experiment were unexpected given the previous findings of other neuroimaging studies of syntactic complexity, the interpretation of the present results as reflecting the involvement of working memory processes is not necessarily contradicting previous work. In most studies it has been discussed that the obtained activation differences might either be due to computational aspects of parsing or to an increased demand on syntactic working memory resources (e.g., Just et al., 1996; Stromswold et al., 1996). The results obtained in Experiment 3, thus, appear to clear up this question, suggesting that inferior frontal and superior temporal brain regions are involved in processes of working memory that are relevant during on-line processing of sentences.

It might be argued that the activation differences observed in inferior frontal regions could be due to an increased involvement of verbal working mechanisms (like, e.g., phonological rehearsal) in the more complex question conditions. However, it was discussed (cf. Section 7.3) that this alternative explanation is unlikely to be true. First, the number of words in the sentences was the same, making it unplausible that phonological back-up storage of the sentences would elicit differential activations. Second, an analysis of time-courses at the maximal of the activation in the left inferior frontal gyrus demonstrated that towards the point in time in the trial when the comprehension task was performed, the two sentence conditions did not differ. Third, as the ERP results suggest, the sustained ERP difference was restricted to a circumscribed region of the sentence. It appeared to be clearly separated from the performance of the behavioral task.

The fact that in the contrast between long object and long subject wh-questions no reliable activation differences were observed was in contrast to the finding of a sustained ERP effect in the corresponding analyses in Experiments 1 and 2. An explorative analysis with a reduced z-threshold suggested that left anterior temporal regions might contribute to the sustained negativity observed in the ERP experiments. However, this finding has to be treated very cautiously (cf. Section 7.3).

The results of the fMRI study demonstrate that event-related fMRI can be used to investigate on-line parsing of sentences differing in structural complexity. This result is important because it suggests that the brain areas involved in sentence processing can be observed with a higher temporal resolution than was possible with previously used blocked designs. Furthermore, the present findings contribute significantly to the current knowledge of the neurocognitive bases of syntactic processing by suggesting that inferior frontal and superior temporal brain regions interact in order to enable the brain to temporarily maintain syntactic information available during sentence processing.

8.2 Integration of ERP and fMRI Results

In some respect, the results from the two experimental techniques that have been used in the course of the present work support each other. However, there are also differences between ERP and fMRI effects that are less easy to explain. First, due to the restrictions in the temporal resolution of fMRI, it was clear from the beginning that the parsing mechansims which were referred to as 'local' in this thesis, i.e., the actual computational processes of analyzing the incoming linguistic input and integrating it into a mental representation of the phrase structure, would be difficult to detect using fMRI. This aspect of parsing can much better be mapped using the ERP technique which offers a very high temporal resolution. Second, while one contrast that elicited slow wave effects in ERPs also led to activation differences in the fMRI data (i.e., the contrast between long and short object wh-questions), the comparison of subject with object questions did not yield differential activations in the fMRI modality although there were clear ERP differences observed in the long questions.

It is unlikely that the cognitive processes that were activated by the participants in the fMRI experiment and in the second ERP experiment were markedly different because the behavioral performance data were very similar in both studies. There are three other alternatives that might explain the difference between the findings of the ERP experiment and the fMRI experiment. First, it might be the case that the brain activity that lead to the sustained ERP negativity can not be deteced with the fMRI technique. While ERPs are a direct measure of the electro-physiological activity of assemblies of neurons, fMRI is a more indirect measurement of brain activity reflecting changes in local blood oxygenation in response to increased neural activity. Although this explanation is not very satisfactory, the direct comparison of two methods that do not measure exactly the same neural processes is always faced with the potential danger of such method-specific differences. Second, it might be the case that although the sustained negativity was clearly identifiable in the ERPs, it was not strong enough to show reliable activation differences in the fMRI experiment. Third, it might also be the case that activations could not be picked up because not the complete brain was covered by the eight slices measured in the fMRI study. When adopting the assumptions that (a) left anterior temporal areas might have contributed to this negativity, and (b) that these areas were only partly covered by the slices measured in this experiment and thus effects in this area were only observable in a subgroup of the participants (cf. Section 7.3), it might well be that an activation difference that was actually present in this or adjacent areas in all participants did not have enough statistical power to reach significance in the group analysis.

On the other hand, the finding that when comparing long and short object questions, the long condition elicited stronger haemodynamic responses and an increased negativity justifies the strategy of comparing data from these two neurocognitive research methods. While the fMRI results alone already can be viewed as important evidence for an involvement of specific brain areas in syntax-specific working memory processes, a conclusion that is relevant for the interpretation of the results of other neuroimaging studies of syntactic complexity, the ERP results further support this conclusion and give strong suggestions about where in the sentence these activation differences were elicited. This result could not have been obtained from neuroimaging data alone.

A more direct integration of data from electrophysiological and hemodynamic methods would be the use of fMRI-constrained inverse modelling of ERPs (e.g., Knösche, 1997; Opitz, 1999). This approach was not chosen in the present research because, due to the restrictions inherent to psycholinguistic studies, the signal-to-noise ratio required for reliable dipole analyses of ERP data could not be reached with the present studies. The restrictions in experimental design are, among others, the limited number of items that are available when trying to avoid repetitions, the relatively long duration of the stimulus sentences which would lead to unacceptably long measurements when trial numbers sufficient for inverse modeling would be recorded, or the concentration on relative ERP effects in the field of psycholinguistics (i.e., relative differences between the ERPs elicited by two conditions; e.g., the sustained negativity), as opposed to absolute ERP effects like early sensory components. However, the present results show that it is also very fruitful to exploit the advantages of both haemodynamic and electrophysiological methods by investigating identical paradigms with these different methods.

8.3 Conclusion

The three experiments reported in this thesis show that the combined investigation of electrophysiological and neuroimaging data in psycholinguistic experiments is important for an understanding of the neurocognitive bases of language processing. This approach can provide evidence regarding the neuroanatomical and temporal organization of parsing mechanisms in the brain. The present work also demonstrates that when investigating event-related brain potentials elicited during the processing of sentences, it is important to consider both local and global effects to obtain a complete picture of the processes that are active during on-line parsing. Furthermore, the results obtained in the present series of experiments are relevant because they demonstrate that by exploiting certain characteristics of German (e.g., SOV, overt case marking), insights can be gained which can not be reached on the basis of studying exclusively the English language.

The present work strongly suggests that the local computations of syntax, on the one hand, and more global processes of temporary maintenance in working memory have to be treated separately in modelling the mechanisms of sentence processing. This distinction is only rarely made explicitly in theoretical models of sentence processing. Models that separate these two aspects of parsing, like the SPLT approach introduced by Gibson (1998) receive empirical support from the ERP experiments reported here. The latter aspect of parsing, maintenance of syntactic information in working memory, is especially relevant in cases when linguistic information can not be integrated immediately. In the present experiments this was the case because an object was moved from its canonical position in the sentence structure to clause initial position.

Furthermore, the results obtained in the first ERP experiment also suggest that local and global mechanisms of parsing, at least when processing German wh-questions, are dependent upon distinct cognitive processing resources. While local parsing mechanisms were not influenced by individual working memory capacity, maintaining the moved object in working memory was found to depend upon the amount of working memory resources available to the participants. This result challenges theoretical notions that postulate unitary resources for all aspects of language processing, such as for example the Capacity Theory of Comprehension (Just & Carpenter, 1992). On the basis of the results of the work reported here, one has to conclude that there appear to be separable cognitive resources for the actual computational processes of reconstructing a phrase structure from the linguistic input and, on the other hand, temporarily storing syntactic information in working memory for later usage.

The fMRI results of Experiment 3 lead to the assumption that the temporary maintenance of syntactic information in working memory is supported by inferior frontal and superior temporal brain regions of both hemispheres. This finding is an important contribution to the present knowledge available regarding the neurocognitive implementation of language processing mechanisms. It sheds new light on the results of previous brain imaging studies of syntactic complexity which did not allow to unequivocally determine the nature of the activation differences observed when comparing sentences of different complexity.

With respect to neurocognitive models of sentence processing, the present results give some clues regarding the functional neuroanatomy of the cognitive parser. It has been suggested (e.g., Friederici, 1999) that after the word category of an input string has been determined, left inferior frontal brain regions become involved in integrating the new linguistic input into the phrase structure. However, the present data suggest that the fronto-opercular region is also implicated in the temporary maintenance of syntactic information. It appears to be a challenge for future research to consider the differential contributions of different sub-regions of the inferior frontal cortex to sentence processing in more detail. Hopefully, the development of more sensitive brain imaging technologies allows to determine in the future how these regions contribute to different aspects of parsing. One proposal has been made recently by Friederici (2001) who suggested that more lateral aspects of the frontal operculum might be involved in syntactic working memory while those opercular regions which are located more medially (i.e., more towards the anterior insula; cf. Figure 3.3) might be responsible for syntactic structure building, in cooperation with regions of the anterior temporal lobe.

8.4 Outlook

The present experiments used event-related brain potentials and functional magnetic resonance imaging in order to investigate how the human brain processes one specific type of sentences, namely German wh-questions. The results that were reported here led to the conclusion that local parsing processes closely interact with more global processes of working memory in order to make a correct understanding of sentences possible. It was observed that the identification of a dislocated object wh-filler in clause-initial position triggered working memory processes responsible for maintaining the moved element in working memory.

Although in good support of theoretical models, the present results also elicited a number of further questions that could not be answered in the context of this thesis. For example, one might ask whether the effects reported here are specific to the types of sentences used in the present studies, i.e., to embedded constituent questions introduced by a wh-interrogative pronoun, or whether these mechanisms are more general in nature. In order to answer this question, it might be useful to investigate other sentence structures that are also derived by transformational movement. For example, the scrambling of full object noun phrases to clause-initial position might yield a comparable (or even greater) working memory load. It is also of interest to find out whether the sustained negativity, which was taken to reflect working memory processes, is due merely to the number of intervening words between the filler and the gap site (i.e., to the time that passes before the gap becomes available) or whether this working memory effect is mainly elicited by the structural complexity of the intervening material. This aspect of the working memory load could be investigated by manipulating the complexity of the material encountered between the filler and the gap while keeping the number of words constant. Furthermore, it might also be of interest to find out how the processing of sentences with long filler-gap dependencies is influenced by concurrent working memory load or concurrent irrelevant articulation, a manipulation which prevents the participants from using subvocal rehearsal mechanisms of the verbal working memory system for performing in the behavioral task.

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Appendix A: Supplementary ERP Plots for Experiment 1

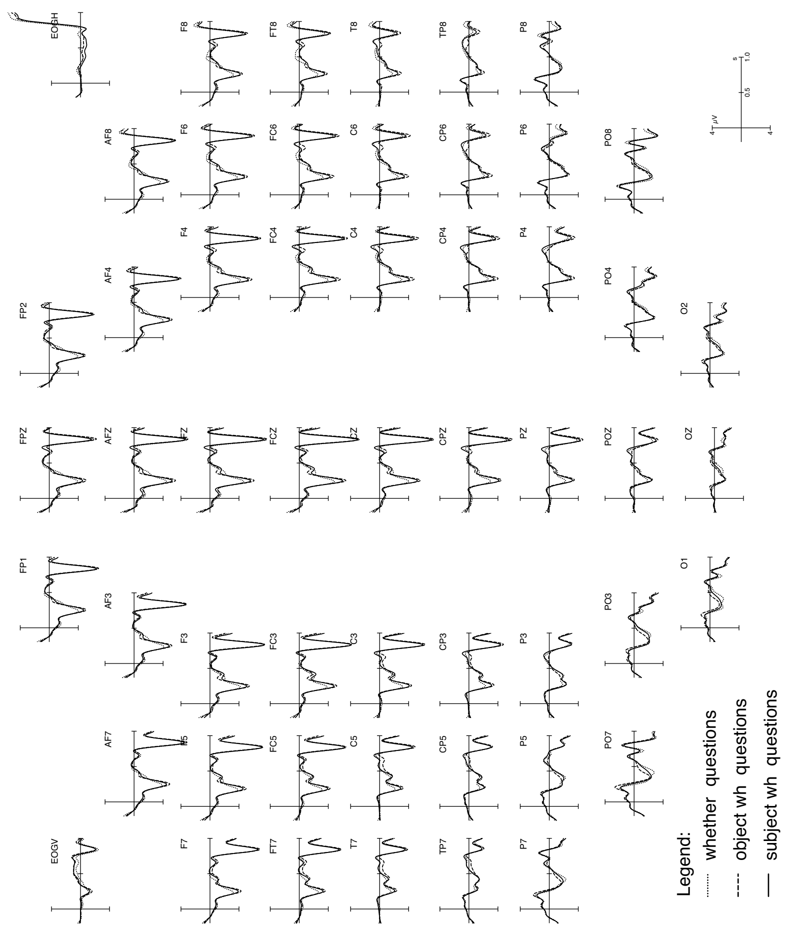

Figure 8.1: *Complete set of 51 electrodes for Figure 5.1. Local ERPs elicited by subject and object wh-questions, as well as whether-questions at the question word (collapsed across sentence length).*

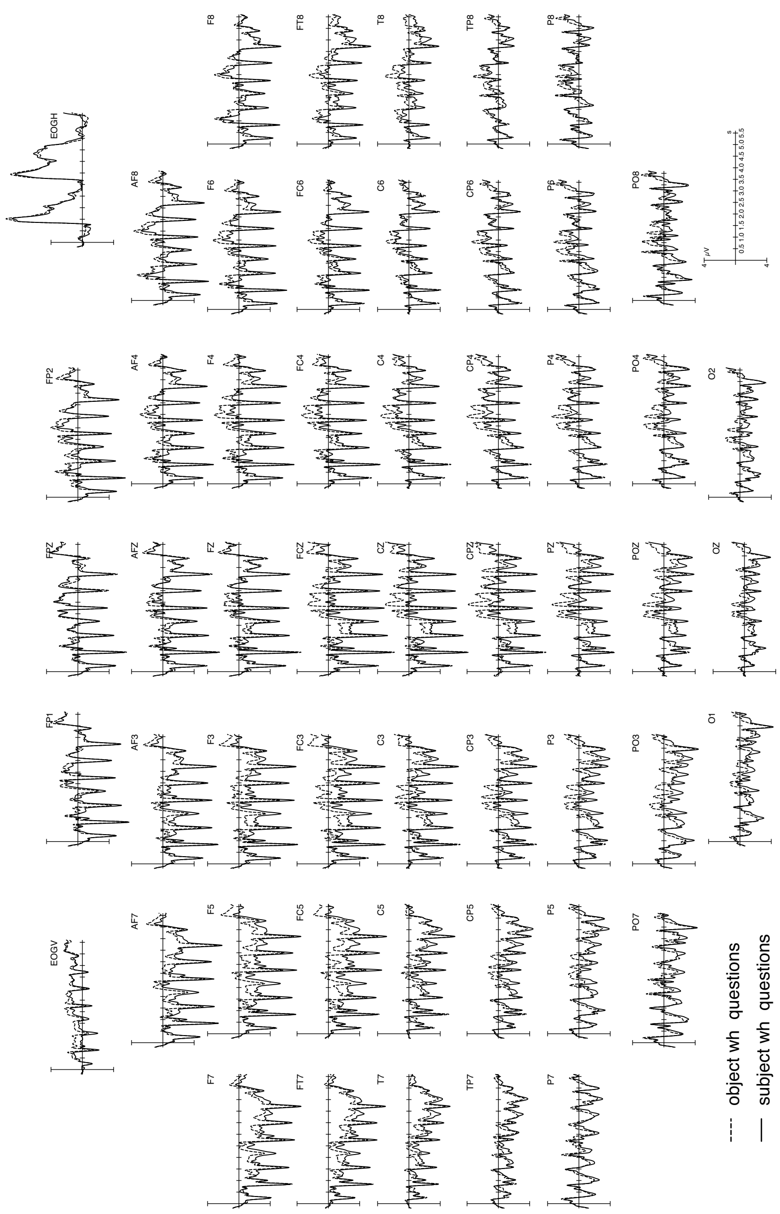

Figure 8.2: *Complete set of 51 electrodes for Figure 5.2. Multi-word ERPs for long subject and long object wh-questions.*

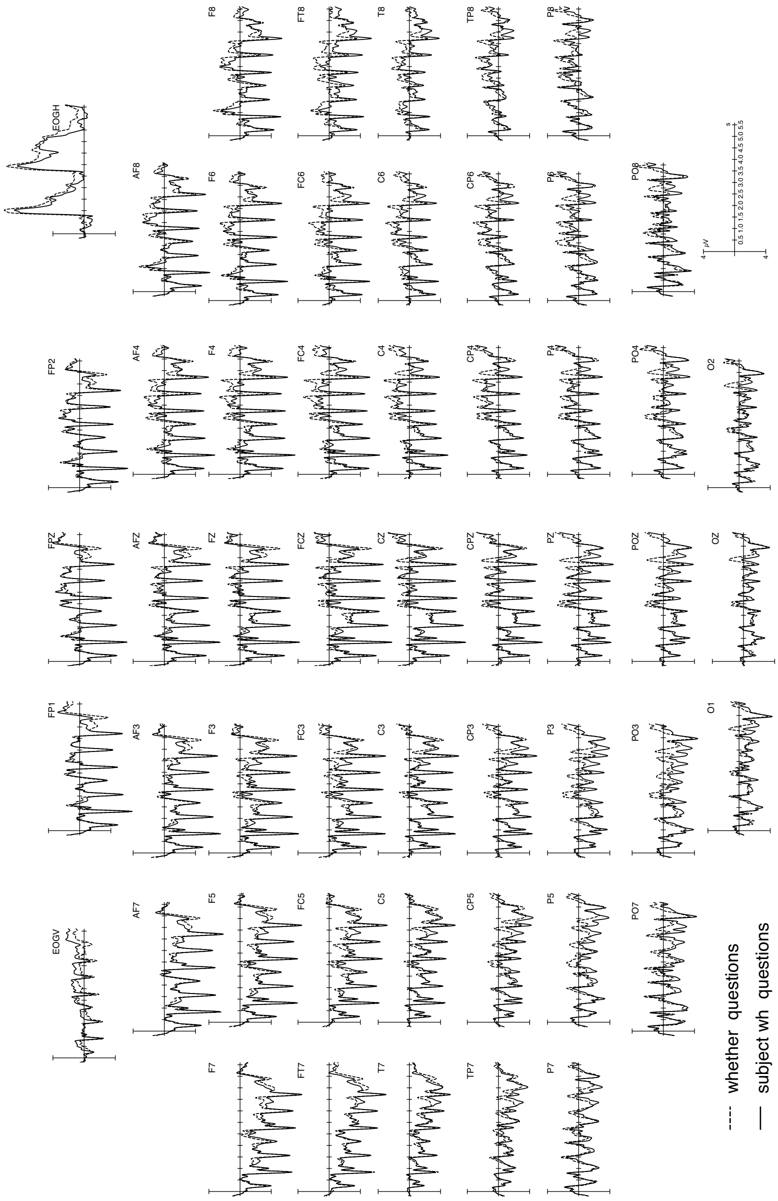

Figure 8.3: *Complete set of 51 electrodes for Figure 5.3. Multi-word ERPs for long subject wh-questions and long whether-questions.*

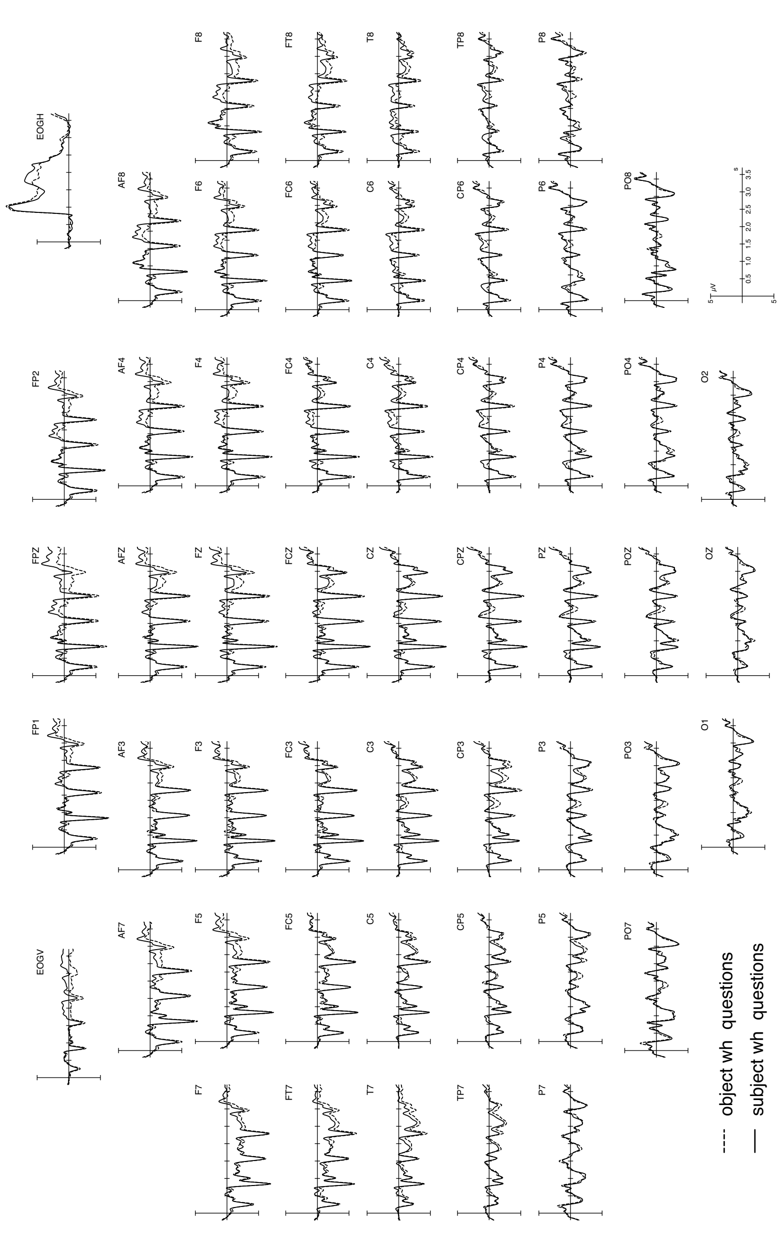

Figure 8.4: *Complete set of 51 electrodes for Figure 5.6. Multi-word ERPs for short subject and short object wh-questions.*

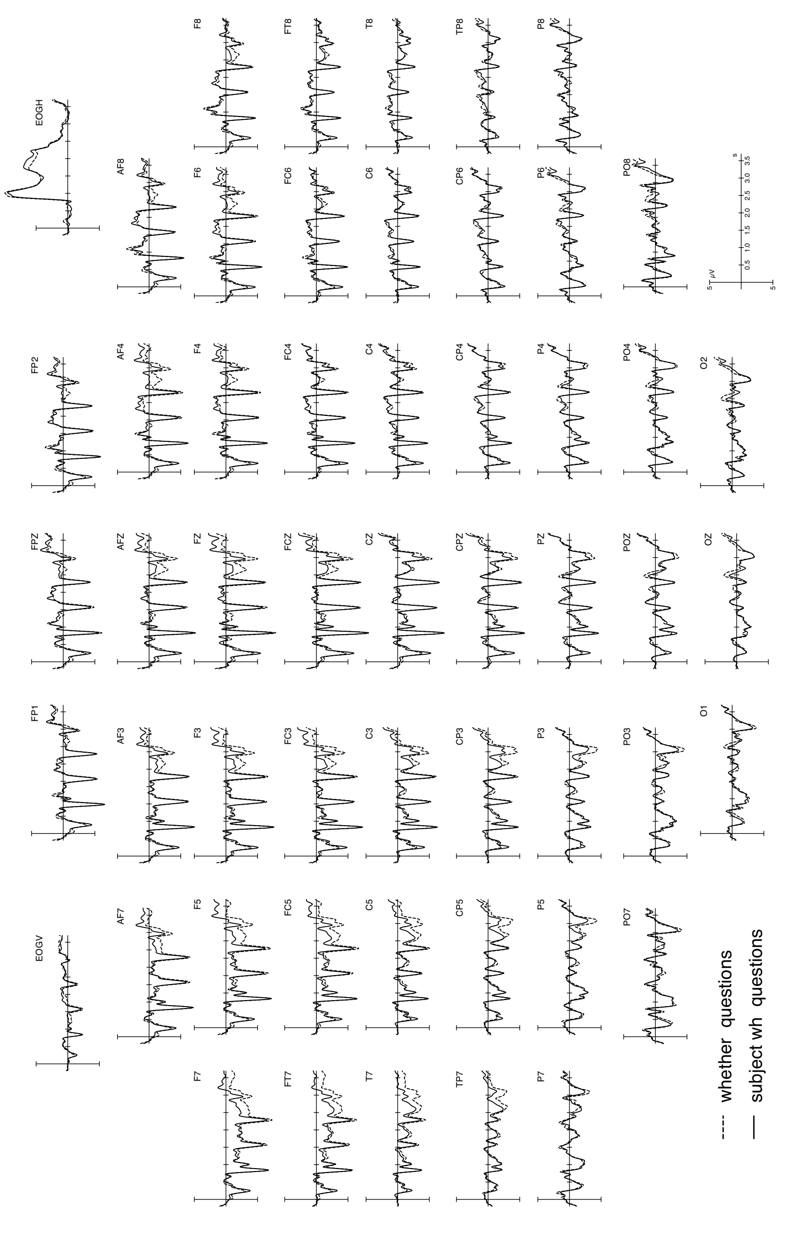

Figure 8.5: *Multi-word ERPs for short subject wh-questions and short whether-questions.*

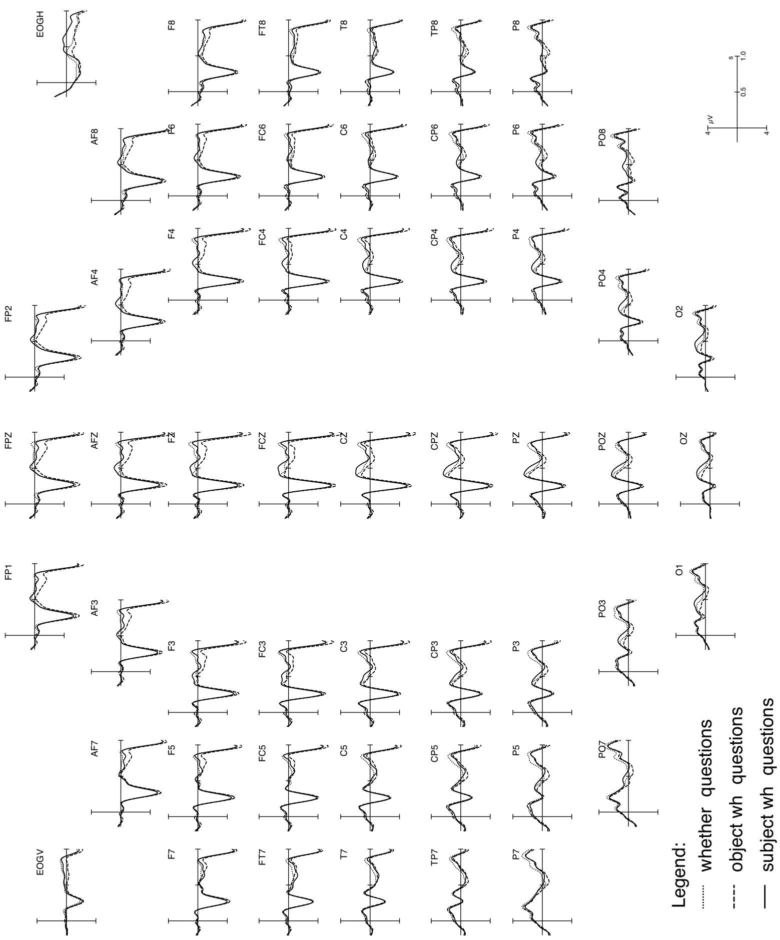

Figure 8.6: *Complete set of 51 electrodes for Figure 5.9. Local ERPs elicited by subject and object wh-questions, as well as whether-questions at the second noun phrase position (collapsed across sentence length).*

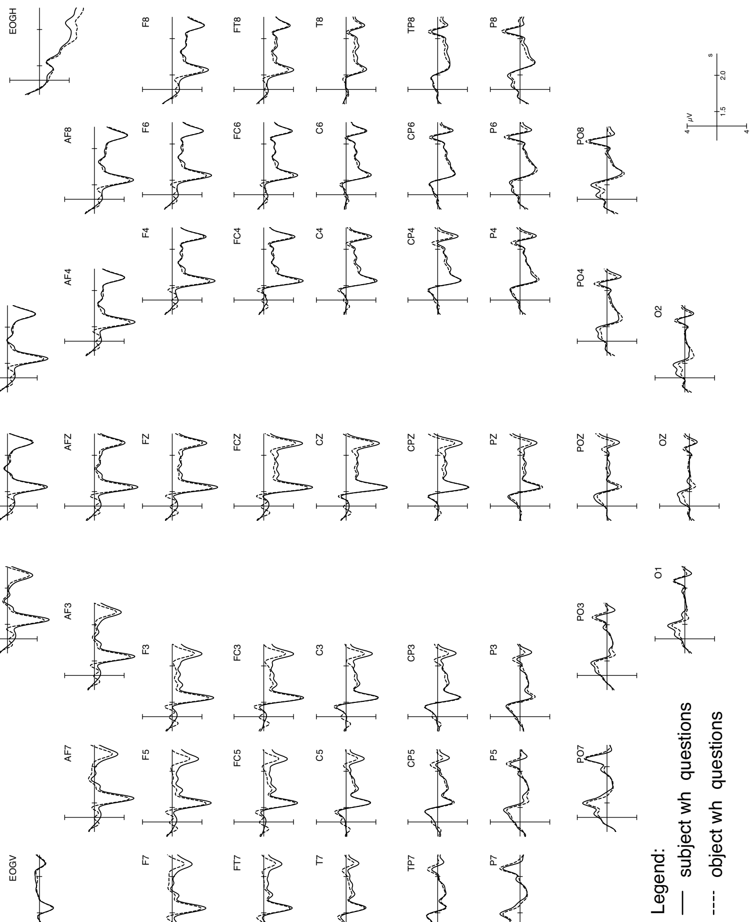

Figure 8.7: ***Local ERPs at the second frame of the prepositional phrase in long subject and object wh-questions (i.e., 'nachmittag' in the examples given in Table 5.1).***

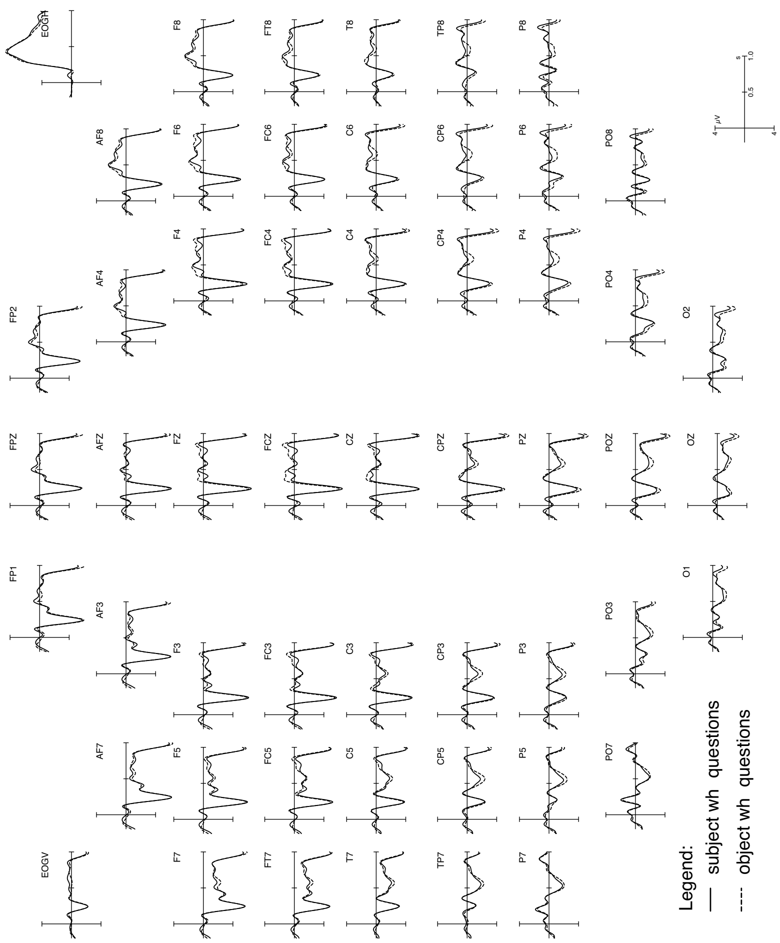

Figure 8.8: ***Local ERPs at the last frame of the prepositional phrase in long subject and object wh-questions (i.e., 'dem Unfall' in the examples given in Table 5.1).***

Appendix B: Stimulus Material

Experiment 1

S-S: short subject wh-questions
S-O: short object wh-questions
S-W: short whether/ob-questions
L-S: long subject wh-questions
L-O: long object wh-questions
L-W: long whether/ob-questions

S-S Udo fragt sich, wer am Montag den Kunden beruhigt hat.
S-O Udo fragt sich, wen am Montag der Kunde beruhigt hat.
S-W Udo fragt sich, ob am Montag der Kunde eingekauft hat.

L-S Udo fragt sich, wer am Montag vormittag in dem Kaufhaus den Kunden beruhigt hat.
L-O Udo fragt sich, wen am Montag vormittag in dem Kaufhaus der Kunde beruhigt hat.
L-W Udo fragt sich, ob am Montag vormittag in dem Kaufhaus der Kunde eingekauft hat.

S-S Jürgen fragt sich, wer am Dienstag den Bastler unterstützt hat.
S-O Jürgen fragt sich, wen am Dienstag der Bastler unterstützt hat.
S-W Jürgen fragt sich, ob am Dienstag der Bastler geholfen hat.

L-S Jürgen fragt sich, wer am Dienstag nachmittag bei der Arbeit den Bastler unterstützt hat.
L-O Jürgen fragt sich, wen am Dienstag nachmittag bei der Arbeit der Bastler unterstützt hat.
L-W Jürgen fragt sich, ob am Dienstag nachmittag bei der Arbeit der Bastler geholfen hat.

S-S Stefan fragt sich, wer am Mittwoch den Kranken angesteckt hat.
S-O Stefan fragt sich, wen am Mittwoch der Kranke angesteckt hat.
S-W Stefan fragt sich, ob am Mittwoch der Kranke geschrien hat.

L-S Stefan fragt sich, wer am Mittwoch vormittag in dem Auto den Kranken angesteckt hat.
L-O Stefan fragt sich, wen am Mittwoch vormittag in dem Auto der Kranke angesteckt hat.
L-W Stefan fragt sich, ob am Mittwoch vormittag in dem Auto der Kranke geschrien hat.

S-S Katja fragt sich, wer am Freitag den Chauffeur abgeholt hat.
S-O Katja fragt sich, wen am Freitag der Chauffeur abgeholt hat.
S-W Katja fragt sich, ob am Freitag der Chauffeur hergezeigt hat.

L-S Katja fragt sich, wer am Freitag nachmittag auf dem Parkplatz den Chauffeur abgeholt hat.
L-O Katja fragt sich, wen am Freitag nachmittag auf dem Parkplatz der Chauffeur abgeholt hat.
L-W Katja fragt sich, ob am Freitag nachmittag auf dem Parkplatz der Chauffeur hergezeigt hat.

S-S Thomas fragt sich, wer am Samstag den Kläger gezwungen hat.
S-O Thomas fragt sich, wen am Samstag der Kläger gezwungen hat.
S-W Thomas fragt sich, ob am Samstag der Kläger geschrieben hat.

L-S Thomas fragt sich, wer am Samstag vormittag bei der Sitzung den Kläger gezwungen hat.
L-O Thomas fragt sich, wen am Samstag vormittag bei der Sitzung der Kläger gezwungen hat.
L-W Thomas fragt sich, ob am Samstag vormittag bei der Sitzung der Kläger geschrieben hat.

S-S Britta fragt sich, wer am Montag den Gärtner ausgefragt hat.
S-O Britta fragt sich, wen am Montag der Gärtner ausgefragt hat.
S-W Britta fragt sich, ob am Montag der Gärtner gelogen hat.

L-S Britta fragt sich, wer am Montag nachmittag bei dem Verhör den Gärtner ausgefragt hat.
L-O Britta fragt sich, wen am Montag nachmittag bei dem Verhör der Gärtner ausgefragt hat.
L-W Britta fragt sich, ob am Montag nachmittag bei dem Verhör der Gärtner gelogen hat.

S-S Felix fragt sich, wer am Dienstag den Gauner verwundet hat.
S-O Felix fragt sich, wen am Dienstag der Gauner verwundet hat.
S-W Felix fragt sich, ob am Dienstag der Gauner gehumpelt hat.

L-S Felix fragt sich, wer am Dienstag vormittag bei dem Treffen den Gauner verwundet hat.
L-O Felix fragt sich, wen am Dienstag vormittag bei dem Treffen der Gauner verwundet hat.
L-W Felix fragt sich, ob am Dienstag vormittag bei dem Treffen der Gauner gehumpelt hat.

S-S Hanna fragt sich, wer am Mittwoch den Boxer beleidigt hat.
S-O Hanna fragt sich, wen am Mittwoch der Boxer beleidigt hat.
S-W Hanna fragt sich, ob am Mittwoch der Boxer verloren hat.

L-S Hanna fragt sich, wer am Mittwoch nachmittag bei dem Wettkampf den Boxer beleidigt hat.
L-O Hanna fragt sich, wen am Mittwoch nachmittag bei dem Wettkampf der Boxer beleidigt hat.
L-W Hanna fragt sich, ob am Mittwoch nachmittag bei dem Wettkampf der Boxer verloren hat.

S-S Christoph fragt sich, wer am Freitag den Dichter geärgert hat.
S-O Christoph fragt sich, wen am Freitag der Dichter geärgert hat.
S-W Christoph fragt sich, ob am Freitag der Dichter zugehört hat.

L-S Christoph fragt sich, wer am Freitag vormittag bei dem Empfang den Dichter geärgert hat.
L-O Christoph fragt sich, wen am Freitag vormittag bei dem Empfang der Dichter geärgert hat.
L-W Christoph fragt sich, ob am Freitag vormittag bei dem Empfang der Dichter zugehört hat.

S-S Karin fragt sich, wer am Samstag den Sportler geschlagen hat.
S-O Karin fragt sich, wen am Samstag der Sportler geschlagen hat.
S-W Karin fragt sich, ob am Samstag der Sportler randaliert hat.

L-S Karin fragt sich, wer am Samstag nachmittag nach dem Training den Sportler geschlagen hat.
L-O Karin fragt sich, wen am Samstag nachmittag nach dem Training der Sportler geschlagen hat.
L-W Karin fragt sich, ob am Samstag nachmittag nach dem Training der Sportler randaliert hat.

S-S Sascha fragt sich, wer am Montag den Jungen angelacht hat.
S-O Sascha fragt sich, wen am Montag der Junge angelacht hat.
S-W Sascha fragt sich, ob am Montag der Junge gezappelt hat.

L-S Sascha fragt sich, wer am Montag vormittag auf der Straße den Jungen angelacht hat.
L-O Sascha fragt sich, wen am Montag vormittag auf der Straße der Junge angelacht hat.
L-W Sascha fragt sich, ob am Montag vormittag auf der Straße der Junge gezappelt hat.

S-S Eva fragt sich, wer am Dienstag den Doktor verständigt hat.
S-O Eva fragt sich, wen am Dienstag der Doktor verständigt hat.
S-W Eva fragt sich, ob am Dienstag der Doktor ausgeharrt hat.

L-S Eva fragt sich, wer am Dienstag nachmittag nach dem Unfall den Doktor verständigt hat.
L-O Eva fragt sich, wen am Dienstag nachmittag nach dem Unfall der Doktor verständigt hat.
L-W Eva fragt sich, ob am Dienstag nachmittag nach dem Unfall der Doktor ausgeharrt hat.

S-S Hanna fragt sich, wer am Mittwoch den Sprecher verwechselt hat.
S-O Hanna fragt sich, wen am Mittwoch der Sprecher verwechselt hat.
S-W Hanna fragt sich, ob am Mittwoch der Sprecher gezögert hat.

L-S Hanna fragt sich, wer am Mittwoch vormittag bei der Rede den Sprecher verwechselt hat.
L-O Hanna fragt sich, wen am Mittwoch vormittag bei der Rede der Sprecher verwechselt hat.
L-W Hanna fragt sich, ob am Mittwoch vormittag bei der Rede der Sprecher gezögert hat.

S-S Tina fragt sich, wer am Freitag den Richter informiert hat.
S-O Tina fragt sich, wen am Freitag der Richter informiert hat.
S-W Tina fragt sich, ob am Freitag der Richter nachgefragt hat.

L-S Tina fragt sich, wer am Freitag nachmittag nach der Pause den Richter informiert hat.
L-O Tina fragt sich, wen am Freitag nachmittag nach der Pause der Richter informiert hat.
L-W Tina fragt sich, ob am Freitag nachmittag nach der Pause der Richter nachgefragt hat.

S-S Udo fragt sich, wer am Samstag den Gegner gefürchtet hat.
S-O Udo fragt sich, wen am Samstag der Gegner gefürchtet hat.
S-W Udo fragt sich, ob am Samstag der Gegner aufgeheult hat.

L-S Udo fragt sich, wer am Samstag vormittag bei dem Rennen den Gegner gefürchtet hat.
L-O Udo fragt sich, wen am Samstag vormittag bei dem Rennen der Gegner gefürchtet hat.
L-W Udo fragt sich, ob am Samstag vormittag bei dem Rennen der Gegner aufgeheult hat.

S-S Gabi fragt sich, wer am Montag den Anwalt eingeweiht hat.
S-O Gabi fragt sich, wen am Montag der Anwalt eingeweiht hat.
S-W Gabi fragt sich, ob am Montag der Anwalt nachgehakt hat.

L-S Gabi fragt sich, wer am Montag nachmittag vor dem Gericht den Anwalt eingeweiht hat.
L-O Gabi fragt sich, wen am Montag nachmittag vor dem Gericht der Anwalt eingeweiht hat.
L-W Gabi fragt sich, ob am Montag nachmittag vor dem Gericht der Anwalt nachgehakt hat.

S-S Heiko fragt sich, wer am Dienstag den Forscher vorgestellt hat.
S-O Heiko fragt sich, wen am Dienstag der Forscher vorgestellt hat.
S-W Heiko fragt sich, ob am Dienstag der Forscher gegrübelt hat.

L-S Heiko fragt sich, wer am Dienstag vormittag vor dem Vortrag den Forscher vorgestellt hat.
L-O Heiko fragt sich, wen am Dienstag vormittag vor dem Vortrag der Forscher vorgestellt hat.
L-W Heiko fragt sich, ob am Dienstag vormittag vor dem Vortrag der Forscher gegrübelt hat.

S-S Silke fragt sich, wer am Mittwoch den Käufer beschwichtigt hat.
S-O Silke fragt sich, wen am Mittwoch der Käufer beschwichtigt hat.
S-W Silke fragt sich, ob am Mittwoch der Käufer gewartet hat.

L-S Silke fragt sich, wer am Mittwoch nachmittag in dem Laden den Käufer beschwichtigt hat.
L-O Silke fragt sich, wen am Mittwoch nachmittag in dem Laden der Käufer beschwichtigt hat.
L-W Silke fragt sich, ob am Mittwoch nachmittag in dem Laden der Käufer gewartet hat.

S-S Jürgen fragt sich, wer am Freitag den Täter verpfiffen hat.
S-O Jürgen fragt sich, wen am Freitag der Täter verpfiffen hat.
S-W Jürgen fragt sich, ob am Freitag der Täter geblutet hat.

L-S Jürgen fragt sich, wer am Freitag vormittag nach dem Zweikampf den Täter verpfiffen hat.
L-O Jürgen fragt sich, wen am Freitag vormittag nach dem Zweikampf der Täter verpfiffen hat.
L-W Jürgen fragt sich, ob am Freitag vormittag nach dem Zweikampf der Täter geblutet hat.

S-S Anja fragt sich, wer am Samstag den Angler vertrieben hat.
S-O Anja fragt sich, wen am Samstag der Angler vertrieben hat.
S-W Anja fragt sich, ob am Samstag der Angler meditiert hat.

L-S Anja fragt sich, wer am Samstag nachmittag an dem Flüßchen den Angler vertrieben hat.
L-O Anja fragt sich, wen am Samstag nachmittag an dem Flüßchen der Angler vertrieben hat.
L-W Anja fragt sich, ob am Samstag nachmittag an dem Flüßchen der Angler meditiert hat.

S-S Anja fragt sich, wer am Montag den Bauern verspottet hat.
S-O Anja fragt sich, wen am Montag der Bauer verspottet hat.
S-W Anja fragt sich, ob am Montag der Bauer zugelangt hat.

L-S Anja fragt sich, wer am Montag vormittag auf dem Landgut den Bauern verspottet hat.
L-O Anja fragt sich, wen am Montag vormittag auf dem Landgut der Bauer verspottet hat.
L-W Anja fragt sich, ob am Montag vormittag auf dem Landgut der Bauer zugelangt hat.

S-S Christoph fragt sich, wer am Dienstag den Klempner gerufen hat.
S-O Christoph fragt sich, wen am Dienstag der Klempner gerufen hat.
S-W Christoph fragt sich, ob am Dienstag der Klempner gerufen hat.

L-S C. fragt sich, wer am Dienstag nachmittag nach dem Rohrbruch den Klempner gerufen hat.
L-O C. fragt sich, wen am Dienstag nachmittag nach dem Rohrbruch der Klempner gerufen hat.
L-W C. fragt sich, ob am Dienstag nachmittag nach dem Rohrbruch der Klempner gerufen hat.

S-S Silke fragt sich, wer am Mittwoch den Makler beauftragt hat.
S-O Silke fragt sich, wen am Mittwoch der Makler beauftragt hat.
S-W Silke fragt sich, ob am Mittwoch der Makler weggehört hat.

L-S Silke fragt sich, wer am Mittwoch vormittag nach dem Gespräch den Makler beauftragt hat.
L-O Silke fragt sich, wen am Mittwoch vormittag nach dem Gespräch der Makler beauftragt hat.
L-W Silke fragt sich, ob am Mittwoch vormittag nach dem Gespräch der Makler weggehört hat.

S-S Heiko fragt sich, wer am Freitag den Cousin verhauen hat.
S-O Heiko fragt sich, wen am Freitag der Cousin verhauen hat.
S-W Heiko fragt sich, ob am Freitag der Cousin aufgelacht hat.

L-S Heiko fragt sich, wer am Freitag nachmittag nach dem Besuch den Cousin verhauen hat.
L-O Heiko fragt sich, wen am Freitag nachmittag nach dem Besuch der Cousin verhauen hat.
L-W Heiko fragt sich, ob am Freitag nachmittag nach dem Besuch der Cousin aufgelacht hat.

S-S Gabi fragt sich, wer am Samstag den Jäger angezeigt hat.
S-O Gabi fragt sich, wen am Samstag der Jäger angezeigt hat.
S-W Gabi fragt sich, ob am Samstag der Jäger geschossen hat.

L-S Gabi fragt sich, wer am Samstag vormittag nach dem Unfall den Jäger angezeigt hat.
L-O Gabi fragt sich, wen am Samstag vormittag nach dem Unfall der Jäger angezeigt hat.
L-W Gabi fragt sich, ob am Samstag vormittag nach dem Unfall der Jäger geschossen hat.

S-S Karin fragt sich, wer am Montag den Priester getröstet hat.
S-O Karin fragt sich, wen am Montag der Priester getröstet hat.
S-W Karin fragt sich, ob am Montag der Priester gelächelt hat.

L-S Karin fragt sich, wer am Montag nachmittag in der Kirche den Priester getröstet hat.
L-O Karin fragt sich, wen am Montag nachmittag in der Kirche der Priester getröstet hat.
L-W Karin fragt sich, ob am Montag nachmittag in der Kirche der Priester gelächelt hat.

S-S Tina fragt sich, wer am Dienstag den Zeugen gesehen hat.
S-O Tina fragt sich, wen am Dienstag der Zeuge gesehen hat.
S-W Tina fragt sich, ob am Dienstag der Zeuge zugeschaut hat.

L-S Tina fragt sich, wer am Dienstag vormittag vor dem Klinik den Zeugen gesehen hat.
L-O Tina fragt sich, wen am Dienstag vormittag vor dem Klinik der Zeuge gesehen hat.
L-W Tina fragt sich, ob am Dienstag vormittag vor dem Klinik der Zeuge zugeschaut hat.

S-S Martin fragt sich, wer am Mittwoch den Läufer überholt hat.
S-O Martin fragt sich, wen am Mittwoch der Läufer überholt hat.
S-W Martin fragt sich, ob am Mittwoch der Läufer resigniert hat.

L-S Martin fragt sich, wer am Mittwoch nachmittag bei dem Wettlauf den Läufer überholt hat.
L-O Martin fragt sich, wen am Mittwoch nachmittag bei dem Wettlauf der Läufer überholt hat.
L-W Martin fragt sich, ob am Mittwoch nachmittag bei dem Wettlauf der Läufer resigniert hat.

S-S Eva fragt sich, wer am Freitag den Gourmet belästigt hat.
S-O Eva fragt sich, wen am Freitag der Gourmet belästigt hat.
S-W Eva fragt sich, ob am Freitag der Gourmet aufgestöhnt hat.

L-S Eva fragt sich, wer am Freitag vormittag nach dem Essen den Gourmet belästigt hat.
L-O Eva fragt sich, wen am Freitag vormittag nach dem Essen der Gourmet belästigt hat.
L-W Eva fragt sich, ob am Freitag vormittag nach dem Essen der Gourmet aufgestöhnt hat.

S-S Sascha fragt sich, wer am Samstag den Schwindler ausgetrickst hat.
S-O Sascha fragt sich, wen am Samstag der Schwindler ausgetrickst hat.
S-W Sascha fragt sich, ob am Samstag der Schwindler hergeblickt hat.

L-S Sascha fragt sich, wer am Samstag nachmittag in dem Geschäft den Schwindler ausgetrickst hat.
L-O Sascha fragt sich, wen am Samstag nachmittag in dem Geschäft der Schwindler ausgetrickst hat.
L-W Sascha fragt sich, ob am Samstag nachmittag in dem Geschäft der Schwindler hergeblickt hat.

S-S Thomas fragt sich, wer am Montag den Zweifler ausgelacht hat.
S-O Thomas fragt sich, wen am Montag der Zweifler ausgelacht hat.
S-W Thomas fragt sich, ob am Montag der Zweifler mitgedacht hat.

L-S Thomas fragt sich, wer am Montag vormittag in der Firma den Zweifler ausgelacht hat.
L-O Thomas fragt sich, wen am Montag vormittag in der Firma der Zweifler ausgelacht hat.
L-W Thomas fragt sich, ob am Montag vormittag in der Firma der Zweifler mitgedacht hat.

S-S Katja fragt sich, wer am Dienstag den Sänger übertönt hat.
S-O Katja fragt sich, wen am Dienstag der Sänger übertönt hat.
S-W Katja fragt sich, ob am Dienstag der Sänger aufgebrüllt hat.

L-S Katja fragt sich, wer am Dienstag nachmittag in der Oper den Sänger übertönt hat.
L-O Katja fragt sich, wen am Dienstag nachmittag in der Oper der Sänger übertönt hat.
L-W Katja fragt sich, ob am Dienstag nachmittag in der Oper der Sänger aufgebrüllt hat.

S-S Stefan fragt sich, wer am Mittwoch den Rentner bespitzelt hat.
S-O Stefan fragt sich, wen am Mittwoch der Rentner bespitzelt hat.
S-W Stefan fragt sich, ob am Mittwoch der Rentner demonstriert hat.

L-S Stefan fragt sich, wer am Mittwoch vormittag in dem Mietshaus den Rentner bespitzelt hat.
L-O Stefan fragt sich, wen am Mittwoch vormittag in dem Mietshaus der Rentner bespitzelt hat.
L-W Stefan fragt sich, ob am Mittwoch vormittag in dem Mietshaus der Rentner demonstriert hat.

S-S Felix fragt sich, wer am Freitag den Schmuggler beliefert hat.
S-O Felix fragt sich, wen am Freitag der Schmuggler beliefert hat.
S-W Felix fragt sich, ob am Freitag der Schmuggler mitgemacht hat.

L-S Felix fragt sich, wer am Freitag nachmittag nach dem Gespräch den Schmuggler beliefert hat.
L-O Felix fragt sich, wen am Freitag nachmittag nach dem Gespräch der Schmuggler beliefert hat.
L-W Felix fragt sich, ob am Freitag nachmittag nach dem Gespräch der Schmuggler mitgemacht hat.

S-S Britta fragt sich, wer am Samstag den Filmstar beglückwünscht hat.
S-O Britta fragt sich, wen am Samstag der Filmstar beglückwünscht hat.
S-W Britta fragt sich, ob am Samstag der Filmstar gekichert hat.

L-S Britta fragt sich, wer am Samstag vormittag bei der Gala den Filmstar beglückwünscht hat.
L-O Britta fragt sich, wen am Samstag vormittag bei der Gala der Filmstar beglückwünscht hat.
L-W Britta fragt sich, ob am Samstag vormittag bei der Gala der Filmstar gekichert hat.

S-S Markus fragt sich, wer am Montag den Künstler beschwindelt hat.
S-O Markus fragt sich, wen am Montag der Künstler beschwindelt hat.
S-W Markus fragt sich, ob am Montag der Künstler rebelliert hat.

L-S M. fragt sich, wer am Montag nachmittag nach dem Frühstück den Künstler beschwindelt hat.
L-O M. fragt sich, wen am Montag nachmittag nach dem Frühstück der Künstler beschwindelt hat.
L-W M. fragt sich, ob am Montag nachmittag nach dem Frühstück der Künstler rebelliert hat.

S-S Anne fragt sich, wer am Dienstag den Autor kritisiert hat.
S-O Anne fragt sich, wen am Dienstag der Autor kritisiert hat.
S-W Anne fragt sich, ob am Dienstag der Autor nachgedacht hat.

L-S Anne fragt sich, wer am Dienstag vormittag bei der Lesung den Autor kritisiert hat.
L-O Anne fragt sich, wen am Dienstag vormittag bei der Lesung der Autor kritisiert hat.
L-W Anne fragt sich, ob am Dienstag vormittag bei der Lesung der Autor nachgedacht hat.

S-S Martin fragt sich, wer am Mittwoch den Lehrer vertreten hat.
S-O Martin fragt sich, wen am Mittwoch der Lehrer vertreten hat.
S-W Martin fragt sich, ob am Mittwoch der Lehrer hergeschaut hat.

L-S Martin fragt sich, wer am Mittwoch nachmittag in der Schule den Lehrer vertreten hat.
L-O Martin fragt sich, wen am Mittwoch nachmittag in der Schule der Lehrer vertreten hat.
L-W Martin fragt sich, ob am Mittwoch nachmittag in der Schule der Lehrer hergeschaut hat.

S-S Anne fragt sich, wer am Freitag den Pächter ruiniert hat.
S-O Anne fragt sich, wen am Freitag der Pächter ruiniert hat.
S-W Anne fragt sich, ob am Freitag der Pächter zugefaßt hat.

L-S Anne fragt sich, wer am Freitag vormittag nach der Pleite den Pächter ruiniert hat.
L-O Anne fragt sich, wen am Freitag vormittag nach der Pleite der Pächter ruiniert hat.
L-W Anne fragt sich, ob am Freitag vormittag nach der Pleite der Pächter zugefaßt hat.

S-S Markus fragt sich, wer am Samstag den Spieler beschummelt hat.
S-O Markus fragt sich, wen am Samstag der Spieler beschummelt hat.
S-W Markus fragt sich, ob am Samstag der Spieler geschummelt hat.

L-S Markus fragt sich, wer am Samstag nachmittag nach dem Training den Spieler beschummelt hat.
L-O Markus fragt sich, wen am Samstag nachmittag nach dem Training der Spieler beschummelt hat.
L-W Markus fragt sich, ob am Samstag nachmittag nach dem Training der Spieler geschummelt hat.

Experiments 2 and 3

S-S: short subject wh-questions
S-O: short object wh-questions
L-S: long subject wh-questions
L-O: long object wh-questions

S-S Udo fragt sich, wer den Pfarrer am Montag vormittag vor dem Kaufhaus beruhigt hat.
S-O Udo fragt sich, wen der Pfarrer am Montag vormittag vor dem Kaufhaus beruhigt hat.

L-S Udo fragt sich, wer am Montag vormittag vor dem Kaufhaus den Pfarrer beruhigt hat.
L-O Udo fragt sich, wen am Montag vormittag vor dem Kaufhaus der Pfarrer beruhigt hat.

S-S Jürgen fragt sich, wer den Bastler am Dienstag nachmittag bei der Arbeit unterstützt hat.
S-O Jürgen fragt sich, wen der Bastler am Dienstag nachmittag bei der Arbeit unterstützt hat.

L-S Jürgen fragt sich, wer am Dienstag nachmittag bei der Arbeit den Bastler unterstützt hat.
L-O Jürgen fragt sich, wen am Dienstag nachmittag bei der Arbeit der Bastler unterstützt hat.

S-S Stefan fragt sich, wer den Vater am Mittwoch vormittag in der Praxis gelangweilt hat.
S-O Stefan fragt sich, wen der Vater am Mittwoch vormittag in der Praxis gelangweilt hat.

L-S Stefan fragt sich, wer am Mittwoch vormittag in der Praxis den Vater gelangweilt hat.
L-O Stefan fragt sich, wen am Mittwoch vormittag in der Praxis der Vater gelangweilt hat.

S-S Katja fragt sich, wer den Chauffeur am Freitag nachmittag auf dem Parkplatz geärgert hat.
S-O Katja fragt sich, wen der Chauffeur am Freitag nachmittag auf dem Parkplatz geärgert hat.

L-S Katja fragt sich, wer am Freitag nachmittag auf dem Parkplatz den Chauffeur geärgert hat.
L-O Katja fragt sich, wen am Freitag nachmittag auf dem Parkplatz der Chauffeur geärgert hat.

S-S Thomas fragt sich, wer den Kläger am Samstag vormittag bei der Sitzung überzeugt hat.
S-O Thomas fragt sich, wen der Kläger am Samstag vormittag bei der Sitzung überzeugt hat.

L-S Thomas fragt sich, wer am Samstag vormittag bei der Sitzung den Kläger überzeugt hat.
L-O Thomas fragt sich, wen am Samstag vormittag bei der Sitzung der Kläger überzeugt hat.

S-S Britta fragt sich, wer den Mörder am Montag nachmittag bei dem Verhör angelacht hat.
S-O Britta fragt sich, wen der Mörder am Montag nachmittag bei dem Verhör angelacht hat.

L-S Britta fragt sich, wer am Montag nachmittag bei dem Verhör den Mörder angelacht hat.
L-O Britta fragt sich, wen am Montag nachmittag bei dem Verhör der Mörder angelacht hat.

S-S Felix fragt sich, wer den Gauner am Dienstag vormittag auf dem Bahnhof ausgefragt hat.
S-O Felix fragt sich, wen der Gauner am Dienstag vormittag auf dem Bahnhof ausgefragt hat.

L-S Felix fragt sich, wer am Dienstag vormittag auf dem Bahnhof den Gauner ausgefragt hat.
L-O Felix fragt sich, wen am Dienstag vormittag auf dem Bahnhof der Gauner ausgefragt hat.

S-S Hanna fragt sich, wer den Boxer am Mittwoch nachmittag bei dem Wettkampf beleidigt hat.
S-O Hanna fragt sich, wen der Boxer am Mittwoch nachmittag bei dem Wettkampf beleidigt hat.

L-S Hanna fragt sich, wer am Mittwoch nachmittag bei dem Wettkampf den Boxer beleidigt hat.
L-O Hanna fragt sich, wen am Mittwoch nachmittag bei dem Wettkampf der Boxer beleidigt hat.

S-S Christoph fragt sich, wer den Dichter am Freitag vormittag bei dem Empfang abgeholt hat.
S-O Christoph fragt sich, wen der Dichter am Freitag vormittag bei dem Empfang abgeholt hat.

L-S Christoph fragt sich, wer am Freitag vormittag bei dem Empfang den Dichter abgeholt hat.
L-O Christoph fragt sich, wen am Freitag vormittag bei dem Empfang der Dichter abgeholt hat.

S-S Karin fragt sich, wer den Sportler am Samstag nachmittag nach dem Training geschlagen hat.
S-O Karin fragt sich, wen der Sportler am Samstag nachmittag nach dem Training geschlagen hat.

L-S Karin fragt sich, wer am Samstag nachmittag nach dem Training den Sportler geschlagen hat.
L-O Karin fragt sich, wen am Samstag nachmittag nach dem Training der Sportler geschlagen hat.

S-S Sascha fragt sich, wer den Kellner am Montag vormittag nach dem Urlaub bestohlen hat.
S-O Sascha fragt sich, wen der Kellner am Montag vormittag nach dem Urlaub bestohlen hat.

L-S Sascha fragt sich, wer am Montag vormittag nach dem Urlaub den Kellner bestohlen hat.
L-O Sascha fragt sich, wen am Montag vormittag nach dem Urlaub der Kellner bestohlen hat.

S-S Eva fragt sich, wer den Doktor am Dienstag nachmittag nach dem Unfall verständigt hat.
S-O Eva fragt sich, wen der Doktor am Dienstag nachmittag nach dem Unfall verständigt hat.

L-S Eva fragt sich, wer am Dienstag nachmittag nach dem Unfall den Doktor verständigt hat.
L-O Eva fragt sich, wen am Dienstag nachmittag nach dem Unfall der Doktor verständigt hat.

S-S Hanna fragt sich, wer den Sprecher am Mittwoch vormittag bei der Rede verwechselt hat.
S-O Hanna fragt sich, wen der Sprecher am Mittwoch vormittag bei der Rede verwechselt hat.

L-S Hanna fragt sich, wer am Mittwoch vormittag bei der Rede den Sprecher verwechselt hat.
L-O Hanna fragt sich, wen am Mittwoch vormittag bei der Rede der Sprecher verwechselt hat.

S-S Tina fragt sich, wer den Richter am Freitag nachmittag nach der Pause informiert hat.
S-O Tina fragt sich, wen der Richter am Freitag nachmittag nach der Pause informiert hat.

L-S Tina fragt sich, wer am Freitag nachmittag nach der Pause den Richter informiert hat.
L-O Tina fragt sich, wen am Freitag nachmittag nach der Pause der Richter informiert hat.

S-S Udo fragt sich, wer den Gegner am Samstag vormittag bei dem Rennen gefürchtet hat.
S-O Udo fragt sich, wen der Gegner am Samstag vormittag bei dem Rennen gefürchtet hat.

L-S Udo fragt sich, wer am Samstag vormittag bei dem Rennen den Gegner gefürchtet hat.
L-O Udo fragt sich, wen am Samstag vormittag bei dem Rennen der Gegner gefürchtet hat.

S-S Gabi fragt sich, wer den Anwalt am Montag nachmittag vor dem Gericht eingeweiht hat.
S-O Gabi fragt sich, wen der Anwalt am Montag nachmittag vor dem Gericht eingeweiht hat.

L-S Gabi fragt sich, wer am Montag nachmittag vor dem Gericht den Anwalt eingeweiht hat.
L-O Gabi fragt sich, wen am Montag nachmittag vor dem Gericht der Anwalt eingeweiht hat.

S-S Heiko fragt sich, wer den Forscher am Dienstag vormittag vor dem Vortrag vorgestellt hat.
S-O Heiko fragt sich, wen der Forscher am Dienstag vormittag vor dem Vortrag vorgestellt hat.

L-S Heiko fragt sich, wer am Dienstag vormittag vor dem Vortrag den Forscher vorgestellt hat.
L-O Heiko fragt sich, wen am Dienstag vormittag vor dem Vortrag der Forscher vorgestellt hat.

S-S Silke fragt sich, wer den Käufer am Mittwoch nachmittag auf der Messe beschwichtigt hat.
S-O Silke fragt sich, wen der Käufer am Mittwoch nachmittag auf der Messe beschwichtigt hat.

L-S Silke fragt sich, wer am Mittwoch nachmittag auf der Messe den Käufer beschwichtigt hat.
L-O Silke fragt sich, wen am Mittwoch nachmittag auf der Messe der Käufer beschwichtigt hat.

S-S Jürgen fragt sich, wer den Täter am Freitag vormittag nach dem Zweikampf verraten hat.
S-O Jürgen fragt sich, wen der Täter am Freitag vormittag nach dem Zweikampf verraten hat.

L-S Jürgen fragt sich, wer am Freitag vormittag nach dem Zweikampf den Täter verraten hat.
L-O Jürgen fragt sich, wen am Freitag vormittag nach dem Zweikampf der Täter verraten hat.

S-S Anja fragt sich, wer den Angler am Samstag nachmittag auf der Insel getröstet hat.
S-O Anja fragt sich, wen der Angler am Samstag nachmittag auf der Insel getröstet hat.

L-S Anja fragt sich, wer am Samstag nachmittag auf der Insel den Angler getröstet hat.
L-O Anja fragt sich, wen am Samstag nachmittag auf der Insel der Angler getröstet hat.

S-S Anja fragt sich, wer den Gärtner am Montag vormittag nach dem Regen vertrieben hat.
S-O Anja fragt sich, wen der Gärtner am Montag vormittag nach dem Regen vertrieben hat.

L-S Anja fragt sich, wer am Montag vormittag nach dem Regen den Gärtner vertrieben hat.
L-O Anja fragt sich, wen am Montag vormittag nach dem Regen der Gärtner vertrieben hat.

S-S C. fragt sich, wer den Klempner am Dienstag nachmittag nach dem Rohrbruch gerufen hat.
S-O C. fragt sich, wen der Klempner am Dienstag nachmittag nach dem Rohrbruch gerufen hat.

L-S C. fragt sich, wer am Dienstag nachmittag nach dem Rohrbruch den Klempner gerufen hat.

L-O C. fragt sich, wen am Dienstag nachmittag nach dem Rohrbruch der Klempner gerufen hat.

S-S Silke fragt sich, wer den Schwimmer am Mittwoch vormittag nach dem Gespräch eingeholt hat.
S-O Silke fragt sich, wen der Schwimmer am Mittwoch vormittag nach dem Gespräch eingeholt hat.

L-S Silke fragt sich, wer am Mittwoch vormittag nach dem Gespräch den Schwimmer eingeholt hat.
L-O Silke fragt sich, wen am Mittwoch vormittag nach dem Gespräch der Schwimmer eingeholt hat.

S-S Heiko fragt sich, wer den Cousin am Freitag nachmittag nach dem Besuch verhauen hat.
S-O Heiko fragt sich, wen der Cousin am Freitag nachmittag nach dem Besuch verhauen hat.

L-S Heiko fragt sich, wer am Freitag nachmittag nach dem Besuch den Cousin verhauen hat.
L-O Heiko fragt sich, wen am Freitag nachmittag nach dem Besuch der Cousin verhauen hat.

S-S Gabi fragt sich, wer den Jäger am Samstag vormittag nach dem Unglück angezeigt hat.
S-O Gabi fragt sich, wen der Jäger am Samstag vormittag nach dem Unglück angezeigt hat.

L-S Gabi fragt sich, wer am Samstag vormittag nach dem Unglück den Jäger angezeigt hat.
L-O Gabi fragt sich, wen am Samstag vormittag nach dem Unglück der Jäger angezeigt hat.

S-S Karin fragt sich, wer den Priester am Montag nachmittag in der Kirche erwartet hat.
S-O Karin fragt sich, wen der Priester am Montag nachmittag in der Kirche erwartet hat.

L-S Karin fragt sich, wer am Montag nachmittag in der Kirche den Priester erwartet hat.
L-O Karin fragt sich, wen am Montag nachmittag in der Kirche der Priester erwartet hat.

S-S Tina fragt sich, wer den Pförtner am Dienstag vormittag vor der Klinik getroffen hat.
S-O Tina fragt sich, wen der Pförtner am Dienstag vormittag vor der Klinik getroffen hat.

L-S Tina fragt sich, wer am Dienstag vormittag vor der Klinik den Pförtner getroffen hat.
L-O Tina fragt sich, wen am Dienstag vormittag vor der Klinik der Pförtner getroffen hat.

S-S Martin fragt sich, wer den Läufer am Mittwoch nachmittag bei dem Wettlauf überholt hat.
S-O Martin fragt sich, wen der Läufer am Mittwoch nachmittag bei dem Wettlauf überholt hat.

L-S Martin fragt sich, wer am Mittwoch nachmittag bei dem Wettlauf den Läufer überholt hat.
L-O Martin fragt sich, wen am Mittwoch nachmittag bei dem Wettlauf der Läufer überholt hat.

S-S Sascha fragt sich, wer den Schwindler am Samstag vormittag vor dem Geschäft angefleht hat.
S-O Sascha fragt sich, wen der Schwindler am Samstag vormittag vor dem Geschäft angefleht hat.

L-S Sascha fragt sich, wer am Samstag vormittag vor dem Geschäft den Schwindler angefleht hat.
L-O Sascha fragt sich, wen am Samstag vormittag vor dem Geschäft der Schwindler angefleht hat.

S-S Eva fragt sich, wer den Maler am Freitag nachmittag nach dem Essen belästigt hat.

S-O Eva fragt sich, wen der Maler am Freitag nachmittag nach dem Essen belästigt hat.

L-S Eva fragt sich, wer am Freitag nachmittag nach dem Essen den Maler belästigt hat.
L-O Eva fragt sich, wen am Freitag nachmittag nach dem Essen der Maler belästigt hat.

S-S Thomas fragt sich, wer den Schaffner am Montag vormittag auf der Fähre ausgelacht hat.
S-O Thomas fragt sich, wen der Schaffner am Montag vormittag auf der Fähre ausgelacht hat.

L-S Thomas fragt sich, wer am Montag vormittag auf der Fähre den Schaffner ausgelacht hat.
L-O Thomas fragt sich, wen am Montag vormittag auf der Fähre der Schaffner ausgelacht hat.

S-S Katja fragt sich, wer den Sänger am Dienstag nachmittag in der Oper übertönt hat.
S-O Katja fragt sich, wen der Sänger am Dienstag nachmittag in der Oper übertönt hat.

L-S Katja fragt sich, wer am Dienstag nachmittag in der Oper den Sänger übertönt hat.
L-O Katja fragt sich, wen am Dienstag nachmittag in der Oper der Sänger übertönt hat.

S-S Stefan fragt sich, wer den Rentner am Mittwoch vormittag nach dem Überfall ermordet hat.
S-O Stefan fragt sich, wen der Rentner am Mittwoch vormittag nach dem Überfall ermordet hat.

L-S Stefan fragt sich, wer am Mittwoch vormittag nach dem Überfall den Rentner ermordet hat.
L-O Stefan fragt sich, wen am Mittwoch vormittag nach dem Überfall der Rentner ermordet hat.

S-S Felix fragt sich, wer den Schmuggler am Freitag nachmittag bei dem Einbruch gesehen hat.
S-O Felix fragt sich, wen der Schmuggler am Freitag nachmittag bei dem Einbruch gesehen hat.

L-S Felix fragt sich, wer am Freitag nachmittag bei dem Einbruch den Schmuggler gesehen hat.
L-O Felix fragt sich, wen am Freitag nachmittag bei dem Einbruch der Schmuggler gesehen hat.

S-S Britta fragt sich, wer den Makler am Samstag nachmittag bei der Gala beglückwünscht hat.
S-O Britta fragt sich, wen der Makler am Samstag nachmittag bei der Gala beglückwünscht hat.

L-S Britta fragt sich, wer am Samstag nachmittag bei der Gala den Makler beglückwünscht hat.
L-O Britta fragt sich, wen am Samstag nachmittag bei der Gala der Makler beglückwünscht hat.

S-S Markus fragt sich, wer den Künstler am Montag vormittag nach dem Frühstück beschwindelt hat.
S-O Markus fragt sich, wen der Künstler am Montag vormittag nach dem Frühstück beschwindelt hat.

L-S Markus fragt sich, wer am Montag vormittag nach dem Frühstück den Künstler beschwindelt hat.
L-O Markus fragt sich, wen am Montag vormittag nach dem Frühstück der Künstler beschwindelt hat.

S-S Anne fragt sich, wer den Autor am Dienstag vormittag bei der Lesung kritisiert hat.
S-O Anne fragt sich, wen der Autor am Dienstag vormittag bei der Lesung kritisiert hat.

L-S Anne fragt sich, wer am Dienstag vormittag bei der Lesung den Autor kritisiert hat.
L-O Anne fragt sich, wen am Dienstag vormittag bei der Lesung der Autor kritisiert hat.

S-S Martin fragt sich, wer den Lehrer am Mittwoch nachmittag in der Schule vertreten hat.
S-O Martin fragt sich, wen der Lehrer am Mittwoch nachmittag in der Schule vertreten hat.

L-S Martin fragt sich, wer am Mittwoch nachmittag in der Schule den Lehrer vertreten hat.
L-O Martin fragt sich, wen am Mittwoch nachmittag in der Schule der Lehrer vertreten hat.

S-S Anne fragt sich, wer den Pächter am Freitag vormittag vor dem Lokal erstochen hat.
S-O Anne fragt sich, wen der Pächter am Freitag vormittag vor dem Lokal erstochen hat.

L-S Anne fragt sich, wer am Freitag vormittag vor dem Lokal den Pächter erstochen hat.
L-O Anne fragt sich, wen am Freitag vormittag vor dem Lokal der Pächter erstochen hat.

S-S Markus fragt sich, wer den Spieler am Samstag nachmittag bei dem Turnier beschummelt hat.
S-O Markus fragt sich, wen der Spieler am Samstag nachmittag bei dem Turnier beschummelt hat.

L-S Markus fragt sich, wer am Samstag nachmittag bei dem Turnier den Spieler beschummelt hat.
L-O Markus fragt sich, wen am Samstag nachmittag bei dem Turnier der Spieler beschummelt hat.

S-S Petra fragt sich, wer den Bettler am Montag vormittag auf der Straße angestarrt hat.
S-O Petra fragt sich, wen der Bettler am Montag vormittag auf der Straße angestarrt hat.

L-S Petra fragt sich, wer am Montag vormittag auf der Straße den Bettler angestarrt hat.
L-O Petra fragt sich, wen am Montag vormittag auf der Straße der Bettler angestarrt hat.

S-S Wolfgang fragt sich, wer den Trainer am Dienstag nachmittag nach dem Testspiel beraten hat.
S-O Wolfgang fragt sich, wen der Trainer am Dienstag nachmittag nach dem Testspiel beraten hat.

L-S Wolfgang fragt sich, wer am Dienstag nachmittag nach dem Testspiel den Trainer beraten hat.
L-O Wolfgang fragt sich, wen am Dienstag nachmittag nach dem Testspiel der Trainer beraten hat.

S-S Kerstin fragt sich, wer den Onkel am Mittwoch vormittag nach der Feier bewundert hat.
S-O Kerstin fragt sich, wen der Onkel am Mittwoch vormittag nach der Feier bewundert hat.

L-S Kerstin fragt sich, wer am Mittwoch vormittag nach der Feier den Onkel bewundert hat.
L-O Kerstin fragt sich, wen am Mittwoch vormittag nach der Feier der Onkel bewundert hat.

S-S Frank fragt sich, wer den Schüler am Freitag nachmittag auf dem Sportplatz verteidigt hat.
S-O Frank fragt sich, wen der Schüler am Freitag nachmittag auf dem Sportplatz verteidigt hat.

L-S Frank fragt sich, wer am Freitag nachmittag auf dem Sportplatz den Schüler verteidigt hat.
L-O Frank fragt sich, wen am Freitag nachmittag auf dem Sportplatz der Schüler verteidigt hat.

S-S Frank fragt sich, wer den Tänzer am Samstag vormittag nach dem Auftritt aufgeweckt hat.
S-O Frank fragt sich, wen der Tänzer am Samstag vormittag nach dem Auftritt aufgeweckt hat.

L-S Frank fragt sich, wer am Samstag vormittag nach dem Auftritt den Tänzer aufgeweckt hat.
L-O Frank fragt sich, wen am Samstag vormittag nach dem Auftritt der Tänzer aufgeweckt hat.

S-S Kerstin fragt sich, wer den Diener am Montag nachmittag bei dem Treffen ausgesperrt hat.
S-O Kerstin fragt sich, wen der Diener am Montag nachmittag bei dem Treffen ausgesperrt hat.

L-S Kerstin fragt sich, wer am Montag nachmittag bei dem Treffen den Diener ausgesperrt hat.
L-O Kerstin fragt sich, wen am Montag nachmittag bei dem Treffen der Diener ausgesperrt hat.

S-S Wolfgang fragt sich, wer den Händler am Dienstag vormittag auf dem Kongreß entlassen hat.
S-O Wolfgang fragt sich, wen der Händler am Dienstag vormittag auf dem Kongreß entlassen hat.

L-S Wolfgang fragt sich, wer am Dienstag vormittag auf dem Kongreß den Händler entlassen hat.
L-O Wolfgang fragt sich, wen am Dienstag vormittag auf dem Kongreß der Händler entlassen hat.

S-S Petra fragt sich, wer den Fahrer am Mittwoch nachmittag an der Ampel verprügelt hat.
S-O Petra fragt sich, wen der Fahrer am Mittwoch nachmittag an der Ampel verprügelt hat.

L-S Petra fragt sich, wer am Mittwoch nachmittag an der Ampel den Fahrer verprügelt hat.
L-O Petra fragt sich, wen am Mittwoch nachmittag an der Ampel der Fahrer verprügelt hat.

Curriculum Vitae

Christian Jens Fiebach

03.05.1971	Geboren in Köln
1990	Abitur am Hardenberg-Gymnasium, Fürth
1991 - 1998	Studium der Psychologie (Diplom) an der Universität Koblenz-Landau, Abteilung Landau; Nebenfach Wirtschaftswissenschaften
1993	Vordiplom in Psychologie
1996 - 1997	Diplomand am Max-Planck-Institut für psychologische Forschung, München, Abteilung Adaptives Verhalten und Kognition (Prof. Dr. Gigerenzer)
1998	Diplom in Psychologie
1998 - 2001	Doktorand am Max-Planck-Institut für neuropsychologische Forschung, Leipzig, Abteilung Neuropsychologie (Prof. Dr. Friederici)
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