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Research report

Syntactic parsing preferences and their on-line revisions: a spatio-temporal analysis of event-related brain potentials

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Abstract

The present study investigates the processes involved in the recovery from temporarily ambiguous garden-path sentences. Event-related brain potentials (ERP) were recorded while subjects read German subject–object ambiguous relative and complement clauses. As both clause types are initially analyzed as subject-first structures, object-first structures require a revision which is more difficult for complement than for relative clauses. The hypothesis is tested that the revision process consists of two sub-processes, namely diagnosis and actual reanalysis. Applying a spatio-temporal principal component analysis to the ERP data, distinct positive sub-components presumably reflecting different sub-processes could be identified in the time range of the P300 and P600. It will be argued that the P600 is not a monolithic component, and that different subprocesses may be involved at varying time points depending on the type of garden-path sentence.

Theme: Neural basis of behavior

Topic: Cognition

Keywords: Event-related potential; Language processing; Syntactic ambiguity; Spatio-temporal principal component analysis; P600/SPS, P300; ERP Sub-component

1. Introduction

One of the issues studied extensively over the years in the field of language comprehension is the way in which the processing system structures the language input as it is encountered. A second relevant issue, not independent of the first, is if and under what condition processes of reanalyzing the initial input become necessary, and how these processes of reanalysis are to be described. These issues have been approached using several different on-line behavioral techniques such as self-paced reading, lexical decision, priming and naming tasks as well as the registration of eye movements during sentence processing. Most recently, the technique of event-related brain potential (ERP) measurement has been used to provide additional data that augment the description of the on-line processes that underlie language comprehension. A number of studies have evaluated the processes used by the parsers by investigating the comprehension of sentences that contain a temporary syntactic ambiguity [14,23,51,54,57,62].

In the following we shall first briefly present the different psycholinguistic models of language comprehension and their view of how syntactic parsing and revision processes may be carried out. Then discuss particular ERP components related to semantic processing and particularly to syntactic parsing will be discussed. The value of the ERP as a tool for monitoring cognitive processing in ‘real time’, as the sentence is being processed, will be reviewed. We shall argue that the appropriate use of the ERP requires careful attention to the behavior of the different ‘components’ of the ERP. Employing a spatio-temporal principal component analysis, the present study will demonstrate

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that the identification of independent sub-components in the ERP can shed new light on subprocesses during language comprehension, which are otherwise difficult to disentangle.

1.1. Garden-path sentences and revision processes

Ambiguities can cause severe comprehension difficulties. What seems so obvious for ambiguous word meanings and for phenomena, such as irony, also holds true for syntactic ambiguities as illustrated by the following famous example:

The horse raced past the barn fell. (1)

Numerous psycholinguistic studies have demonstrated that readers experience processing difficulties in understanding a reduced relative clause (1), (to be read as '*The horse that was raced past the barn*, *fell*'; cf. [16]). The human sentence processor seems to have a strong preference to initially interpret the verb '*raced*' as the main verb of the sentence ('*The horse raced*') and cannot easily recover from this error. As a consequence of this initial preference, the sentence processor is necessarily 'led up the garden-path', resulting in increased reading times or even comprehension errors. Sentences such as (1) have thus been labeled 'garden-path sentences'. However, not all garden-path sentences cause problems as severe as that in sentence (1).

John knew the answer very well. (2a)

John knew the answer was wrong. (2b)

Although 'the answer' in (2) is preferably interpreted as the direct object of '*knew*' (as required in (2a)), the non-preferred reduced complement clause structure in (2b) is not difficult to comprehend (e.g., [33]).

Different models have been proposed to account for the different strengths of garden-path effects. Some *constraint satisfaction models* (e.g., [51]) deny any independent syntactic processing and argue in favor of a pure lexical ambiguity account. According to this view, the difficulties in sentence (1) are due to the fact that the verb '*raced*' is more frequently used in its active intransitive form which inhibits the required passive transitive interpretation. In this framework, very rare combinations of lexical items may be responsible for strong garden-path effects. More recent implementations of constraint based models rely on rather strong 'non-lexical', i.e. structural frequency biases, that can be interpreted as encoding general syntactic and/or word order preferences [53]. In this framework, the low frequency of a particular construction is held responsible for strong garden-path effects.

Other models attribute the garden-path effect to differences in the syntactic complexity of structural relations and language-specific processes. The so-called garden-path model [17–19] and similar *serial syntax-first models* (e.g., [21,33]) assume, that a specific syntactic parser has the inherent tendency of generating only the 'simplest' syntactic structure compatible with the input. The respective definition of 'simplicity' may vary across serial models, but is always derived from a syntax theory. When encountering subsequent words which are incompatible with the initial simplest analysis, the parsing mechanism must initiate a reanalysis in order to achieve a new alternative structural interpretation. Strong garden-path effects are predicted if the *reanalysis* requires considerable changes to the initial structure (as in sentence (1)) rather than slight changes (as in sentence (2b); cf. [33]).

Ranked parallel models in contrast, claim that in the case of ambiguities all possible syntactic analyses are immediately computed in parallel, but some of these receive a higher activation (or ranking) than others (e.g., [31,32,39]). From this perspective, garden-path sentences generally require changes in the respective ranking. However, if the activation of an analysis under consideration sinks below a certain threshold, it will not be pursued further. If later in the sentence, this analysis turns out to be the correct one, it cannot be simply reactivated, and a strong garden-path effect results.[1]

Other investigators claim, that the ease with which non-preferred structures are recovered is not a function of the actual reanalysis required but rather a function of the ease, i.e. the cost of *diagnosis* which alterations are needed, to achieve the alternative structure [16]. The authors suggest that a garden-path becomes particularly difficult if the 'symptom' (i.e., the first word incompatible with the initial analysis) does not directly indicate where in the current structure a repair must be applied. They argue that, for the human parser, it is extremely difficult to infer the successful revision in sentence (1), but not in (2b). Fodor and Inoue [16] conclude, that 'the cost of repair is not the cost of doing but the cost of deducing what to do'. According to Meng and Bader [56], garden-path sentences are erroneously considered 'ungrammatical' if the parser is unable to discover a successful revision. Moreover, Bader [1] demonstrates that prosody, i.e. sentence intonation, may be an important factor in determining the strength of garden-path effects. Thus, sentence (1) may partly be

[1]Parallel to this discussion of whether only one or all possible structures are considered by the parser on-line, Just and Carpenter [43] introduced a model in which parsing strategies are viewed to depend on individual differences in working-memory capacity. This Capacity Constraint Parsing Model [50] holds, that the individual working-memory capacity for language materials constrains language processes in general and the processing of syntactic ambiguity in particular. When a reader encounters a syntactic ambiguity, she or he initially always constructs multiple representations, and it is only after this initial construction of multiple representations that processing differs for readers with a high or a low working-memory capacity. Low span but not high span readers are assumed to abandon representations that initially received a lower activation level, as a result of being low frequent, pragmatically implausible or syntactically highly complex (see, however, [29,30]).

difficult to reanalyze because readers have to additionally insert a prosodic boundary between ‘the horse’ and ‘raced’ when revising the structure. A similar operation is not required in sentence (2b).

1.2. Language processing and event-related brain potentials (ERP)

Most psycholinguistic studies investigating garden-path effects employed measures of overt behavior, such as response times and error rates, as the dependent variables in the study. In the past few years, the ERP technique has joined the list of methods used to examine processing difficulties with on-line ambiguity resolution. Different ERP components have been found to correlate with specific processes during language comprehension. The components are defined in terms of their scalp distribution and their responsiveness to experimental variables [11].

In a series of pioneering studies, Kutas and Hillyard [46,47] found that *semantic* anomalies elicited a large negative component with a peak around 400 ms subsequent to the onset of the anomalous word, the so-called *N400* component. The amplitude of the N400 has been shown to be a function of the semantic fit between target and preceding context [48]. It is of interest that the processing of lexical ambiguities seems also to be reflected by this component [37,41,77]. Although the precise cognitive processes underlying the N400 are not known yet, it has been suggested (a) that the N400 amplitude is inversely related to the amount of contextual priming of the target [40], (b) that it reflects the build-up of semantic constraints imposed by the context [79], and (c) that its occurrence crucially depends on whether lexical integration is successfully being carried out [5,28].

With respect to the processing of *syntactic* information, two different components have been identified: a *left anterior negativity* and a *late centro-parietal positivity*. Of these, the left anterior negativity seems to be a novel component that has been observed strictly within the domain of syntactic processing. This anterior negativity with a left localized maximum has been observed to follow outright syntactic violations, i.e. in correlation with phrase structure errors [25,27,58,59] as well as following inflectional errors [36,68] (but see also [38] and [66]).

The late centro-parietal positivity has also been interpreted by some investigators as a specific ‘syntactic positive shift’ (SPS; [38]). This raises some serious interpretational problems. This centro-parietal positivity has been reported to be evoked by two classes of syntactic anomalies, namely by violations of structural preference in garden-path sentences [62–64] and by outright syntactic violations [25,28,38,52,59], as well as in correlation with more complex and possible less expected syntactic structures [44]. The ‘syntactic positive shift’ was also labeled ‘P600’ component, as it was typically observed with a peak latency around 500–600 ms after the critical word and with a duration of several hundred milliseconds [62]. A recent discussion focused on the issue of whether the P600 is a specific component observed in correlation with syntactic anomaly and, thereby, different from the well known domain-general P300. The P300 is a component which is easily elicited by rare events embedded in a sequence processed by the subject. The common paradigm used to elicit the P300 is the so-called oddball paradigm in which a subject is presented with a sequence of events, that can be categorized in one of two classes. The subject is assigned a task which cannot be performed without classifying the events. Under these conditions, if events in one of the categories are rare these events will elicit a P300 (e.g., [9]). The conditions under which the P600 is recorded can also be viewed as versions of the oddball paradigm. That is, the event that a word cannot be smoothly integrated into the sentential context (indicating a garden-path or violation) occurs relatively rarely. Moreover, it is a task relevant event in most studies. Previous P300 studies have shown that the oddball paradigm is not restricted to simple sequences of stimuli (e.g., tones) but can also be successfully applied to quite complex event sequences (e.g., [45]).

The P600 differs from the P300 in its superficial appearance: most obviously they differ in their latencies. However, this cannot be taken as an argument for a functional difference, as it has been well established (see, for example, [78]) that the latency of the P300 is measured relative to an internal event, rather than relative to the external stimulus. The stimulus-related latency of the P300 depends on the duration of the processes that are required to identify the stimulus as a member of the rare category (cf. [49]). Thus the enhanced latency of the P600 to external syntactic deviations cannot, by itself, serve to justify the rejection of the hypothesis that these syntactic anomalies do elicit a P300. Moreover, there is an ongoing debate on whether the scalp distribution of this presumably specifically syntactic component P600 is identical to the scalp distribution of the P300 component [6,65] or not.

With respect to the functional role of the P600 two contrasting suggestions have been made. Several investigators suggested that the processes manifested by the late positivity are specifically engaged in syntactic processing [44,61,65,76]. Arguments for a functional distinction of the P600 and the P300 have been based on the finding that these components behave additively when syntactic anomalies and physical violations (e.g., upper case letters in the context of lower case letters) are presented simultaneously [65]. The second perspective views the P600 as an instance of the P300 component reflecting processes of context updating and reorganization of working memory contents, possibly triggered by syntactic processing, however, representing a general purpose element of the executive control system rather than a domain-specific syntactic module [6,36]. Arguments taken to support the domain-general view are based on the finding that the amplitude of the P600, like the P300, varies as a function of the probability of occurrence of the rare event [36].

This dispute arises particularly in the context of the processing of garden-path sentences, because positivities with different latencies have been reported when ERPs were recorded while subjects were reading such sentences. The positivity observed for difficult garden-path sentences in English, similar to the previous example given in (1), was found to peak around 600 ms [62–64,66]. In contrast, both the Mecklinger et al. [54] and the Steinhauer et al. [76] studies, investigating a less severe garden-path effect in German object relative clauses, found a similarly distributed positivity peaking around 350 ms for participants with a high reading span [7]. As the recovery from German object relative clauses is described to be easy on both structural [35] and processing grounds [26], it was hypothesized that the positivity's latency may be a function of the ease of the revision process [26].

Recall that, theoretically, the recovery from garden-path sentences may be determined either solely by the difficulty with which the necessary reanalysis can be diagnosed [16], or by the costs of the structural reanalysis proper, or by both. Possible differences could, in principle, also be accounted for by a model based on the frequency of occurrence of different clause types. However, the frequency of use itself may be a reflection of the underlying structural differences. The independence of these two factors has not yet been demonstrated. Here it is assumed, that the underlying structural differences and their processing consequences will affect the observable performance. Under the consideration that both aspects, diagnosis and reanalysis, play a role we might formulate a processing view according to which the process of revision is subdivided into two subprocesses: a first one during which the parser diagnoses what to do, and a second one during which the actual reanalysis takes place. Note, that a frequency approach would assume only one factor, namely frequency, to underlie possible behavioral differences. In the extant psycholinguistic ERP literature, the entire revision stage has been correlated with the late centro-parietal positivity. It will be of interest whether the hypothesized two processing steps of the revision stage are associated with different aspects of the late positivity.

1.3. The present study

The present study, will investigate this issue in an ERP experiment evaluating the ERPs related to revision processes in temporarily ambiguous subject-first and object-first sentences containing different clause types, namely relative clauses and complement clauses. Based on structural linguistic considerations discussed below, revision processes are assumed to be easier for relative clauses than for complement clauses.

Behavioral studies focusing on the analysis and reanalysis in temporarily ambiguous subject-first and object-first sentences have shown a strong initial tendency to disambiguate these sentences towards a subject-first reading in Dutch [18,22], in Italian [8] and in German [2,56,69,70]. A large number of different linguistic and psycholinguistic explanations have been put forward for this subject-first preference the discussion of which is beyond the scope of this paper. (For details we refer to [3,8,19,22,26,33–35,69].

The different aspects of the revision process are tested in a sentence reading paradigm with the continuous registration of event-related potentials. Two types of non-preferred structures were examined, each requiring differently complex types of reanalysis in German, namely temporarily ambiguous object-first relative clauses and complement clauses (cf. Table 1). Most important, the employed structures allow to predict differences for both the diagnosis and the actual reanalysis. Note that, in contrast to the English subject–verb–object (SVO) word order, in German sentences the verbs stand in clause final position in subordinate clauses. That is, subject (S) and object (O) noun phrases both precede the verb, either in the preferred SOV or in the non-preferred OSV order. Due to the case ambiguity (nominative/accusative) of the relative pronoun all structures in Table 1 are subject–object ambiguous unless they are disambiguated by the number marking in the sentence final auxiliary, which always has to agree with the number marking of the subject noun phrase (so-called 'subject–verb agreement'). Because subject and object nouns always differ in number (singular vs. plural), the number of the auxiliary '*hat*'/'*haben*' ('has'/'have') unambiguously determines which of the nouns must be the subject.

As pointed out above, the garden-path effects in the object-first relative clauses (OR) and the object-first complement clauses (OC) are due to the fact, that in both cases the corresponding subject-first clause (i.e., SR and SC, respectively) is the initially preferred analysis. Thus, in both OR and OC clauses, the sentence final disambiguating auxiliary requires a revision towards the object-first reading.

It is assumed, that the revision process is more difficult for object-first complement sentences than for object-first relative sentences with respect to both aspects, diagnosis and reanalysis. This assumption needs some further explanation which can best be illustrated by the phrase markers in Fig. 1.[2]

In both relative clauses, namely the SR and OR clause, respectively (Fig. 1A), the relative pronoun *'die'* ('that') is assumed to be a moved constituent (or 'filler') that leaves

[2]Note, that this structural representation is, in principle, compatible with both serial and parallel parsing models, but not with the lexical constraint satisfaction account. In fact, it is impossible to explain the subject-before-object preference in German on a purely lexical basis (see also [20]).

Table 1
Examples of sentence types constructed from one triplet with literal English translations (S indicates the ambiguously marked subject, O indicates the ambiguously marked object, underlining indicates disambiguating element)

Subject-first, relative clause (SR)	
(1)	*Das ist die Direktorin, die* (S) *die Sekretärinnen* (O) *gesucht* <u>*hat*</u>. This is the director that the secretaries sought has.
(1′)	*Das sind die Sekretärinnen, die* (S) *die Direktorin* (O) *gesucht* <u>*haben*</u>. These are the secretaries that the director sought have.
Object-first, relative clause (OR)	
(2)	*Das ist die Direktorin, die* (O) *die Sekretärinnen* (S) *gesucht* <u>*haben*</u>. This is the director that the secretaries sought have.
(2′)	*Das sind die Sekretärinnen, die* (O) *die Direktorin* (S) *gesucht* <u>*hat*</u>. These are the secretaries that the director sought has.
Subject-first, complement clause (SC)	
(3)	*Er wußte, daß die Sekretärin* (S) *die Direktorinnen* (O) *gesucht* <u>*hat*</u>. He knew that the secretary the directors sought has.
(3′)	*Er wußte, daß die Direktorinnen* (S) *die Sekretärin* (O) *gesucht* <u>*haben*</u>. He knew that the directors the secretary sought have.
Object-first, complement clause (OC)	
(4)	*Er wußte, daß die Sekretärin* (O) *die Direktorinnen* (S) *gesucht* <u>*haben*</u>. He knew that the secretary the directors sought have.
(4′)	*Er wußte, daß die Direktorinnen* (O) *die Sekretärin* (S) *gesucht* <u>*hat*</u>. He knew that the directors the secretary sought has.

behind a ‘gap’ (or ‘trace’ [t]) at its original position.[3] The small i indexes the relation between the filler and its trace. To understand the sentence correctly, a reader must mentally assign the filler with its gap (fillers and gaps are marked by arrows). Even in the preferred SR clause, the relative pronoun is assumed to be a filler (cf. Fig. 1). That is, when encountering the relative pronoun the reader of such sentences can immediately predict either a subject or an object gap to follow later in the sentence. A preference for SR over OR sentences is predicted on the basis of the ‘Active Filler Hypothesis’ [22], holding that the human parser tries to assign the filler to the first possible gap position, which is the subject gap. This preference must be revised in OR garden-path clauses when encountering the disambiguating auxiliary indicating that the correct gap must be postulated in object position instead.

In complement clauses (Fig. 1B), by contrast, the preferred SC clause displays the canonical German SOV order without any moved constituents, whereas the OC sentence does contain a filler-gap dependency (indicated by arrows) for the moved object noun phrase. Thus, in OC clauses which have initially been parsed as SC clauses, the first noun phrase is not identified as being a moved constituent until the disambiguating auxiliary is perceived. On encountering the auxiliary a completely new syntactic structure with a moved constituent must be generated. As Meng and Bader [55] point out, this syntactic revision may also involve changes of the so-called *information structure*[4] which is known to affect the prosodic structure. It has been repeatedly demonstrated that phonological and prosodic patterns are activated even during silent reading [1,4,15,67,74].

With these differences in mind, we can specify the prediction of a more severe garden-path in OC than OR clauses for both the diagnosis and the reanalysis account: First, diagnosis may be harder for complement clauses as the filler to be moved to the gap is not yet specified in the initial SC structure (Fig. 1B) whereas it is for the relative clauses (Fig. 1A). Second, structural reanalysis as such may be harder for complement clauses because the parser has to posit a new filler-gap relation. This operation, illustrated in Fig. 1B, requires quite dramatic alterations in the syntactic tree structure. Moreover; it may also require

[3]This movement is similar to that in WH-question. For example, in WH-questions asking for the object (e.g., ‘Peter read *the book*’ – ‘*WHAT* did Peter read —?’) the pronoun WHAT (representing the object) is moved in sentence initial position leaving behind a gap (‘—’) at the original object position after the main verb (thereby changing the normal English SVO word order).

[4]The information structure specifies which parts of a sentence are new (or important) and which parts are already known (less important). Roughly speaking, the important part is *in focus* and carries a sentence accent.

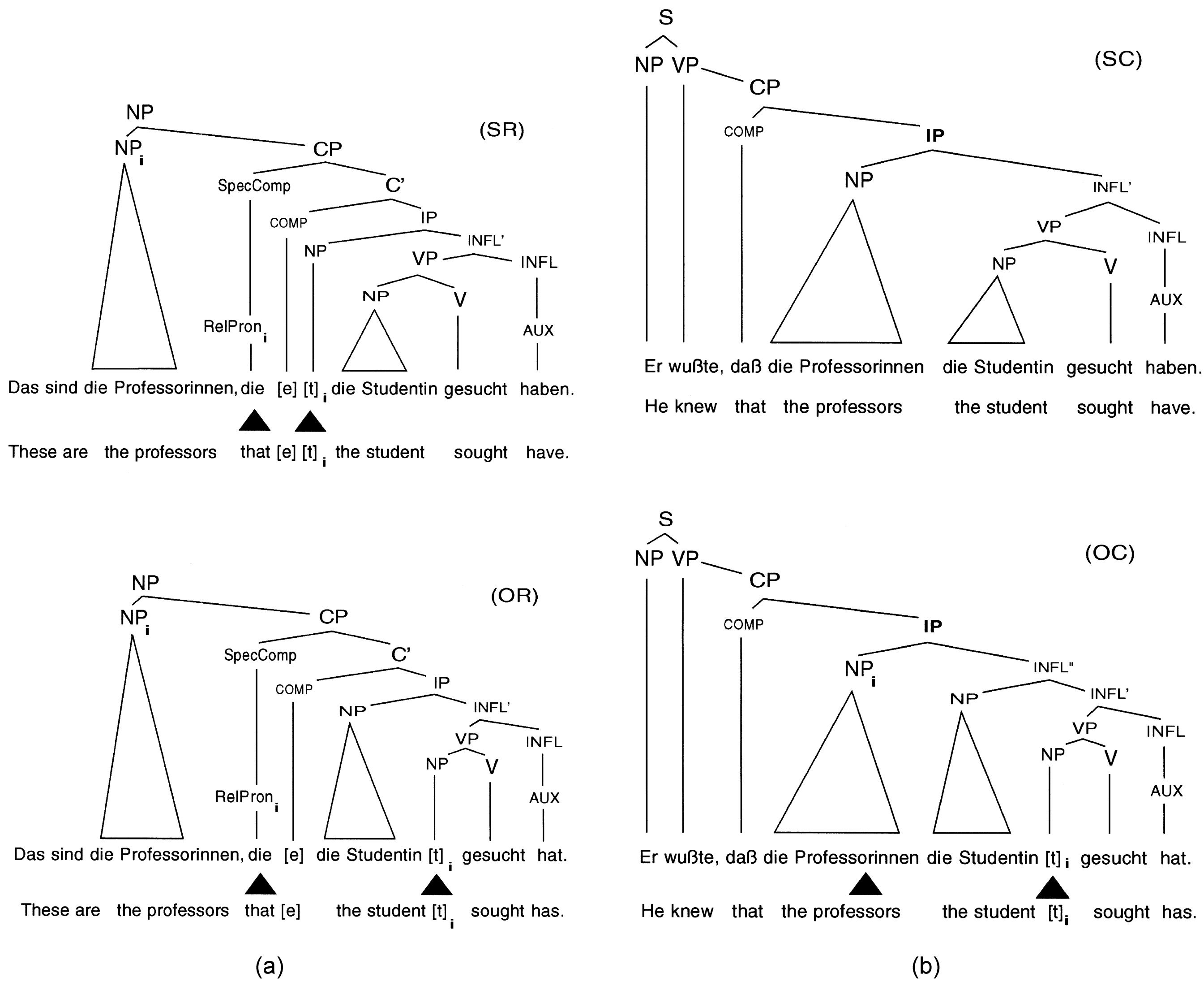

Fig. 1. *Phrase marker diagrams*. Structural trees of subject relative clause sentences (SR) and object relative clause sentences (OR) (Fig. 1A), and of subject-first complement clause sentences (SC) and object-first complement clause sentences (OC) in Fig. 1B. Note that [t]$_i$ indicates the gap, and Relpron$_i$/NP$_i$ the respective filler.

to change the information structure and thereby the prosodic structure [3].

The present study will investigate whether the expected different strengths of garden-path effects affect the late positivity in the ERP, and more specifically, whether the two hypothesized aspects of sentence revision, i.e. diagnosis and reanalysis constitute two separate subprocesses or not. The circumstance that both garden-path sentences are disambiguated by the same lexical item (i.e., the auxiliary ‘*hat*’/‘*haben*’) can rule out any lexical confounds.

A preliminary report on an initial analysis of 10 participants reading subject- and object-first relative clause and complement clause sentences [24] suggested that the revision processes for relative and complement clauses were associated with qualitatively different positive ERP deflections. When compared to subject relative clauses, the sentence final auxiliary in object relative clauses elicited an early positivity with a latency of 350 ms followed by a second less pronounced positivity between 600 and 900 ms. The former component resembled those observed in two previous studies investigating German OR clauses [54,76]. It was thus taken to reflect the obligatory processes necessary to recover from the garden-path. The latter component which had not been observed in the two other studies appeared to be due to the more complex experimental design rather than to the revision of OR clauses as such. The finding of both an early and a late positivity for relative clauses in the study that included also complement clauses is evidence against a simple latency shift of the positivity. It rather suggests that the late positivity reflected an additional process such as re-checking.

Object complement clauses, by contrast, elicited *only one* late positivity which was most prominent between 500 and 900 ms. That is, the respective ERP correlates presumably reflecting garden-path effects in German object-first structures differed in latency between relative clauses (350 ms) and complement clauses (600 ms). This finding led to the tentative interpretation, that the severity of garden-path effects might be reflected not only by the amplitude but also by the latency of P600-like positivities [24]. More specifically, the onset latency was assumed to correlate with diagnosis whereas amplitude and duration of the positivity were related to the reanalysis proper. A drawback with this interpretation is, that both the late positivity in relative clauses (i.e., the second positivity for these sentence types) and the positivity observed in complement clauses seemed to display similar latencies and scalp distributions, although they were attributed to different cognitive processes, namely reanalysis in OC clauses and re-checking in OR clauses, respectively. Moreover, both deflections resembled the classical P600 which Osterhout and Holcomb [62] reported for words indicating the processing of garden-path sentences or other types of syntactic anomalies [38,64].

To determine the functional characteristics of these ERP deflections in more detail and to examine their correspondence to other ERP components it is necessary to examine in detail the scalp distribution associated with each deflection. Spatio-temporal principal component analyses (PCA) have been applied successfully in disentangling overlapping ERP components and in reducing the spatial and temporal dimensionality in a variety of ERP data bases [12,72]. In order to determine whether the two hypothesized processing aspects during syntactic revisions are associated with topographically different ERP components, we thus employed a spatio-temporal PCA and also extended our analysis to a larger group of participants (N = 18).

2. Materials and methods

2.1. Participants

Eighteen students (nine female) of the Free University of Berlin and the University of Leipzig participated as paid volunteers. Their mean age was 25.1 years (range 21–30 years). All were right-handed according to the Edinburgh Handedness Inventory [60]. They were all native speakers of German with normal or corrected to normal vision. Prior to the ERP experiment participants were tested for their reading span with a German version of the Daneman and Carpenter [7] reading test. Only participants with a high reading span (>4) entered this study (mean span 4.65, range 4.0–6.0).[5]

2.2. Materials

The experimental material consisted of 256 sentences. Noun phrases (NPs) in these sentences were ambiguously marked for case (feminine noun phrases). There were additional 256 filler sentences in which the NPs were unambiguously marked for case (masculine noun phrases). Experimental and filler sentences belonged to 4 different categories of 64 items each: Subject relative clause sentences (SR), object relative clause sentences (OR), subject-first complement clauses (SC), and object-first complement clauses (OC) (for examples of experimental sentences, see Table 1). 32 NP–NP–Verb combinations ('triplets') were used to construct the 64 items for each category (see Appendix A). Each noun appeared equally often in subject and object position. In half of the sentences the NP1 was plural and NP2 was singular marked whereas in the remaining half of the sentences the order was reversed. Note, that all verbs were transitive requiring a direct accusative object. In order to minimize plausibility effects, nouns were chosen in such a way that both nouns were equally likely to be the agent, and thereby the subject of the sentence, given the verb. To control for the role assignment of the two nouns for a particular verb each noun appeared in subject and in object position.

Grammaticality judgments for the material obtained from 38 students in separate paper and pencil tests suggested that native speakers of German consider even the difficult OC garden-path clauses as 'grammatically acceptable' in 61% of the cases, once informed about the difference of 'grammatically correct' and 'commonly or frequently used' (cf. [29]). Given these findings, we decided to instruct the participants of the ERP main experiment that some of the sentences they would read, although grammatically correct, may seem unusual and infrequently used. This was exemplified prior to the experiment by a variety of sentence types including object-first clauses.

[5] Ten additional participants (seven female) were assigned to a low span group (<3.5; mean span 3.25, range 2.5–3.5). As pilot tests had shown that low span readers perform at chance level for the processing of object-first complement structures. They were not included in this study. As a prior experiment [54] had shown interesting differences between high and low span readers for case ambiguous relative clauses both groups were also tested for the processing capacities in case unambiguous and case ambiguous relative clause sentences used in this study. The results are discussed in a separate paper [29] as they cannot contribute to the issue under investigation here, namely the difference between the processing of relative and complement clause structures.

2.3. Procedure

The participants of the ERP study were seated comfortably in a dimly illuminated room in front of a VGA monitor. The sentences were displayed in six displays, hereafter called chunks, of either one or two words. Each trial started with the presentation of a fixation cross in the center of the screen for 300 ms. 500 ms later, the stimulus sentences were presented according to one out of two presentation schemes (i.e., 'A' for the relative clause sentences and 'B' for the verb complement sentences as displayed in Fig. 2). Presentation time (plus subsequent Inter Stimulus Intervals, ISIs) were 550 ms (+550 ms) for both the noun phrases and the main verb and 400 ms for the critical sentence final auxiliary.

Two seconds after the offset of the auxiliary a 'yes/no' – question concerning the content of the preceding sentence (e.g., 'Was the director sought?') was presented until the participant responded with a button press or until 2 s had elapsed. Each response was immediately followed by a feedback stimulus (600 ms) that informed the subjects about the accuracy of their response (correct/incorrect). The fixation cross marking the beginning of the next trial appeared 1700 ms after the feedback stimulus. The 2-s interval between the offset of the last word of the sentence (which, it will be recalled, was always an auxiliary) and the onset of the question provided the subject with time in which to prepare for the comprehension question.

The words were presented in black letters against a light gray background in the center of a 17″ computer screen. Proportional fonts were used, with a letter height of 1 cm. The use of lower- and uppercase letters conformed to the rules of German orthography. The participants sat at a distance of 70–80 cm from the screen and used the two keys of a response box to answer the question. Response key assignments were counterbalanced across participants. The participants were instructed to respond as quickly and as accurately as possible, to avoid large body movements, and to blink their eyes in the time interval between the response and the onset of the next trial. The 512 sentences were distributed over 8 blocks, so that each block contained four sentences representing each of the 16 conditions. The blocks which lasted about 12 min were separated by short breaks of about 3 min. Each of the two sessions, including a practice sequence of 24 trials, four experimental blocks, breaks and electrode application and removal, lasted about 2.5 h.

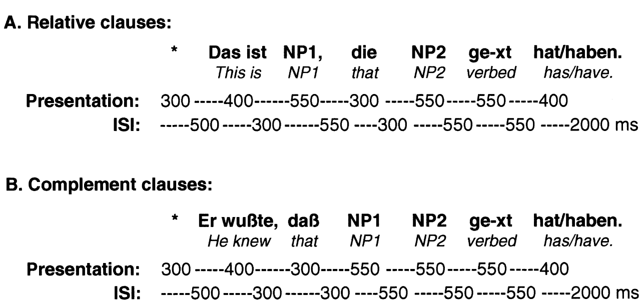

Fig. 2. *Temporal scheme of sentence presentation.* (A): Relative clause sentences and (B): Complement clause sentences. Presentation times and interstimulus intervals (ISIs) are given in milliseconds.

2.4. EEG recordings

The EEG activity was recorded by means of tin electrodes mounted in an elastic cap (ElectroCap International) from 26 electrodes referenced to the left mastoid. The scalp sites included the 19 positions of the 10–20 System. Recordings were also taken from six nonstandard locations, including Wernicke's and Broca's areas (WL and BL), and their right hemisphere homologues (WR, BR).[6] The right mastoid was recorded as an additional channel. The ground electrode was positioned anterior to Fz 10% of the nasion–inion distance. The vertical EOG was monitored with two electrodes located above and below the participants' right eye. The horizontal EOG was recorded from electrodes placed at outer canthus of each eye. Electrode impedances were kept below 5 kΩ. EEG and EOG signals were amplified by Neuroscan amplifiers (DC to 30 Hz) and recorded continuously for each block of trials. Signals were A/D converted with 12-bit resolution at a rate of 250 Hz. Data collection was controlled by an IBM-compatible 486 computer.

2.5. Data analysis

2.5.1. Behavioral data

Reaction time (RT) was defined as the interval between the onset of the question and the participant's key press. All of the RT averages were composed of correct responses. Within each condition, response times which were more than two standard deviations above or below the mean of the respective condition were eliminated and replaced by the subject's mean RT in this condition.

2.5.2. ERP data

ERPs were calculated for each subject over an epoch from 200 ms prior to the auxiliary onset until 900 ms after. Only trials on which the question was answered correctly ('correct trials') were used in the computation of the average ERPs. Epochs containing ocular artifacts (criterion >50 μV) or other movement artifacts were excluded from further analyses. On the basis of this latter procedure, approximately 13% of the 'correct trials' were rejected due to artifacts; this proportion of rejected trials was constant across conditions. The subject averages were digitally filtered with a phase-true digital low-pass filter (−3 dB at 10 Hz, −45 dB at 23 Hz).

[6] For further details of electrode placing see [55].

2.5.3. Spatio-temporal principal component analysis

Principal components analysis (PCA) is an analysis procedure that creates linear combinations [10] of the data that have the desirable property that the linear combinations are orthogonal. They thus parse the variance in the data into components that behave in a consistent manner in response to the experimental manipulations. The advantage of PCA is that it provides measures which are not affected by component overlap. Like all statistical techniques, PCA must be applied, and interpreted, with caution. Wood and McCarthy [82] have pointed out that under certain circumstances PCA may lead to a misallocation of the variance among the components. However, as they noted, when PCA misallocates variance, so would windowed amplitude measurement inasmuch as virtually all reported instances of misallocation of variance have appeared in simulations, and there has yet to be a reported instance in which conclusions based on a PCA had to be withdrawn because of demonstrable misallocation of variance, we believe that it is appropriate to analyze the data of the present study using PCA.

The particular manner in which we have applied PCA is adopted from the procedures applied by Spencer and colleagues [72] to the analysis of Dense Electrode Array data (see also [12], for a more detailed description of the approach). The process begins with a 'spatial' PCA, which examines the variance among the electrodes. Computing the principal components of a matrix representing the pair-wise covariances among all electrodes across all time points (0–900 ms), across the four experimental conditions, subjects and sessions constituted the 'spatial' PCA. The database entered in this analysis consisted of 8064 ERPs (18 subjects×4 conditions×112 time points). Note that only every second sample point entered this analysis. A covariance matrix was used and 8 'spatial' factors that accounted for 95% of the total variance were extracted and then rotated using the Varimax rotation. These spatial factors (or 'virtual electrodes') reflect characteristic topographic patterns in the data set. That is, each of the electrodes is found. to contribute to a certain degree to each of the factors. Virtual electrodes are displayed and discussed in more detail in the result section. The loading for a given electrode is a measure of the contribution of the data at this particular electrode to the spatial factor. We refer to such a factor as a 'virtual electrode' in that it acts as a filter that can be applied to the EEG data recorded from all electrodes at a given time point. These data can be combined to one value by multiplying the voltage recorded at that time point at each electrode by a scaled function of the loading for that electrode. These values called usually the 'component scores' (and which are by definition linear combinations) can be obtained for each time point. Thus, each virtual electrode yields an amplitude time function that is the 'virtual' ERP measured for a given condition, in a given subject for a given experimental condition. Such virtual ERPs can, of course, be obtained for each of the virtual electrodes. In effect, this process transforms the data set from a set of ERPs measured at the *M* original electrodes into a set of ERPs measured at the *N* virtual electrodes, and *N* is much smaller than *M*. Virtual ERPs are illustrated and are examined in more detail in the results section.

The virtual ERPs can be subjected to a subsequent temporal PCA. At this stage we aim at identifying segments of the epoch over which the data are intercorrelated, so that they can be considered to represent ERP components in the sense used by Donchin and colleagues [11]. The temporal PCA analyses the covariance between the virtual voltages at all time points, across each virtual electrode, condition and subject. The database submitted to this PCA comprised 576 ERPs (18 subjects×4 experimental conditions×8 virtual electrodes). Nine factors that accounted for 95% of the variance were extracted for Varimax rotation. The component scores for each subject for the temporal factors were used as dependent variables in repeated-measure ANOVAs (see result section). All effects with two or more degrees of freedom in the numerator were adjusted according to the formula of Huynh-Feldt [42].

3. Results

3.1. Behavioral data

Table 2 presents mean response times and performance accuracy for question answering in each of the experimental conditions. As apparent from the table, accuracy was higher for relative clauses than for complement clauses, $F(1,17) = 9.98$, $P < 0.001$, and also higher for subject-first than for object-first structures, $F(1,17) = 4.63$, $P < 0.04$. Moreover, a highly significant interaction between word order and clause type was found, $F(1.17) = 22.91$, $P < 0.002$, indicating that performance accuracy was lowest for the object complement clauses. The same interaction was also obtained for response times, $F(1.17) = 13.06$, $P < 0.002$, indicating that response times were largest in the object complement clause condition.

Table 2
Mean response times [ms] and accuracy [% correct] for question answering in each of the four experimental condition. The standard error of the mean is displayed in parentheses

Clause type	Relative	Complement
Subject-first	686 ms (34) 89.5% (2.0)	667 ms (35) 92.0% (1.2)
Object-first	666 ms (34) 93.2% (1.2)	713 ms (38) 81.6% (2.8)

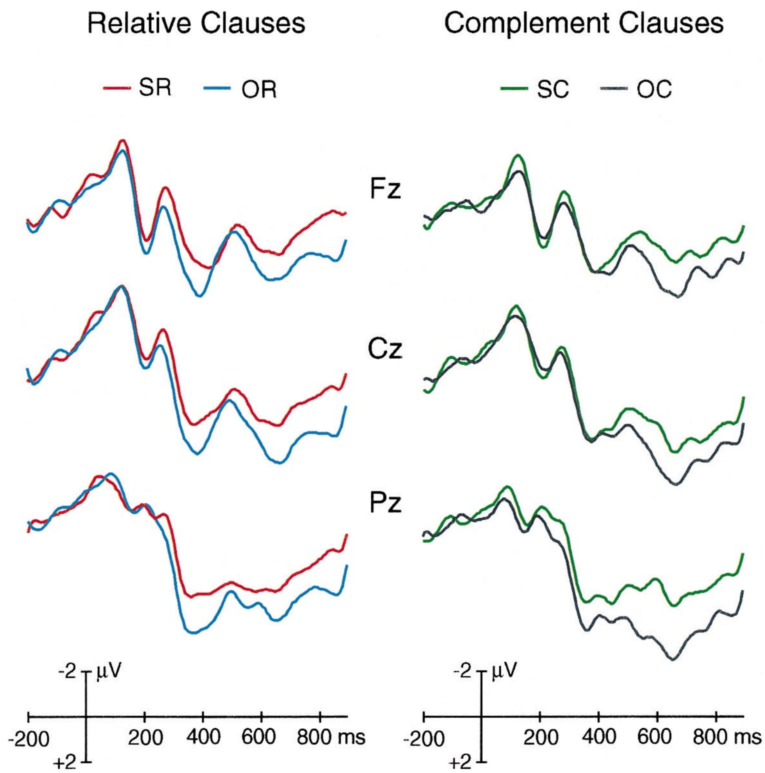

Fig. 3. *Grand average ERPs at the three midline electrode sites* (*Fz*, *Cz*, *Pz*). The ERPs were elicited by the disambiguating sentence final number marked auxiliary of the relative clause sentences (left panel) and the complement clause sentences (right panel). The waveforms are superimposed for the subject-first and object-first sentences. The vertical line indicates the onset of the critical word (SR = subject relative, OR = object relative, SC = subject-first complement, OC = object-first complement).

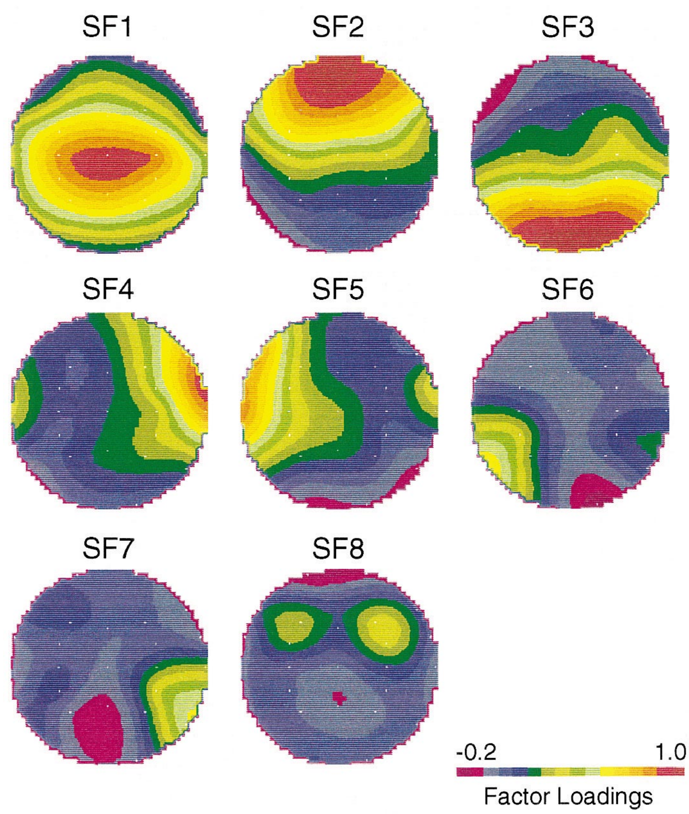

Fig. 4. *Spatial Factors*. Loadings of eight spatial factors from the spatial PCA displayed as topographic maps.

3.2. Event-related potentials

In the following the traditional time window analyses for the ERPs evoked by the sentence final disambiguating auxiliary will be presented briefly, before focusing on the corresponding spatio-temporal PCA analysis.

Fig. 3 displays the grand average ERPs *elicited* by the auxiliary at the three midline electrode sites for the relative clauses (sentences 1 and 2; left panel) and the complement clauses (sentences 3 and 4; right panel), respectively. Note that for all four conditions, the auxiliary is the only element carrying the disambiguating information. In each of the plots the ERPs from the subject-first and the object-first sentences are superimposed and negative amplitudes are plotted upwards.

Despite the larger sample of 8 additional participants, the present plots reveal almost the same pattern as that reported by Friederici [24]. That is, an early positivity around 350 ms followed by a second P600-like component for object relatives, and one late P600-like positivity between 500 and 900 ms for object-first complements. These observations could be confirmed statistically.[7]

3.3. Spatio-temporal PCA

Fig. 4 displays the scalp topography of the factor loadings for each of the eight spatial factors extracted by the PCA between 0 and 900 ms. Recall that these 'loadings' represent the relative contribution of a given electrode to the total activity measured by the virtual electrode represented by each map. Red colors indicate topographic regions that are positively correlated with this factor. The first factor, SF1, represents a centro-parietal distribution, generally characteristic of the P300 component of the ERP. The loading map for SF2 reflects a frontal scalp distribution while SF3 has highest loadings at parietal and occipital recording sites. The identification of SF2 and SF3 with standard ERP components is not obvious, as it seems these two components share contributions from a mix of the so-called 'Slow Wave' and the P300. The loadings of the other factors, i.e. SF4 to SF8, show scalp distributions which appear to represent noise factors in the variance as none of these factors is affected in a systematic manner by any of the experimental manipulations.

As described above, a factor score can be computed for each of the spatial factors at each of the time points, for each of the experimental conditions. These factor scores measure the amount of activity with the scalp distribution represented by the factor at a given time point. A plot of the factor scores as a function of time yields the waveform of the activity measured at the 'virtual electrode' represented by the factor and can be considered a 'virtual ERP'. An examination of the virtual ERPs revealed that only two of the spatial factors, namely SF1 and SF3, showed pronounced activity in the two respective intervals. Fig. 5 displays the virtual ERPs associated with spatial factors SF1 and SF3. Visual inspection indicates that the centro-parietal factor SF1 shows largest activity in a late time interval, whereas the occipital factor SF3 was more active in an early time interval. The centro-parietal factor SF1 shows largest activity for object relative clauses in the early time interval. In the late time interval activity of SF1 was more dominant both object-first structures than the subject-first structures. The occipital spatial factor SF3 is also most active in the early time interval for object relatives, while showing intermediate activity for subject relatives and object complements, and fewest activity for subject complements. In the late time interval, by contrast, SF3 separates object complement structures (high factor scores) from the other three conditions (low scores).

As ERP components are defined as activities over a given time interval, with a specific scalp distribution and a unique pattern of responsiveness to experimental manipulations, it is entirely possible for the same scalp distribution to characterize two different components, each operating over a different epoch and each responding differently to experimental manipulations. Therefore, it is necessary to decompose the variance in the virtual ERPs across the epoch so that we can identify intervals within the epoch of recording into ranges of time points over which the activity in the virtual electrodes is highly correlated over the experimental manipulations. This decomposition is achieved by performing a 'temporal PCA' that analyzed the covariance between all time points across each virtual electrode, experimental condition and subject. The loadings of the nine Varimax rotated factors that accounted for 95% of the variance are displayed in Fig. 6. There are two temporal factors (TF) that show high loadings in an early latency range: TF2 showing high loadings between 300 and 500 ms, and TF8 reflecting activity between 300 and 400 ms, and one temporal factor showing largest loadings in a late time interval, TF7 reflecting activity between 500 and 700 ms. Since only these latter temporal factors reflect activity in the time windows of interest the scores of these three temporal

[7]The three-way repeated-measure ANOVA performed for the relative clauses with the factors WORD ORDER (subject-first vs. object-first), TIME WINDOW (early 300–400 ms vs. late: 600–800 ms) and ELECTRODE revealed main effects of word order, $F(1,17) = 32.49$, $P < 0.001$ and electrode, $F(10,170) = 2.89$, $P < 0.02$. The interaction word order × time window was not significant, $F(1,17) = 0.01$, $P < 0.94$, indicating that object relatives elicited larger positive components in both time intervals. Conversely, the same analysis performed for the complement clauses revealed a significant word order × time window interaction, $F(1,17) = 4.85$, $P < 0.04$. Subsequent ANOVAs indicated that object complements elicited larger positivities than subject complements in the late, $F(1,17) = 8.98$, $P < 0.008$, but not in the early time interval, $F(1,17) = 1.31$, $P < 0.26$. No other effects reached the significance level.

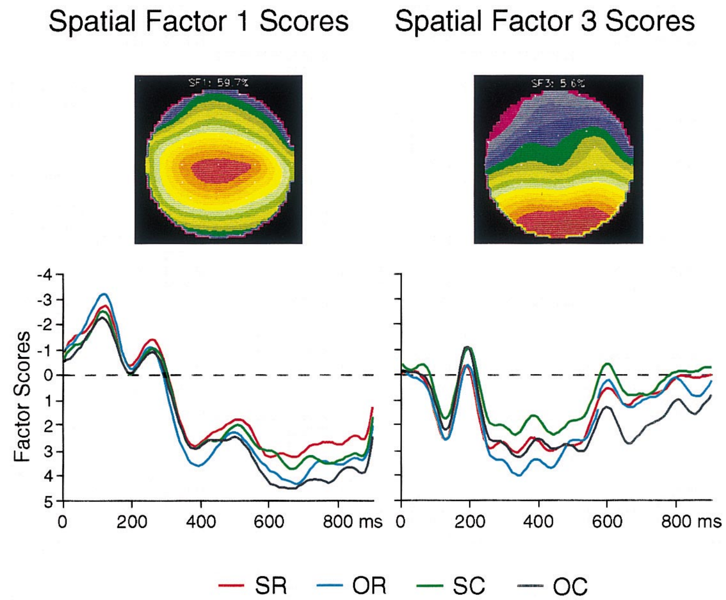

Fig. 5. *Factor scores for two spatial factors (SF1 and SF3).* The scores are averaged across participants for each timepoint and sentence type, yielding a set of virtual electrodes.

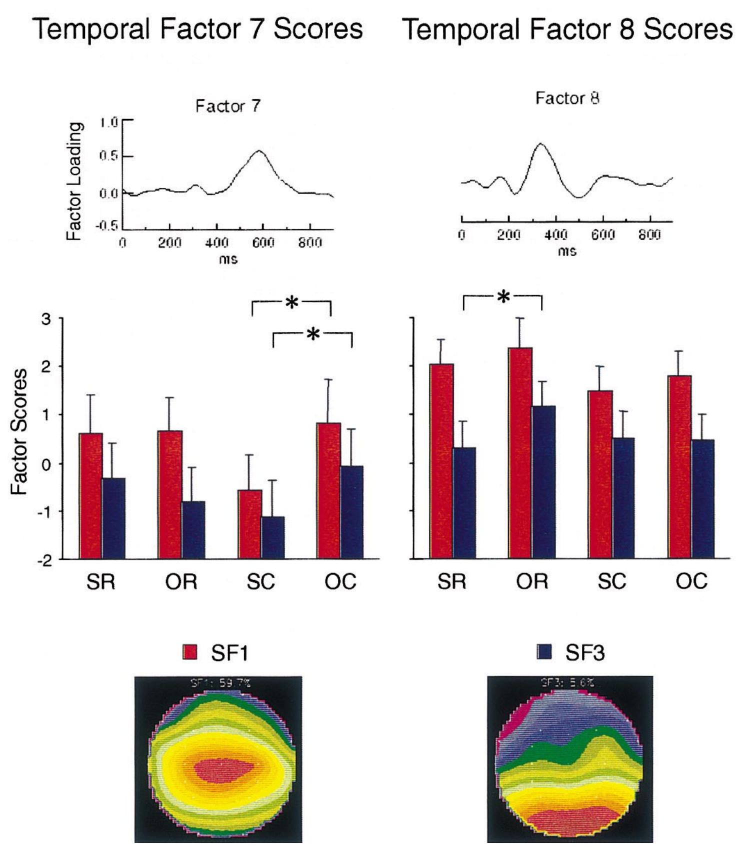

Fig. 7. *Scores for the temporal factors.* Displayed are the scores for the two temporal factors TF7 and TF8 applied to the spatial factors SF1 and SF3.

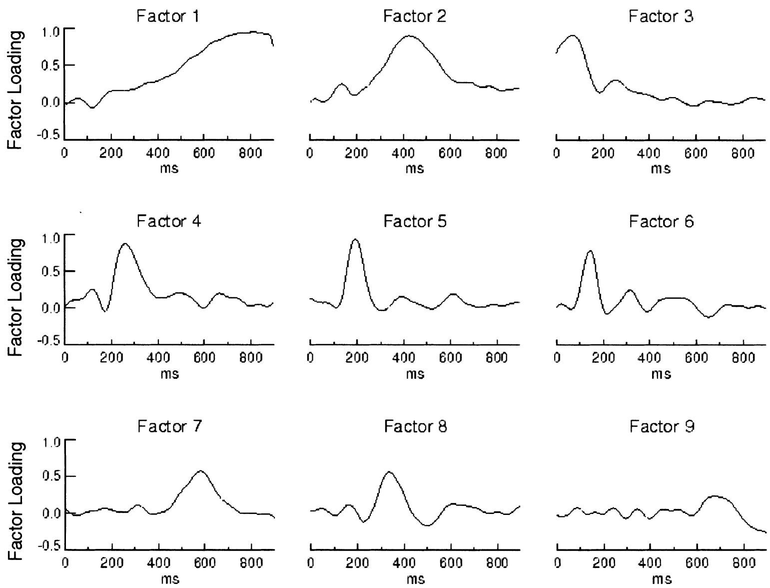

Fig. 6. *Temporal Factors*. Loadings of nine temporal factors from a temporal PCA analyzing the co-variance between timepoints across each virtual electrode, condition, and participant.

factors were considered for statistical analyses at SF1 and SF3.

The statistical analysis for the early time interval revealed the following. For TF2, representing activity in the 300 to 500 ms time range, the scores were slightly larger for relative clauses than for complement clauses for the occipital factor (SF3) and for the centro-parietal factor (SF1), however these differences were not statistically significant, P's$>$0.05. For TF8, representing activity between 300 and 400 ms, scores were larger for object relative clauses than for subject relative clauses, for the occipital factor (SF3), $F(1,17)=6.35$, $P<0.02$. For the complement clauses no corresponding differences were obtained (see also Fig. 7). Its factor scores for the centro-parietal factor (SF1) revealed no reliable differences neither as a function of clause type nor of word order. This pattern of results indicates that in the early time interval, larger activity was found for object relatives than for subject relatives for the occipital factor SF3. A differential pattern of results was obtained in the late time interval: TF7, representing activity in the 500 to 700 ms time range shows larger scores for object complements than for subject complements for both the occipital factor SF3, $F(1,17)=5.57$, $P<0.03$, and the centro-parietal spatial factor SF1, $F(1,17)=4.52$, $P<0.04$. No corresponding effects were obtained for the relative clauses in this late time interval.

4. Discussion

In the present study we investigated processes underlying the revision of different types of non-preferred sentence structures. Event-related brain potentials were recorded while German native speakers with high reading spans read temporarily ambiguous subject-first and object-first sentences. Disambiguating information was available by number agreement late in the sentence, i.e. at the clause final auxiliary. ERP measurements were used to specify the processes underlying parsing and revision processes for preferred subject-first and non-preferred object-first sentence structures. We focused on the late positivity repeatedly observed in the ERP in correlation with the processing of non-preferred syntactic structures [62,54]. Based on a preliminary analysis of a smaller number of participants we hypothesized [24], that two aspects of the revision process, namely the diagnosis for the possibility of reanalysis and the actual reanalysis itself, might be associated with differential positive ERP deflections evoked by non-preferred object first structures. In order to determine whether the revision consists of two subprocesses, a spatio-temporal PCA was employed in addition to the standard time window analysis and.

Two types of garden-path sentences were compared, object-first relative clause sentences and object-first complement clause sentences. Based on linguistic considerations as well as processing assumptions, recovery from a subject-first complement to an object-first complement reading was assumed to be more difficult as it could be viewed to involve more difficult structural alterations than recovery from a subject relative to an object relative reading. It was hypothesized that the underlying revision processes for these two types of garden-path sentences might differ due to a differential involvement of two sub-processes (i.e., diagnosis and actual reanalysis). The outcome of the spatio-temporal PCA is compatible with this view. Two spatial factors were identified and their functional and temporal characteristics suggest that they are associated with the two aspects of the structural revision processes in garden-path sentences. The more detailed discussion of the different effects will be structured as follows. After a brief discussion of the behavioral effects we will discuss the ERP effects from the standard time window analysis and the results of the spatio-temporal PCA in relation to prior ERP studies on syntactic processing. Finally the results will be related to psycholinguistic models of syntactic parsing and revision.

4.1. Off-line behavioral effects

The subjects' responses to questions presented after the end of each sentence indicated that subjects responded more slowly, and less accurately, when asked about the content of object complement clauses. This pattern of results reflects the fact that the revision processes are more demanding, and perhaps longer lasting, for object-first complement clauses than for object-first relative clauses. The observed difference may, however, either be attributable to the different structural alterations required during reanalysis (e.g., [26,33]), or to the circumstance that diagnosis in the former structure might be easier than in the latter [16]. On the basis of the behavioral data one cannot decide whether the observed effect is due to one of these factors or both.

4.2. General ERP effects

The ERP patterns observed in the present study indicate first, that there is a clear on-line advantage of processing subject-first over object-first structures for both relative and complement clauses in German. Second, the data suggest a difference in the revision processes when disambiguating information is encountered in object-first relative clauses and in object-first complement clauses.

The on-line advantage for subject-first structures is reflected in the finding that the disambiguating clause final auxiliary elicited an ensemble of positive deflections that were larger in amplitude for object-first sentences than for subject-first sentences in both clause types. In the light of earlier findings this difference in amplitude presumably is associated with the costs of additional processing [64] or more specifically, with syntactically guided revision processes [54]. For the relative clauses this positivity had a first significant peak between 300 and 400 ms after the onset of the auxiliary and a second less pronounced peak at 600 ms. For the object-first complement clauses, only a late positivity between 600 and 900 ms was obtained. Thus, the ERP pattern elicited by the disambiguating word clearly differed as a function of the type of clause to be revised.

The finding of an early positivity peaking between 300 and 400 ms for object relative clauses replicates results from two earlier studies investigating the processing of relative clause sentences either under varying semantic conditions [54] or with varying proportions of the non-preferred object relative clauses [76]. In the present, but not in the earlier studies, this early positivity was followed by a second late positivity between 600 and 900 ms. A tentative account for these differential effects for the late positivity can be derived from the different experimental designs of the three studies. Whereas the earlier studies confronted readers only with case ambiguous subject and object clause sentences which were always disambiguated at the sentence final number marked auxiliary, the present study additionally included relative and complement clauses with nonambiguous case marking as filler items. We have argued previously that the early positivity is associated with a fast revision effect, by which a correct interpretation of an object relative clause sentence could be achieved by a recoindexation process of the relative pronoun '*die*' and its trace [t] in the underlying structure (see Fig. 1) [54]. The figure indicates that for relative clauses (Fig. 1A) a trace is already present in the subject relative clause though at an other position than in the object relative clause. This means that the revision process for object relatives does not require the new establishment of a structure containing a trace, as it does for object complement clauses (Fig. 1B), but rather it requires a new indexation between the moved element (the relative pronoun) and the trace position. As all sentences in the former studies were disambiguated at the sentence final auxiliary either towards a subject- or an object-first clause, readers only had two options of structural assignments. Moreover, the structural revision required in object relative clauses does not involve any changes of the information structure [55] or the subvocally activated prosodic pattern. That is, the detection of the unexpected inflectional number marking suffix at the auxiliary may give immediate rise to the non-preferred structure. In the present study the ambiguously case marked subject- and object-first relative clause sentences only made up a quarter of all the sentences. This larger variety of sentence structures could have led to additional processes by which the structure under consideration was re-checked. The extent to which the late positivity observed in object relative clauses is indeed some kind of re-checking process or rather includes actual structural re-computation requiring different resources when revising different sentence structures might be resolved by the spatio-temporal PCA.

4.3. Spatio-temporal PCA

The results of the spatio-temporal PCA enable a more detailed consideration of the early and late positive components and also allow more detailed inferences regarding their functional role during syntactic revision processes. In the present study two spatial factors with high loadings at centro-parietal (SF1) and occipital recording sites (SF3) showing pronounced activity in the early and late time intervals are of major relevance. Analyses of the temporal variance of both spatial factors revealed a clear functional dissociation: For the occipital factor (SF3) there was larger activity for object relative clauses as compared to subject relative clauses in the early time interval. The same spatial factor revealed a corresponding effect for the complement clauses only in the late time interval. For the centro-parietal factor (SF1), there was a larger activity for object complement clauses relative to subject complement clauses in the late time interval. No such effect was obtained for relative clauses in either time interval. This implies that only the revision of complement clauses was associated with an additional and topographically different late ERP response.

Our interpretation of this pattern of results is that the two spatial factors, namely SF1 and SF3, indeed reflect variance associated with two different aspects of the revision process. The occipital factor SF3 distinguished object-first from subject-first sentences in general, namely in the early time interval the relative clauses and in the late time interval the complement clauses. Thus, this factor seems to be associated with aspects of diagnosis, the essential step for revision. The difference in latency may suggest that diagnosis was carried out faster for the easy-to-revise relative clause structures than for the difficult-to-revise complement clause structures. The finding that the centro-parietal factor SF1 was only active for the complement clauses in the late time window indicates that some additional aspect of revision must be considered for these clause types in contrast to relative clauses. This second aspect of the revision process maybe associated with processing costs reflecting the computation of a new syntactic structure when deriving object complements from subject complements. In this framework, the absence of any effects for relative clauses on the centro-parietal factor (SF1) in the present study also suggests that the late positive ERP component obtained for object relative clauses in complex experimental designs [26] cannot be considered as an electrophysiological correlate of structural re-computation comparable to that in complement clauses. This finding along with the complete absence of a late positivity in other studies [54,76] suggests that this positivity may rather be associated with more unspecific and design-dependent rechecking processes [24], possibly requiring attentional resources.

The present data indicate that the parser's revision processes are qualitatively different for the two object-first structures. A possible description of the underlying processes in relative clauses would assume that when encountering the disambiguating element the parser diagnoses the possibility of an alternative structure quite immediately without additional costs of recomputation (presence of SF3 in the *early* time interval). For these easy-to-revise object relative clause structures the alternative structure may be directly available once diagnosis is performed. For this type of garden-path, any subsequent processes eliciting late positivities must be taken as optional because they do not occur reliably (cf. [54]). In contrast, encountering the disambiguating element in the object-first complement structure is exclusively associated with pronounced activity in the *late* time interval, on factor SF3 but also on factor SF1. This suggests that the spatial factor (SF3) reflects the same obligatory process as in relative clauses, possibly the diagnosis, but with a different temporal characteristic. Moreover, the computation of an alternative structure for the difficult-to-revise object complement clause structures appears to require an additional process associated with a separate spatial factor (SF1). For complement clauses the act of diagnosing may not automatically provide the alternative structure, but its revision may rather be associated with additional processing costs reflected in qualitatively distinct brain activity. Bader and colleagues [1,3] suggested that the reanalysis of object-first complement clauses but not of object relative clauses is likely to involve changes in the information structure. As changes in the information structure are tidely connected to changes in the intonational pattern, readers recovering from the initial SC towards the required OC reading can be assumed to change their subvocally activated intonation pattern accordingly [1]. In fact, the influence of prosodic aspects on syntactic parsing was not only demonstrated during speech perception (e.g. [81,71]) but also during silent reading [74,75]. On the basis of a series of ERP experiments Steinhauer et al. [73] hypothesized, that the P600 component may reflect not only syntactic but also prosodic revisions. In the present case, additional activation of SF1 observed in OC clauses may be due to both kinds of reanalyses.

4.4. Positive components in the ERP

When relating the two spatial factors SF1 and SF3 to other positive ERP components classically discussed in the literature, one may consider their temporal as well as their spatial characteristics. When focusing on the spatial characteristics, it appears that the centro-parietal factor (SF1) reflects variance usually ascribed to the domain-general P300 component whereas the occipital factor (SF3) does not. When considering the temporal aspect it may be interesting to note that additional studies using the same sentence structures have shown that the early positivity (possibly represented by early variance of the occipital factor (SF3)) is independent of the probability of subject-first and object-first sentences in an experiment whereas the late positivity (possibly reflected predominantly by late variance of the centro-parietal factor (SF1), is not [76]. As the positivity's sensitivity to the probability variation of the 'deviant' event has been used as a diagnostic for the domain-general P300 [12,13] the observed sensitivity of the late positivity in the sentence processing study confirms that SF1, rather than SF3, reflects domain-general aspects of processing.

Moreover, it is noteworthy that the late positivity in sentence processing studies (apparently reflected by SF1) varies as a function of additional memory load whereas the early positivity (apparently reflected by SF3) does not [80]. This finding seems to provide an additional argument for the suggestion that the occipital factor (SF3) reflects a process which is independent of more general processing aspects such as strategic influence (probability) and additional memory load and therefore, may be considered to be domain-specific.

The spatio-temporal analysis suggests that the more complex revision process assumed for complement clauses, comprises two aspects: the diagnosis and the updating of a current model of the structural context. The fact that the late ERP activity evoked by complement clauses can be decomposed in two functionally dissociable spatial factors one of which bears similarities with the P300 component also has implications for the interpretation of positive deflections to syntactic anomalies usually found in this time interval. It suggests that these late positivities are manifestations of multiple neuronal events, some of which also contribute to the P300 component. The present data show that a fine-grained analysis of the topographical characteristics of ERP components is required to disentangle the multiple processing aspects reflected by P600-like components.

4.5. Psycholinguistic models

The reported ERP patterns, in accordance with previous work, showed a clear on-line preference for subject- over object-first structures when reading temporarily ambiguous sentences. The preference was indicated by the ensembles of positivities observed for both object-first relative clauses and object-first complement clauses compared to the respective subject-first structures. These positivities are taken to reflect revision processes triggered by a mismatch between the actual input and initial structural expectations.

Given that the existing studies on lexical ambiguities report N400 rather than P600-like effects [37,41,77], we believe that our findings of positive going waveforms are incompatible with the lexical approaches of constraint satisfaction models (e.g., [51]). Given that our PCA analysis revealed one factor active for the relative clause sentence and two factors for the complement clause sentences, the present data cannot be taken to support constraint based models relying on frequency biases as these would predict one factor associated with frequency only. However, data are in general compatible with both serial [20,33]) and parallel parsing models (e.g., [31,39]), both assuming processes of revision explicitly.

In particular, the spatio-temporal PCA of the ERP data are compatible with a view formulated by Friederici [24], assuming two different processing aspects during revision, a first one representing the diagnosis and a second one representing the actual reanalysis. The assumption of two processing aspects was based upon two independent proposals. The first one holds that the ease of diagnosis predicts the ease of the revision process [16]. The other one assumes that the complexity of the syntactic repair itself [26,33] along with its information structural and prosodic implications [1,3] determine the ease of the revision process.

The results from the PCA indicated that these two aspects of the revision process could in fact account for the observed pattern and that each of them is associated with a topographically distinct ERP process. One factor is effective in an early time window for relative clauses and in a late time window for complement clauses and may reflect diagnostic processes. The finding that the activity of this factor differs in latency as a function of clause structure, seems to suggest that the respective positivity reflects the termination of diagnosis process rather than its onset.[8] The second factor only separates object from subject complement clauses in the late time window and may therefore be taken to reflect actual structural recomputation processes. Similar processes of recomputation may not be necessary for relative clauses as for these structures the alternative structure could be available as soon as diagnosis has taken place.

The present data are in partial agreement with the proposal of Fodor and Inoue [16] who claim that the diagnosis determines the ease of revision (easy-to-revise object relative clauses versus difficult-to-revise complement clauses). They disagree with the diagnosis model in so far as the revision process for the difficult-to-revise complement clauses appears to be determined by two although temporally overlapping factors (diagnosis <u>and</u> recomputation) which could be disentangled by the present spatio-temporal PCA of the ERP data. The results from the PCA are clearly compatible with the view that both diagnosis and reanalysis determine the revision process [33,24]. They may specify this view in showing that for some easy garden-path sentences the alternative structure is directly available without additional computations whereas difficult-to-revise structures require processes of recomputation in addition to the process of diagnosis.

Given the large number of proposals concerning the underlying cognitive processes while recovering from garden-path sentences, other interpretations may be possible in principle. Parallel parsing models, for example, may be able to account for the pattern. Recall that these models assume that the parser computes different structural representations in parallel. Very unlikely alternatives, however, will be abandoned during the subsequent parse. Under this view, the processing of complement clauses will differ from that of relative clauses with respect to the

[8]We thank Lee Osterhout (personal communication) for drawing our attention to this point.

unlikeliness of the alternative structure. In complement clauses, in contrast to relative clauses, the unlikely object-first structure can be assumed to be abandoned all together very early so that in addition to diagnosing that the current structure is not valid a recomputation becomes necessary. Within its own logic, however, the parallel approach would encounter the severe problem with the present data that the crucially different processes of reactivation (in relative clauses) and recomputation (in complement clauses) would be reflected by the same ERP subcomponent.

5. Conclusion

The present data clearly suggest that sentence revision consists of distinct sub-processes involving different neuronal assemblies. Whereas the reported centro-parietal subcomponent (SF1) shows typical characteristics of the domain-general P300, the occipital subcomponent (SF3) would be a candidate for a more language specific ERP component. As a consequence, the late positivity called syntactic positive shift (SPS) or P600 does not appear as a monolithic component but rather seems to comprise a mixture of subcomponents, possibly reflecting very different processes such as diagnosis, syntactic and prosodic reanalysis, rechecking and integration. The application of a spatio-temporal PCA to language-related ERPs appears to be a useful tool in disentangling partly overlapping sub-processes of higher cognitive functions during language processing.

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Appendix A. Noun phrases and verbs (past participles) used to construct the sentence material

1.	Direktor (director)	Sekratär (secretary)	getötet (killed)
2.	Bürger (citizen)	Politiker (politician)	gegrüßt (greeted)
3.	Radfahrer (cyclist)	Jogger (jogger)	gesehen (noticed)
4.	Ingenieur (engineer)	Physiker (physicist)	gesucht (looked for)
5.	Lehrer (teacher)	Schüler (pupil)	geachtet (respected)
6.	Psychiater (psychiatrist)	Zahnarzt (dentist)	gemieden (avoided)
7.	Sänger (singer)	Musiker (musician)	gestört (disturbed)
8.	Komissar (officer)	Mörder (murderer)	gefürchtet (feared)
9.	Läufer (runner)	Turner (gymnast)	geschubst (pushed)
10.	Kellner (waiter)	Koch (cook)	gemocht (liked)
11.	Gastgeber (host)	Freund (friend)	getröstet (consoled)
12.	Schiwmmer (swimmer)	Taucher (diver)	gewarnt (warned)
13.	Botschafter (ambassador)	Minister (minister)	geehrt (honored)
14.	Schauspieler (actor)	Regisseur (director)	gemalt (painted)
15.	Anwalt (lawyer)	Buchhalter (accountant)	getäuscht (cheated)
16.	Juwelier (jeweler)	Händler (trader)	geschädigt (harmed)
17.	Erzieher (social teacher)	Alkoholiker (alcoholic)	geschlagen (beaten)
18.	Verkäufer (salesman)	Kaasierer (cashier)	gerufen (called for)
19.	Siedger (winner)	Verlierer (loser)	gefuden (found)
20.	Vermieter (house owner)	Makler (estate agent)	geschätzt (esteemed)
21.	Mechaniker (mechanic)	Chemiker (chemist)	gerettet (rescued)
22.	Unternehmer (employer)	Forscher (researcher)	gelobt (praised)
23.	Retner (pensioner)	Enkel (grandchild)	geküßt (kissed)
24.	Geiger (violinist)	Dieb (thief)	gehört (heard)
25.	Pfleger (nurse)	Arzt (doctor)	geimpft (inoculated)
26.	Richter (judge)	Betrüger (swindler)	gehaßt (hated)
27.	Pförtner (porter)	Gärtner (gardener)	geholt (got for)
28.	Manager (manager)	Trainer (coach)	getadelt (criticized)
29.	Dichter (poet)	Maler (painter)	gepriesen (praised)
30.	Gastwirt (innkeeper)	Winzer (wine grower)	gefördent (promoted)
31.	Redakteur (editor)	Reporter (reporter)	geweckt (woke up)
32.	Segler (yachtsman)	Surfer (surfer)	geärgert (annoyed)

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