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Research report

Is human sentence parsing serial or parallel? Evidence from event-related brain potentials

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Abstract

In this ERP study we investigate the processes that occur in syntactically ambiguous German sentences at the point of disambiguation. Whereas most psycholinguistic theories agree on the view that processing difficulties arise when parsing preferences are disconfirmed (so-called garden-path effects), important differences exist with respect to theoretical assumptions about the parser's recovery from a misparse. A key distinction can be made between parsers that compute all alternative syntactic structures in parallel (parallel parsers) and parsers that compute only a single preferred analysis (serial parsers). To distinguish empirically between parallel and serial parsing models, we compare ERP responses to garden-path sentences with ERP responses to truly ungrammatical sentences. Garden-path sentences contain a temporary and ultimately curable ungrammaticality, whereas truly ungrammatical sentences remain so permanently—a difference which gives rise to different predictions in the two classes of parsing architectures. At the disambiguating word, ERPs in both sentence types show negative shifts of similar onset latency, amplitude, and scalp distribution in an initial time window between 300 and 500 ms. In a following time window (500–700 ms), the negative shift to garden-path sentences disappears at right central parietal sites, while it continues in permanently ungrammatical sentences. These data are taken as evidence for a strictly serial parser. The absence of a difference in the early time window indicates that temporary and permanent ungrammaticalities trigger the same kind of parsing responses. Later differences can be related to successful reanalysis in garden-path but not in ungrammatical sentences.

Theme: Neural basis of behavior

Topic: Cognition

Keywords: ERP; Sentence-processing; Syntactic reanalysis; N400; LAN

1. Introduction

Human sentence processing is astonishingly efficient and fast—a property that, unfortunately, eludes simple experimental exploration. Conventional experimental methods (measurement of reaction times and reading times, error rates) have provided numerous data to shape general models of sentence processing but have left unsettled a number of central questions that mainly concern the time course of the computations involved. An experimental approach that potentially overcomes limitations of temporal resolution is provided by event-related brain potentials (ERPs). ERPs, which can be used to investigate neural activity related to sentence processing at a time scale of milliseconds, have revealed valuable insights into time course and interactions of semantic, syntactic, pragmatic and, most recently, prosodic information during reading [10,13,18,22,23,26,27,34–39,43].

One central question that theories of sentence processing still need to answer is how local syntactic ambiguities are processed. Which principles guide sentence processing when more than one syntactic analysis becomes temporarily compatible with the input? Several basic architectures of the human sentence parsing mechanism (henceforth referred to as 'parser') have been proposed which model syntactic ambiguity resolution in qualitatively different ways (see Ref. [31] for a recent review). Parsers with parallel architecture are assumed to compute all possible syntactic analyses in parallel when an ambiguity arises [14,15,20]. At the later point of disambiguation the incompatible analysis will simply be discarded from working

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memory while the correct analysis remains. In contrast, parsers with serial architecture like the garden-path model of Frazier [6,8] accord a so-called 'no-bookkeeping constraint' [7]. That is, a serial parser continuously updates one single preferred analysis in accordance with certain principles of computational economy and without considering any possible alternatives. In case of disambiguation towards an unpreferred syntactic analysis, the parser will stumble because no information about possible alternatives is available. This has been termed 'garden-path (GP) effect'—central evidence in favor of a serial parsing architecture. After being garden-pathed the parser must reparse at least parts of the sentence to derive the appropriate reading (reanalysis). A number of ERP studies have provided data compatible with serial parsing [12,18,30,37,38]. For example, Osterhout et al. [37] investigated ambiguities between a simple main clause versus a reduced relative clause reading in English sentences like: The broker *hoped*/*persuaded* to sell the stock . . . Intransitive verbs like *hope* allow only a main clause reading whereas transitive verbs like *persuade* are ambiguous between a main clause and a (syntactically more complex) reduced relative clause reading of the sentence. The following word (to) that disambiguates the sentence towards the relative clause reading elicited a large positivity around 600 ms (P600) which was not found after intransitive verbs like *hope*. The P600 effect was taken to reflect the presence of a garden-path in these sentences, and was therefore taken to support a serial architecture of the parser. Hopf et al. [21] investigated the ERP signature of Case assignment in ambiguous German accusative/dative sentences like: *Dirigenten*$^{(Acc,Dat)}$ *. . . sollte man unbedingt umjubeln*$^{(Acc)}$/*zujubeln*$^{(Dat)}$ (conductors . . . one should unconditionally cheer at). The unpreferred dative assignment to the noun *Dirigenten* which is required by the second verb elicited a prominent negativity between 300 and 900 ms over the right central-posterior scalp (referred to as N400-like negativity). The ERP response to the preferred accusative reading, in contrast, did not differ from unambiguous (dative) control sentences. Again, the negativity for the unpreferred dative reading was taken as evidence for a serial architecture of the parser.

The finding of a unique ERP response like the P600 or an N400-like component in GP-sentences is generally a plausible argument in support of a serial parser, but it is not sufficient to rule out parallel architectures. This is because parallel parsers have been developed that rank alternative syntactic representations along the lines of more and less preferred interpretations. Such a ranking could make an immediately available but lower ranked alternative harder to access which would explain the presence of GP-effects in parallel parsers as well as related ERP responses.

In the present study we will provide stronger evidence for a strictly serial parsing architecture by showing that under certain conditions ERP responses directly contradict the predictions of a parallel parser even when augmented by ranking alternative syntactic structures. The rationale for our approach is as follows: In GP-sentences a temporary ungrammaticality arises at the point of disambiguation.[1] In a serial parser, this temporary ungrammaticality will initiate reanalysis of the sentence. In a parallel parser, in contrast, a precomputed alternative structure is already available at the point of disambiguation. Consider now what happens when the parser encounters precisely the same ungrammaticality as temporarily present in GP-sentences but without a preexisting grammatical alternative, that is, a truly ungrammatical sentence. When detecting a temporary ungrammaticality, a serial parser cannot immediately know whether a grammatical alternative exists (GP-sentence) or not (ungrammatical sentence). In both GP-sentences and ungrammatical sentences, a serial parser therefore starts certain processes in order to determine whether a grammatical alternative exists or not. For GP-sentences, these processes will ultimately lead to a correct reanalysis of the sentence. For ungrammatical sentences, these processes will at some point block because no grammatical alternative exists. In contrast to a serial parser, a parallel parser can without disruption distinguish between GP-sentences and ungrammatical sentences because for GP-sentences, but not for ungrammatical sentences, a lower ranked precomputed alternative would be available to which the parser can switch. Thus, even if ERP responses in GP-sentences alone couldn't tell reparsing actions (serial parser) from operations of switching to a precompiled alternative (parallel parser), ERP responses to corresponding ungrammatical sentences would be clearly distinct for parallel and serial parsing architectures. For a serial parser, ERP responses to GP-sentences and ungrammatical sentences would be identical for initial processing stages that should last until the grammatical alternative is found in GP-sentences. For parallel parsers, the ERP response should instantly discriminate between both sentence types. Moreover, the ERP response could be expected to be qualitatively different (opposite relative polarity, different scalp topography) for GP-sentences and ungrammatical sentences because resulting parsing actions are—unlike in a serial parser—qualitatively different.

2. The present study

In the present study we will investigate the above predictions concerning serial versus parallel parsing architectures by using and extending experimental materials of a previous study on the processing of GP-sentences in German [21] with a new group of 16 subjects. In Hopf et al. [21] it was shown that the disfavored resolution of certain syntactic ambiguities can give rise to GP-effects that lead to a negative, N400-like component of the ERP. N400 effects have been found in connection with semantic

[1]We prefer to speak about ungrammaticality as opposed to anomaly because the former notion rests on a precise definition in linguistic theory.

anomaly detection (see Refs. [26,27]) while GP-effects have normally been found to result in P600 components. The effects in Hopf et al. [21] arose due to a mismatch between a postulated case on the sentence-initial noun phrase (NP) and the verb which closes off the sentence. While the detection of a case mismatch may tap into processes of argument integration and therefore also semantic integration, it is not at all clear how case mismatch could be reduced to semantic anomaly. It is a fact of the grammar of modern German that in simple transitive clauses as used in this study, the cases under consideration (accusative and dative) are not semantically transparent. It is therefore appropriate to relate the N400-like effect to a structural syntactic rather than a lexico-semantic problem, i.e. a GP that emerges in the processing of case information.[2] Moreover, it should be noted that experimental evidence speaks against a rigid relation between late positive ERP components like P600 and interruptions of structural syntactic processing. For example, scalp negativities with a more left frontal scalp distribution (LAN effects) have been found after violations of word category expectation (phrase structure violations) [10,11,36,37] or in filler-gap constructions, in particular related to storage and retrieval of filler items [23,24,36].

The GP-effects in this study arise due to ambiguities of the German Case system which sometimes leave noun phrases (NPs) in a sentence compatible with different syntactic functions. For example, in sentences (1a) and (1b) the initial NP *Dirigenten* is morphologically ambiguous as to whether it serves as an accusative object or as a dative object.[2]

The initial nouns in (2a) and (2b), on the other hand, are unambiguously distinguished morphologically. The dative (2a) is explicitly marked by the *-n* in *Musiker-n*.

2.1. Ambiguous sentences

(1a) *Dirigenten*$_{Acc/Dat}$, *die ein schwieriges Werk einstudiert haben, kann ein Kritiker ruhig applaudieren*$_{Dat}$.
conductors$_{Acc/Dat}$ who a difficult opus rehearsed have, can a critic safely applaud$_{Dat}$.
(A critic can safely applaud conductors who have rehearsed a difficult opus)

(1b) *Dirigenten*$_{Acc/Dat}$, *die ein schwieriges Werk einstudiert haben, kann ein Kritiker ruhig umjubeln*$_{Acc}$.
conductors$_{Acc/Dat}$ who a difficult opus rehearsed have, can a critic safely cheer$_{Acc}$.
(A critic can safely cheer conductors who have rehearsed a difficult opus)

2.2. Unambiguous control sentences

(2a) *Musikern*$_{Dat}$, *die ein schwieriges Werk einstudiert haben, kann ein Kritiker ruhig applaudieren*$_{Dat}$.
musicians$_{Dat}$ who a difficult opus rehearsed have, can a critic safely applaud$_{Dat}$]
(A critic can safely applaud musicians who have rehearsed a difficult opus)

(2b) *Musiker*$_{Acc}$, *die ein schwieriges Werk einstudiert haben, kann ein Kritiker ruhig umjubeln*$_{Acc}$.
musicians$_{Acc}$ who a difficult opus rehearsed have, can a critic safely cheer$_{Acc}$.
(A critic can safely cheer musicians who have rehearsed a difficult opus)

2.3. Ungrammatical sentences

(3a) *Musiker*$_{Acc}$, *die ein schwieriges Werk einstudiert haben, kann ein Kritiker ruhig applaudieren*$_{Dat}$.
musicians$_{Acc}$ who a difficult opus rehearsed have, can a critic safely applaud$_{Dat}$.
(A critic can safely applaud musicians who have rehearsed a difficult opus)

(3b) *Musikern*$_{Dat}$, *die ein schwieriges Werk einstudiert haben, kann ein Kritiker ruhig umjubeln*$_{Acc}$.
musicians$_{Dat}$ who a difficult opus rehearsed have, can a critic safely cheer$_{Acc}$.
(A critic can safely cheer musicians who have rehearsed a difficult opus)

[2] As a matter of fact, the plural nouns in (1a), (1b), and (2b) are also legitimate representatives of nominative Case and may, therefore, serve as subjects. This ambiguity is already ruled out in favor of an object interpretation after the finite verb (modal) is received. In (1a) and (1b), a Case ambiguity between accusative and dative remains until the clause final verb is reached. In (2b), the dative interpretation is ruled out from the outset, the only option remaining an accusative interpretation.

The ambiguity in (1a) and (1b) remains unresolved until the sentence final verb appears. In (1a) the verb *applaudieren*$_{\mathrm{Dat}}$ disambiguates the NP towards a dative object, in (1b) the verb *umjubeln*$_{\mathrm{Acc}}$ disambiguates the NP towards an accusative object. We could show that the final verb triggers a robust garden-path in sentences like (1a) but not in (1b) [21]. Similarly, (1a) elicited a prominent negative shift of the ERP between 250 and 900 ms in comparison to unambiguous control sentences like in (2a). In contrast, ERP responses to final verbs that disambiguate towards an accusative object like in (1b) and unambiguous control sentences (2a) were indistinguishable.

Our interpretation was that the parser does not uphold the ambiguity in (1a) and (1b) until the clause-final verb. Instead, it immediately assigns a syntactic function to the initial NP. For reasons of simplicity in parsing, this assignment is guided by a preference for accusative objects over dative objects in German.[3]

In (1b) the preferential interpretation of an accusative object turns out to be correct. In (1a), however, a temporary ungrammaticality arises (GP-effect) when the clause-final verb is encountered because—unexpectedly—the verb requires a dative object.

What are the predictions of the two parsing architectures? In (1a), a serial parser would decide to strictly pursue an accusative object interpretation of the initial NP *Dirigenten*. When arriving at the final verb that requires a dative object interpretation, the parser will not know that such an alternative is viable and will start to reanalyze the current parse. A parallel parser would rank the accusative interpretation of (1a) highest, but nevertheless keep track of the alternative dative object interpretation until the final verb. At this point the parser would simply switch to the already computed dative interpretation. Now, let us consider the sentence in (3a) which represents the ungrammatical counterpart of (1a). Here, if the initial NP should be taken to be an object, it can only be an accusative object (the dative form being *Musiker-n*). Since the final verb requires a dative object, an incurable ungrammaticality results. Note that from a processing perspective (1a) and (3a) give rise to identical ungrammaticalities that only differ as to the presence of a grammatical alternative in (1a).[4] In (3a) both types of parsers would pursue one and the same accusative object interpretation. When arriving at the final verb, a dative object interpretation is required that renders the current parse ungrammatical. A serial parser would find itself in the same situation as in the ambiguous case (1a) and start efforts to reanalyze the sentence because knowledge about the absence of a grammatical alternative is not available. A parallel parser, on the other hand, could immediately classify the sentence as being definitively ungrammatical without starting efforts to switch to a not existing alternative. With respect to their behavior on (1a) and (3a), serial and parallel parsers therefore show an essential difference. While a serial parser starts qualitatively the same actions in (1a) and (3a), the parallel parser does different things in principle. In (1a) it reactivates a preprocessed alternative, in (3a) it discards an analysis instantaneously.

In sum, the present study will focus on the particular relationship between the GP-sentences in (1a) and their ungrammatical counterparts in (3a). As outlined above, both parsing architectures can account for ERP responses showing enhanced processing difficulties in GP-sentences since reparsing (serial parser) or reactivation of precompiled alternatives (parallel parser with ranked alternatives) may require additional efforts in comparison to unambiguous sentences. Consequently, ERP data from GP-sentences alone may be inconclusive regarding a decision between these principal parsing architectures. This is not the case for unambiguous ungrammatical sentences like in (3a) for which the two parsing architectures predict qualitatively different ERP responses. Measuring ERPs to ungrammatical sentences will therefore allow a decision between serial and parallel parsing models.

To complete the experimental design, we also included ungrammatical accusative sentences (3b) and related grammatical control sentences (2b). As a secondary issue of this study, the inclusion of these sentences will allow us to address questions about how different degrees of overt Case marking influence ERP responses in ungrammatical

[3]In Hopf et al. [21] we explained the garden-path effect in (1a) as the consequence of a so-called '*Case Preference Principle*', according to which the parser prefers to assign structural (nominative, accusative) over lexical Case (dative) in ambiguous situations. The appearance of a negative shift has been proposed to reflect the parser's attempt to check the lexicon for the compatibility of the ambiguous NP with dative Case. There are a large number of syntactic reasons to believe that in German datives are morpho-syntactically more complex than accusatives (cf. Ref. [2]). If this is relevant for the parser, it follows that parsing economy disfavors the dative against the accusative. The latter would simply require less action of structure building.

[4]Unfortunately, a direct analogue of the type of case ambiguities under investigation in this study cannot be found in English. Nevertheless, to illustrate the difference between GP-sentences like (1a) and related ungrammatical sentences like (3a) to the English readership we provide slightly similar examples from English:

(i) Who did you show (t) that they have observed t? [gardenpath, but grammatical]
(ii) Who did you show (t) that they have repaired t? [ungrammatical]

Show is preferentially transitive; thus, *who* is associated with the trace in brackets, but then *observe* is obligatorily transitive such that the earlier filler-gap parse has to be revised. In (ii) this is not successful because although *repair* is transitive, the filler *who* cannot—due to selectional reasons—be associated with the following trace.

sentences. Consider the example sentence (3b). Here, the initial NP is unambiguously inflected for dative Case while the sentence final verb requires an accusative object interpretation. This is directly opposed to the situation in (3a), where the initial NP acts as an accusative object and the final verb requires a dative object interpretation. From a purely syntactic perspective, the conflict regarding the syntactic function of the initial NP in (3a) and (3b) seems to be symmetrical. This is, however, not the case. The reason is that as a dative object the initial NP carries an explicit morphological marker (the *-n* in *Musiker-n*) for dative Case. As an accusative object in (3a) the initial NP is not specifically marked for accusative Case. In other words, the initial NP in (3a) is only negatively defined as an unambiguous accusative object due to the absence of a specific Case marker, while *Musiker-n* in (3b) is positively defined as an unambiguous dative object.

3. Materials and methods

3.1. Subjects

Sixteen subjects (students of the University of Jena, nine female; mean age: 25.5) were paid for participation in this experiment. All subjects were native speakers of German, right-handed and with normal or corrected to normal visual acuity. There was no history of neurological or psychiatric illnesses in any of the subjects. The experiment was undertaken with the understanding and written consent of each subject.

3.2. Materials

One example of the whole set of sentences used in this experiment is presented in Section 2 under (1a), (1b), (2a), (2b), (3a) and (3b).

3.3. Procedure

Sentences were presented on a microcomputer-controlled video screen in a framewise manner as indicated in (4):

[Dirigenten,]	conductors
[die ein schwieriges Werk einstudiert haben,]	who have rehearsed a difficult opus
[sollte]	should
[man]	one
[ruhig]	safely
[applaudieren]	applaud

(4)

Square brackets separate subsequent video frames that were presented for 750 ms spaced by a 750-ms blank screen with one exception, namely the relative clause, which was presented for 2800 ms. Subjects were instructed to read the sentences for meaning. To guarantee attention and careful reading of the sentences, an additional word appeared 2000 ms after the final verb. Subjects were required to decide whether this word had appeared in the previous sentence (which was the case in 50% of the sentences) or not by pressing one of two response buttons.[5] The end of each trial was signaled by three asterisks upon which subjects were allowed to relax fixation and make eyeblinks.

A total of 180 sets of sentences of each of the six grammaticality conditions (1a), (1b), (2a), (2b), (3a), (3b) were prepared (i.e. a total of 1080 sentences) and divided into six blocks containing 30 sentences of each sentence type. Within each block sentence types occurred in random order. Subjects always performed on two blocks that were randomly selected from the set of six experimental blocks. Performing on one block took about 40 min. The blocks were separated by a resting period of 5 min. Within each set of sentences care was taken to match the semantic content of the initial nouns with respect to the sentence meaning as closely as possible. This was done to prevent confounds due to differences in semantic relatedness which could otherwise lead to unwanted modulations of the ERP response to the sentence final verbs.

3.4. Recordings

EEG was recorded from 64 Ag/AgCl electrodes located according to the 10% system of the American Electroencephalographic Society [42] with reference to the right mastoid. Resistance was always kept below 5 kOhm. The EEG was amplified using two coupled 32-channel DC-amplifiers (Synamps, Neuroscan Inc.) with a system bandpass of DC to 30 Hz and a sampling rate of 250 Hz. Horizontal and vertical eye movements (electro-oculogram, EOG) were recorded using bipolar montages of two electrodes at the outer canthi of both eyes (horizontal EOG), and above and below the right eye's upper and lower orbital ridge (vertical EOG). Artifact rejection was performed offline by removing EEG epochs containing artifacts due to eye movements, blinking, and muscle

[5] One may wonder whether this task could have distracted subjects from reading the sentences for meaning in an ordinary way. This is unlikely for a number of reasons: (1) Subjects were instructed to read the sentences carefully. (2) The experimental task was adopted from our previous study [21] in which reliable ERP effects of sentence processing were obtained. Importantly, in Ref. [21] the results of a questionaire study (awkwardness ratings) closely mirrored the results obtained with ERPs suggesting that task specificity did not inhibit normal sentence processing. (3) It has been shown that typical ERP effects of syntactic processing like P600/SPS do appear independent of specific task requirements even under conditions of no task at all [18]. (4) It is widely known that an eventual strategy to memorize sentences as word lists would increase memory demands tremendously, in contrast to reading under syntactic parsing (see Ref. [16] for a discussion of this issue). It is, therefore, unlikely that subjects were adopting some strategy unrelated to normal sentence processing.

tensions which led to a rejection rate of approximately 10% of the trials. For further analysis, EEG was algebraically rereferenced against a mean of the left and right mastoid electrode. For example, the potential recorded at electrode Cz (Cz^{rec}) was rereferenced (Cz^{reref}) by computing $Cz^{reref} = Cz^{rec} - 0.5 \cdot LM^{rec}$. Since $Cz^{rec} = Cz - RM$ and $LM^{rec} = LM - RM$, proof can be expanded to $Cz^{reref} = Cz - RM - 0.5 \cdot (LM - RM)$, which gives $Cz^{reref} = Cz - 0.5 \cdot (RM + LM)$, i.e. the potential at Cz with reference to the mean of both mastiod electrodes.

3.5. Data analysis

Average waveforms (ERPs) elicited by the final verb were computed for each subject and grammatical condition based on 60 occurrences of each sentence type.

A 250-ms pre-stimulus epoch served as time window for baseline correction. For further statistical analysis mean amplitudes were measured in time windows covering ERP components of interest which were defined upon visual inspection of the wave forms. That is, the N1 component was measured between 80 and 150 ms, the P2 component was measured between 150 and 300 ms. Following epochs of the ERP wave forms were analyzed using steps of 200 ms (300–500, 500–700, 700–900 ms) and a final window between 1000 and 1500 ms. Separate statistical analyses were conducted for each time window by means of a repeated measures analysis of variance (RANOVA). First, overall one-way RANOVAs with sentence type as a six-level factor were performed to find ERP epochs that show substantial modulation due to the experimental conditions. Violations of variance homogeneity were controlled by readjusting the type I error using the Greenhouse–Geisser epsilon [17]. Corrected error type I levels are reported in conjunction with the original dimensions of freedom. To illustrate the general scalp distribution of the overall effects statistical maps of F-values resulting from separate RANOVAs for each electrode site were derived.

Second, depending on significant effects of the overall RANOVAs in each separate time window, additional pairwise comparisons were computed to gain detailed insight into processing effects. Statistical effects are reported for electrode sites showing maximum effects. To illustrate the scalp distribution of the ERP effects, voltage difference maps were computed in time windows showing significant pairwise comparisons.

4. Results

4.1. The clause final verb: overall analysis

Fig. 1 shows the topographical distribution of the overall statistical effect of sentence type. The shown maps of F-values (F-maps) were derived from overall repeated measures analyses of variance (RANOVAs) at each electrode site in subsequent time windows. This overall analysis was performed in order to licence the following detailed ERP analysis which will be exclusively based on pairwise comparisons between sentence types. Since this bears the problem of multiple comparisons, only time windows showing significant overall effects will be considered in further analyses. The overall RANOVA revealed no significant effect in the N1 time range between 80 and 150 ms (maximum at AF7 $F[5,75] = 1.4$, $P = 0.26$, $\epsilon = 0.53$). Between 150 and 300 ms significant effects appear at left frontal-central sites with a maximum at FC1 ($F[5,75] = 3.25$, $P = 0.028$, $\epsilon = 0.64$). In the following 300–500 ms time window significant overall effects occur around central electrode sites with maximum at Cz ($F[5,75] = 3.16$, $P = 0.02$, $\epsilon = 0.75$). Between 500 and 700 ms significant overall effects appear broadly distributed with a maximum at right temporal sites (T8: $F[5,75] = 5.047$, $P = 0.003$, $\epsilon = 0.7$). In the subsequent time windows (700–900 and 1000–1500 ms) no significant overall effect appeared. Hence, the latter two time windows, as well as the time range between 80 and 150 ms, will not be considered further on. For the remaining presentation of results, any comparison that reached significance in any of the considered time windows will be reported. Comparisons that are not reported have been computed but were not significant.

4.1.1. Ambiguous dative sentences (GP-sentences) versus ungrammatical dative sentences (sentence types (1a) and (3a) versus (2a))

In Fig. 2, ERPs elicited by the clause-final dative verb of GP-sentences ((1a), solid line), ungrammatical sentences ((3a), broken line), and grammatical control sentences ((2a), dotted line) are superimposed. As can be seen, a prominent negative shift starting approximately 300 ms after verb onset becomes apparent in both GP-sentences and ungrammatical sentences in comparison to control sentences. This negative shift appears with comparable amplitude and onset latency in both sentence types and lasts approximately until 500 ms after the onset of the final verb. The corresponding voltage difference maps ((1a) minus (2a) and (3a) minus (2a)) in the 300–500-ms time window (Fig. 3 A,B) show similar central-parietal scalp distributions. In addition, in GP-sentences a right anterior negativity is slightly more prominent than in corresponding ungrammatical sentences. Pairwise RANOVAs for GP-sentences versus control sentences ((1a) versus (2a)) and ungrammatical versus control sentences ((3a) versus (2a)) in the 300–500-ms time window revealed significant statistical effects at central, parietal, and frontal electrode sites. For both GP-sentences and ungrammatical sentences, maximum statistical effects appeared at the central-parietal site CPz (GP-sentences: $F[1,15] = 6.92$, $P = 0.02$, ungrammatical sentences: $F[1,15] = 12.8$, $P = 0.003$).

In contrast to the 300–500-ms time window, ERP responses to GP-sentences and corresponding ungrammati-

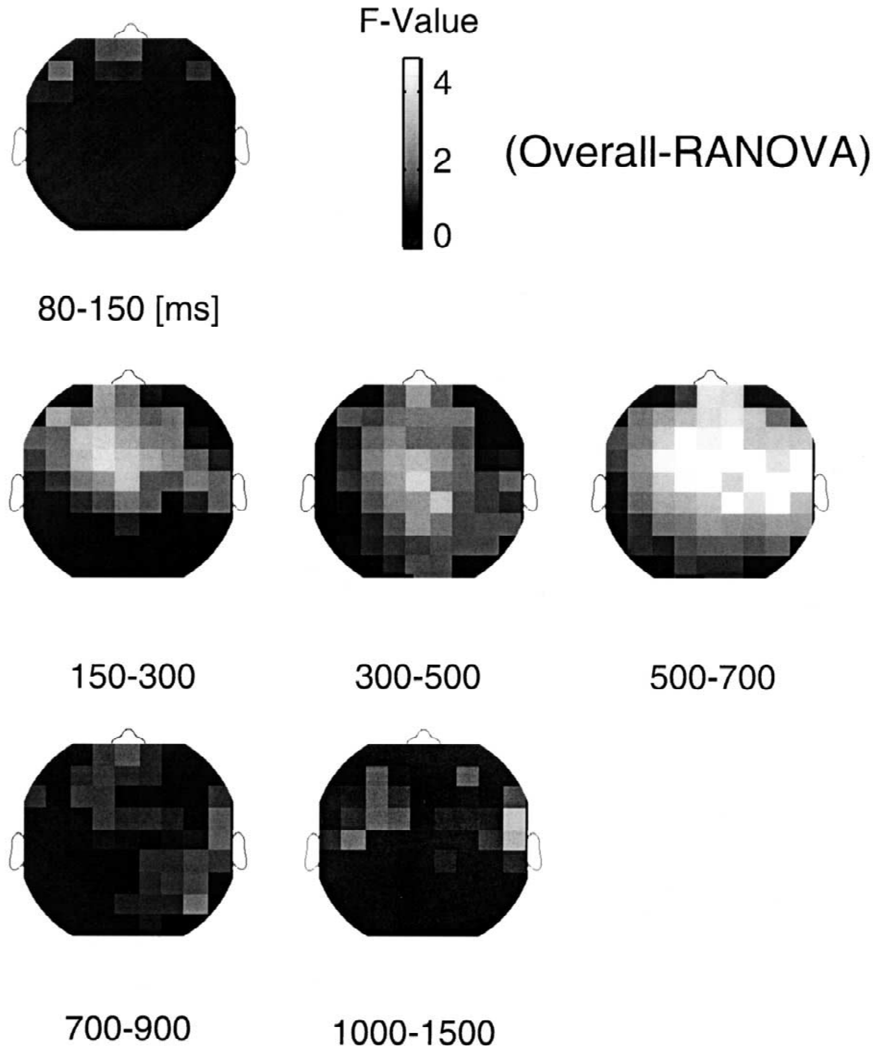

Fig. 1. Topographical maps of F-values derived from overall RANOVAs (six sentence types, $F[5,75]$) at each electrode site to ERPs elicited by the final verb. Squares represent separate electrode sites. White and bright grey indicate scalp regions with significant overall effects.

cal sentences differ in the following 500–700-ms time window.

While the negative shift to GP-sentences disappears over central and right parietal sites (cf. C4), the negativity in ungrammatical sentences continues until roughly 700 ms. Pairwise RANOVAs for this time window show significant effects for ungrammatical versus control sentences with a maximum effect at the right central electrode site C4 ($F[1,15]=23.18$, $P=0.0003$). In GP-sentences significant effects were observed at a frontal-central, slightly left lateralized scalp region with a maximum at electrode site FC1 ($F[1,15]=11.4$, $P=0.005$).

To further characterize the apparent difference between GP-sentences and ungrammatical sentences in this time window, voltage maps of the difference ungrammatical sentences minus GP-sentences ((3a) minus (1a)) were computed. As visible in Fig. 3C, the maximum voltage difference locates to right central-parietal electrode sites. Consistent with this distribution, the respective RANOVA in the 500–700-ms time window revealed a maximum statistical effect at electrode site C6 ($F[1,15]=7.6$, $P=0.016$).

4.1.2. Ambiguous accusative sentences versus ungrammatical accusative sentences (sentence types (1b) and (3b) versus (2b))

Fig. 4 shows ERPs elicited by the clause-final accusative verb of ambiguous sentences ((1b), solid line), ungrammatical sentences ((3b), broken line), and grammatical control sentences ((2b), dotted line). In ungrammatical sentences of type (3b), a clear negative shift of the ERP appears with an onset around 150 ms after the presentation of the final verb. A pairwise RANOVA ((3b) versus (2b)) in the time window between 150 and 300 ms reveals significant statistical effects over left frontal sites with a maximum over electrode F1 ($F[1,15]=10.07$, $P=0.0073$). Although this negativity endures throughout the following time windows, a respective pairwise RANOVA reveals

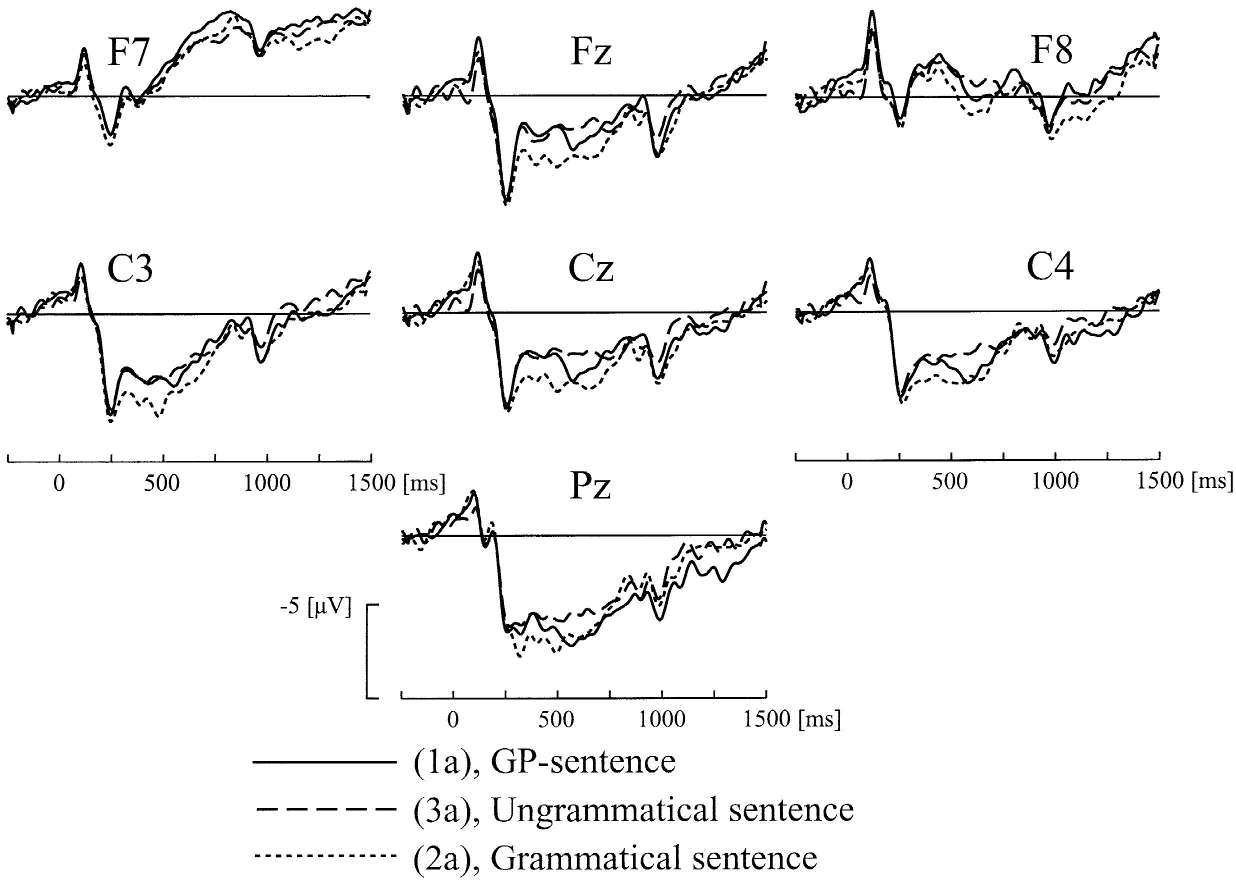

Fig. 2. Average ERP waveforms to final dative verbs of GP-sentences (1a), unambiguous ungrammatical sentences (3a), and grammatical control sentences (2a). The short phasic ERP response around 900 ms represents the offset potential to the disappearance of the final verb.

only marginal significance between 300 and 500 ms (maximum at Cz $F[1,15]=4.2$, $P=0.06$) and no effect between 500 and 700 ms.

A visual inspection of the ERP response to ambiguous sentences and control sentences reveals no substantial effect all along the whole ERP epoch. A related pairwise

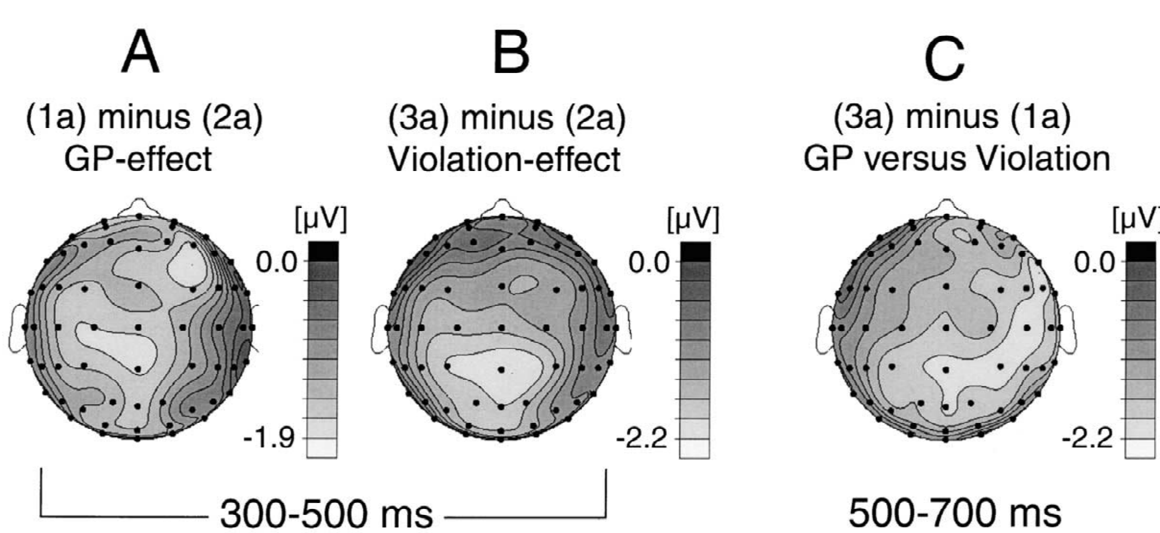

Fig. 3. Topographical voltage difference maps of the GP-effect (A) and the effect of permanent ungrammaticality (B, violation-effect) in the 300–500-ms time window. The scalp distribution of the voltage difference between the permanent ungrammaticality (3a) and the GP-effect (1a) in the 500–700-ms time range is shown in (C).

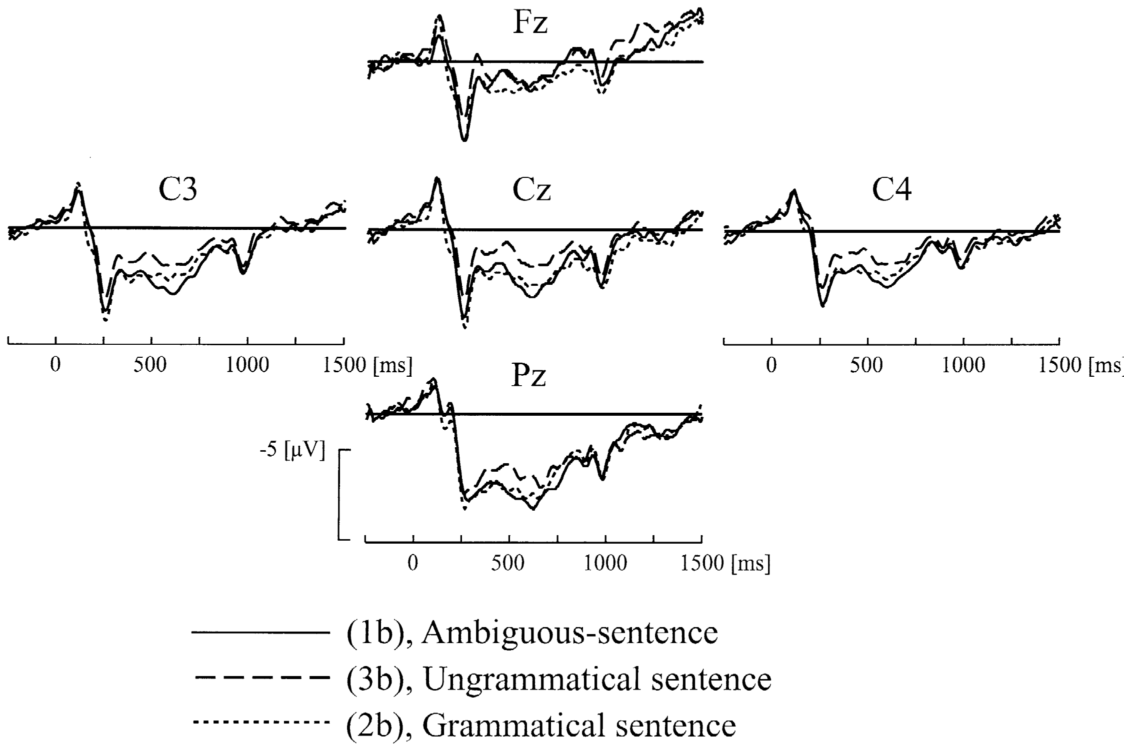

Fig. 4. Average ERP waveforms to the final accusative verbs of ambiguous sentences (1b), unambiguous ungrammatical sentences (3b), and grammatical control sentences (2b).

RANOVA ((1b) versus (2b)) confirms this impression by showing that no significant effect appeared in any time window after 150 ms. Note that the null result of this comparison contrasts with the clear negative shift in ambiguous dative sentences (GP-sentences, (1a) versus (2a)).

4.1.3. Ungrammatical accusative versus ungrammatical dative sentences (sentence types (3a) versus (3b))

As visible in Figs. 2 and 4, both types of ungrammatical sentences ((3a) and (3b)) give rise to prominent negative shifts of the ERP in comparison to their unambiguous grammatical counterparts ((2a) and (2b)). However, a closer look at scalp topography and onset latency reveals significant differences. That is, the negativity in ungrammatical accusative sentences of type (3b) starts already around 150 ms after verb onset which is approximately 150 ms before the negativity appears in ungrammatical dative sentences (3a). The gray areas in Fig. 5A illustrate this difference in onset latency. Furthermore, the negativity in ungrammatical accusative sentences ((3b) minus (2b)) between 150 and 300 ms displays a maximum over the left frontal scalp (Fig. 5B) which contrasts with the central-parietal distribution of the negativity in ungrammatical dative sentences (cf. Fig. 3B).

4.2. The initial noun: overall analysis

ERPs to initial nouns (Fig. 6) were derived by collapsing over sentences beginning with the same type of noun (N_{amb}, N_{dat}, N_{acc}). As can be seen in Fig. 6, no substantial effect of Case markedness of the initial nouns appears across the whole time range of interest. An overall RANOVA (N_{amb} vs. N_{dat} vs. N_{acc}) confirms the visual impression with only marginal effects in the 300–500-ms time window at electrode POz ($F[2,30]=2.49$, $P=0.101$, $\epsilon=0.97$), and between 1000 and 1500 ms at FC3 ($F[2,30]=3.08$, $P=0.064$, $\epsilon=0.93$). Since no overall effect was found further pairwise comparisons were not considered.

5. Discussion

5.1. Serial versus parallel parsing architecture

In the present paper we focused on evidence from ERP data to address a question that is central to psycholinguistic theories of sentence processing: How does the human sentence parser resolve syntactic ambiguities during reading. Two principal parsing architectures that have been discussed in the literature are the serial and the parallel architecture. The serial architecture proposes that the parser builds just one syntactic analysis without keeping track of any possible alternative interpretations when syntactic ambiguities arise (serial parser). The alternative parallel architecture assumes that the parser computes all possible alternative interpretations on-line, and eventually,

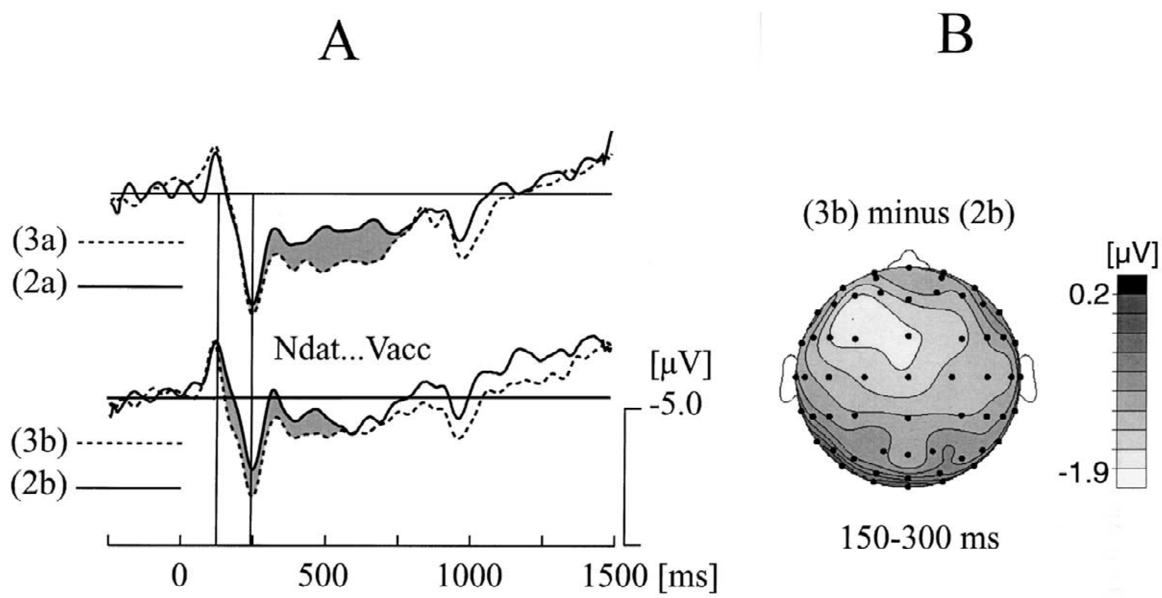

Fig. 5. (A) Average ERP waveforms for the two types of ungrammatical sentences (3a, 3b) and their related control sentences (2a, 2b) at a frontal electrode site (Fz). The ERP difference related to the ungrammaticality is illustrated by shaded areas. Vertical lines mark the difference in onset latency between both effects. (B) Topographical distribution of the voltage difference between (3b) and (2b) in the 150–300-ms time window.

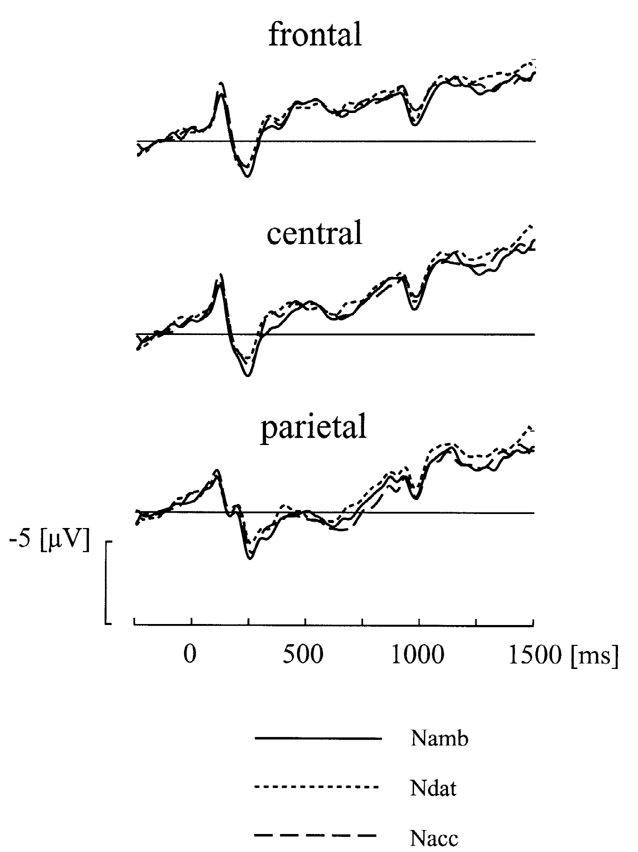

Fig. 6. Average ERPs elicited by the initial nouns. Waveforms for case ambiguous nouns (N_{amb}), dative nouns (N_{dat}), and accusative nouns (N_{acc}) are superimposed. Waveforms are shown collapsed over frontal (F3, F1, Fz, F2, F4), central (C3, C1, Cz, C2, C4), and parietal (P3, P1, Pz, P2, P4) electrode sites. The short phasic ERP response around 900 ms represents the offset potential to the disappearance of the noun.

ranks alternatives into more or less preferred syntactic analyses (parallel parser).

To summarize first, the results of the present ERP study clearly support a serial architecture of the parser and contradict predictions of a parallel parser for several reasons.

First, a prominent negative shift appeared in ambiguous sentences of type (1a) whose final verb required a dative object interpretation of the initial NP, while ERPs to final verbs that required an accusative object interpretation of the same ambiguous sentences (1b) remained indistinguishable from their unambiguous counterparts in (2b). In addition, ERPs elicited by case ambiguous initial NPs (1a,1b) and unambiguous initial NPs (2a, 3a, and 2b, 3b) did not show significant differences. These findings replicate and extend results of our previous experiment using similar sentence materials [21]. In Hopf et al. [21], we proposed that the only plausible interpretation of this ERP pattern is that the parser is garden-pathed in sentences like (1a) but not (1b) because the parser prefers an accusative object interpretation over a dative object interpretation during first pass reading of the ambiguous initial NP.

Insofar as the mere existence of garden-path effects in syntactic ambiguities is a prima-facie argument in favor of serial parsing, this ERP result provides initial evidence for a serial architecture.

As already pointed out in the introduction, this evidence is not sufficient to rule out parallel architectures. Parsers with a parallel architecture can model the existence of a preferred syntactic analysis by ranking alternative interpretations. Hence, switching to a lower ranked alternative at the point of disambiguation in parallel models and efforts to reparse the sentence in serial models may cause equivalent ERP responses.

To gather more conclusive information to differentiate between parallel and serial architectures we compared ERP responses in GP-sentences of type (1a) and related unambiguous ungrammatical sentences of type (3a) with the following prediction: In a parallel architecture, the parser would know about the presence of a grammatical alternative in GP-sentences and the absence of such alternatives in ungrammatical sentences. This should trigger qualitatively different parsing actions. Hence, ERP responses should immediately differ for both sentences types. In contrast, in a serial architecture sentences (1a) and (3a) should initially trigger similar ERP responses, since the parser would start similar parsing actions until it has determined whether an alternative parse is possible (GP-sentence) or not (ungrammatical sentence).

As our ERP data show, in GP-sentences (1a) and ungrammatical sentences (3a) negative shifts with similar onset—latencies, amplitudes and scalp distributions appear between 300 and 500 ms after the onset of the final verb (Figs. 2 and 3A,B), suggesting that similar parsing actions are triggered in both sentence types. This is consistent with a strictly serial parser but contradicts the predictions of a parallel parser.

The only difference between GP-sentences and ungrammatical sentences pertains to the duration of the negativity at certain scalp sites. In a time window between 500 and 700 ms, the negativity to GP-sentences disappears preferentially at central parietal sites of the right hemisphere, while the negativity to ungrammatical sentences continues until 900 ms (cf. Fig. 3C). In Hopf et al. [21], we discussed the negativity in GP-sentences as reflecting the process of reanalysis after the garden-path. In particular, we hypothesized that the negative shift relates to reaccessing the lexicon in order to check whether the ambiguous initial NP is morphologically compatible with a dative object interpretation. Since the parser will find a grammatical alternative in GP-sentences but not in ungrammatical sentences, the shorter negative shift in garden-path sentences may be related to successful reanalysis leading to the termination of the search for an alternative. In contrast, ungrammatical sentences do not allow successful termination of the search for an alternative, and the longer lasting negative shift may arise due to an exhaustive search for a non-existent alternative.

The contention that the difference between GP-sentences and ungrammatical sentences in the 500–700-ms time interval pertains to the retrieval of lexically based information about Case features of the initial NP is furthermore supported by the scalp topography of this ERP difference in the 500–700-ms time window (cf. Fig. 3C). A clear right parietal distribution of the negative difference wave is revealed. This distributional pattern is reminiscent of the scalp topography of the well known N400 group of negativities, which usually show a central-parietal and, in the visual modality, somewhat right lateralized distribution [25,29]. Considerable evidence indicates that negativities of the N400 type represent signatures of lexical–semantic processing [3,4,19,28] which contrast with other, more anteriorly distributed negativities to the processing of unbounded dependencies, subcategorization violations, or violations of word category expectations [9,11,23,36,41].

Finally, it seems worth discussing potential objections to the interpretations offered here. One could, for example, object that the finding of a N400-like negative shift to the sentence final verb in sentences like (1a) in comparison to (2a) actually reflects differences in the semantic relatedness between the initial NP and the final verb rather than a syntactic relation. However, as outlined in the methods section, the semantic content of the initial NPs within each set of sentences was carefully matched with respect to sentence meaning. Therefore, confounding effects of semantic relatedness are not a plausible account for the present data. This is substantiated by comparing sentences (1b) and (2b). Here, the same difference in initial NPs does not lead to any significant differences of the ERP response to the final verb, which would be expected if semantic relatedness had been a critical factor.

Furthermore, sentences containing syntactic violations may give rise to N400-effects at the final word probably reflecting difficulties of semantic integration [37]. However, as we have noted already in Section 1, this is unlikely given that at least in simple transitive clauses of the kind used in the present study, dative Case can hardly be semantically predicted. For instance, both the verbs *loben* (‘to praise’) and *applaudieren* (‘to applaud’) discharge a beneficiary semantic role (or ‘theta role’) to their object. Nevertheless, the former selects accusative while the latter selects dative Case. Obviously, the Case frame has to be learned with each verb. Additional cross-linguistic support of this view is provided in Ref. [2]. Finally, in the present sentences the ungrammaticality is triggered by the final word proper. That is, syntactically conditioned processing related to the ungrammaticality will be initiated at this point and give rise to specific ERP responses independently of whether processes of sentence-level semantic integration interfere or not.

5.2. Saliency and markedness

As pointed out in the introduction, the initial NPs of our ungrammatical sentences (3a) and (3b) display essential differences in the way their syntactic function (as dative in (3b) or accusative in (3a)) is determined. That is, the dative object in (3b) is unambiguously marked for dative Case by an overt morphological marker (the *-n* in *Musikern*) whereas the accusative object is only negatively defined by the absence of a special morphological marker. Hence, the comparison of both sentence types should inform us about the ERP effects of these differences in morphological markedness because the ungrammaticality in both sentence types arises from a similar, although symmetrical, conflict between syntactic functions of the initial NP.

If we compare the ERP response of the two types of ungrammatical sentences (3a) and (3b) with their grammatical counterparts (2a) and (2b), negative shifts appear in both conditions. However, these negativities differ in onset-latency and scalp topography. As illustrated in Fig. 5A, the negative shift in (3b) appears early, already around 150 ms after the onset of the final verb. Moreover it shows a left anterior topography instead of a central-parietal distribution as in sentences (3a) (cf. Figs. 3A and 5B).

Hence, one may wonder whether this difference in scalp topography can be related to differences of morphological Case marking of the initial NPs. Indeed, there is some evidence supporting this idea. First of all, in experiments in which subjects had to judge the grammaticality of sentences under time pressure (speeded grammaticality judgments), sentences containing a Case violation comparable to the violation in (3b) were recognized as ungrammatical with higher accuracy than sentences comparable to (3a) [1]. Furthermore, various types of morpho-syntactic illformedness give rise to so-called 'Left Anterior Negativities' (LAN) frequently in addition to so-called 'Syntactic Positive Shifts' (SPS) or P600 components. For example, LANs were found in violations of subject–verb number and tense morphology [27,39], pronoun–noun case agreement [5,33,34], and regularization errors of irregular participles [40] and plurals [44] in German. Recently, Coulson et al. [5] report a LAN effect to violations of overt Case marking on pronouns, while violations of subject–verb number agreement led to a more centro-parietal negativity. The authors relate the LAN effect in pronoun Case violations to the larger saliency of this violation in English despite the fact that English appears to be morphologically impoverished in comparison with languages like German. The difference in morphological markedness might also explain the approximately 150 ms earlier onset of the negativity in (3b) (Fig. 5A). The existence of a morphological marker in (3b), but not in (3a), might signal the impossibility of finding a grammatical structure in a more salient way in (3b) than in (3a). This could be explained by assuming that it is sufficient for the parser to simply check the morphological marker of the initial NP (the *-n* in *Musikern*) to rule out (3b), but it will take a deeper lexical search to discard ex negativo sentences like (3a) where no marker of morphological case exists.

Evidence has been provided that LAN might also relate to working memory demands like storage and retrieval of filler items in filler-gap constructions [23] or the processing of object-relative sentences in comparison to less demanding subject-relative sentences [22,32]. Such a working memory account is not directly compatible with the assumption that LAN, in particular the 'left-anteriorness', relates to the saliency of the processing difficulty. However, a dissociation into two separate LAN-effects has recently been proposed, with a slow potential LAN reflecting increased verbal working memory load and a more phasic LAN related to morpho-syntactic illformedness [24].

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