Available online at www.sciencedirect.com
ScienceDirect
Brain and Language 100 (2007) 301–316
Brain and Language
www.elsevier.com/locate/b&l

Brain responses to filled gaps

Arild Hestvik [a,*], Nathan Maxfield [b], Richard G. Schwartz [a], Valerie Shafer [a]

[a] *Ph.D. Program in Speech and Hearing Sciences, The Graduate Center, 365 Fifth Avenue, City University of New York, NY 10016, USA*
[b] *Department of Communication Sciences and Disorders, University of South Florida, USA*

Accepted 25 July 2006
Available online 12 September 2006

Abstract

An unresolved issue in the study of sentence comprehension is whether the process of gap-filling is mediated by the construction of empty categories (traces), or whether the parser relates fillers directly to the associated verb's argument structure. We conducted an event-related potentials (ERP) study that used the violation paradigm to examine the time course and spatial distribution of brain responses to ungrammatically filled gaps. The results indicate that the earliest brain response to the violation is an early left anterior negativity (eLAN). This ERP indexes an early phase of pure syntactic structure building, temporally preceding ERPs that reflect semantic integration and argument structure satisfaction. The finding is interpreted as evidence that gap-filling is mediated by structurally predicted empty categories, rather than directly by argument structure operations.

Keywords: Event-related potentials; LAN; ELAN; Sentence comprehension; Gap-filling; Filled-gap effect; Long-distance dependencies; Empty categories

1. Introduction

1.1. Background

A central property of natural language syntax is the *displacement property* (Hauser, Chomsky, & Fitch, 2002), whereby a word or phrase occurs in a syntactic position that is different from the position which determines its basic semantic role. This is illustrated by the relative clause construction (1b), where *the zebra* has been displaced from the object position of *kissed* in (1a):

(1) a. [The hippo kissed the zebra on the nose] and then ran far away.
b. [The zebra that the hippo kissed on the nose] ran far away.

Generative linguistic theory (Chomsky, 1981, 1995) models the displacement property by a transformation that moves the object to a higher syntactic position, leaving a silent copy in the original object position (a "trace" or a "gap"). This ensures that the displaced phrase is interpreted as the object of the verb, just as a non-displaced phrase would be. Alternatively, other theories model displacement without the use of syntactically represented traces. Generalized Phrase Structure Grammar (Pollard & Sag, 1993; Sag & Fodor, 1995) relies on feature transmission in trace-less syntactic representations, and Lexical-Functional Grammar (Bresnan, 2001) encodes the relationship at a functional, non-syntactic level of representation. In this article, we present experimental results that have a bearing on whether displacement should be modeled by a syntactically present trace or not. The premise is that the representations postulated by linguistic theories can be viewed as being constructed in real time by psycholinguistic processing mechanisms, and that consequently, empirical findings about processing can be used to decide between theories of representation. We next review how the two theoretical approaches to displacement find their correlates in two alternative processing models, and how electrophysiological measures can be used to differentiate between the theories.

* Corresponding author. Fax: +1 212 817 1537.
E-mail address: ahestvik@gc.cuny.edu (A. Hestvik).

0093-934X/$ - see front matter © 2006 Elsevier Inc. All rights reserved.
doi:10.1016/j.bandl.2006.07.007

In psycholinguistics, the problem of reconstructing the filler's semantic role is known as "gap-filling", and can be characterized as follows: After a phrase has been identified as a filler, it must be kept in working memory until a verb is found that it can be related to. In (1b), no noun phrase follows *kissed*, which suggests that an object is missing in this position. At this point in time, the filler can be identified as the object of the verb *kissed* and integrated with the verb's argument structure. Evidence for this dynamic process of storage and reintegration has come from studies which show that the semantic information associated with the filler is "reactivated" at the gap position (Bever & McElree, 1986; Nicol, Fodor, & Swinney, 1994; Shapiro, Swinney, & Borsky, 1998; Swinney, Ford, & Bresnan, 1989; Swinney & Osterhout, 1990; Swinney & Zurif, 1995). Reactivation has been taken as evidence that the parser constructs a mentally represented trace (Clifton & Frazier, 1989), but the effect is also consistent with a model where the filler associates directly with the verb's argument structure (Pickering, 1993; Pickering & Barry, 1991; Sag & Fodor, 1995; Traxler & Pickering, 1996). According to these authors, gap-filling involves identifying a verb and associating the filler directly with an unsaturated position in the argument structure of the verb, obviating the need for a trace. In these accounts, the reactivation effect comes from the processing of the verb itself.

Some authors have argued against direct association by demonstrating that antecedents are reactivated in trace positions that are non-adjacent to the verb. For example, reactivation has been reported for pre-verbal object gaps in verb-final languages (Clahsen & Featherston, 1999; Nakano, Felser, & Clahsen, 2002), as well as for post-verbal but non-adjacent object positions in English (Roberts, Marinis, Felser, & Clahsen, in press). However, Phillips and Wagers (in press) counter that this argument is inconsistent with look-ahead effects in parsing (Crocker, 1996; Gibson & Hickok, 1993), where a verb position is constructed in advance of the verb itself. If so, the argument goes, direct association could be made to account for these results as well.

Another source of evidence that could distinguish between direct association and the trace model comes from the *active filler* strategy (Frazier & Clifton, 1995; Frazier & Fodor, 1978). This strategy entails that the parser continuously makes guesses about which structure to build next as each new word is perceived. In the context of gap-filling, the parser's eagerness to complete long-distance dependencies then sometimes leads it to posit gaps prematurely, which in turn leads to "surprise" effects and reanalysis when the error is discovered (Clifton & Frazier, 1986, 1989; Crain & Fodor, 1985; Frazier & Flores d'Arcais, 1989; Stowe, 1986; Stowe, Tanenhaus, & Carlson, 1991). For example, Clifton and Frazier (1989) observed longer reading times after *to his fiancée* in sentences such as (2b) compared with (2a) (***t*** denotes the gap position):

(2) a. What$_i$ did the cautious old man whisper $\mathbf{t}_i$ to his fiancée during the movie last night?
b. What$_i$ did the cautious old man whisper ($\mathbf{t}_i$) to his fiancée about $\mathbf{t}_i$ during the movie last night?

Their explanation is that the parser initially posits a trace after *whisper* in both cases. This will eventually be correct in (2a). However, when encountering *about* in (2b), the analysis must be revised, because the parser now realizes that the verb is the intransitive version of *whisper*, followed not by a trace but by the PP *to his fiancée*. The increased reading time at *about* is interpreted as a reflection of this revision. However, Phillips and Wagers (in press) argue that this effect is also consistent with the direct association hypothesis. They suggested that the effect could be caused by the parser first associating the filler with the argument structure of a transitive version of *whisper*. Once *about* is encountered, the verb is reanalyzed as intransitive, and a new search is initiated for an argument taker with which to associate the filler. Phillips and Wagers (in press) conclude that neither antecedent reactivation nor the filled-gap effect provide clear evidence for syntactic traces during processing, and that what is missing from previous research is a clear timing prediction that distinguishes between direct association and the trace model.

1.2. Electrophysiology and the time course of sentence processing

We suggest that this kind of timing prediction is provided by the neurophysiological time course model of syntactic parsing developed by Friederici and her colleagues (Friederici, 1995, 2002; Friederici, Hahne, & Mecklinger, 1996, 1998). Friederici's model claims that sentence comprehension proceeds through several distinct phases in time, where each phase is related to different aspects of processing. Violations during each phase can be measured and associated with distinct "signature" event-related potentials (ERPs). In particular, early syntactic structure building processes take place during the 100–200 ms time region after phonetic analysis. Violations of word category expectations and phrase structure rules during this phase are associated with an early left anterior negativity (eLAN) with a peak latency around 150 ms (Friederici et al., 1996). During the next phase, the 300–500 ms time range, processes of argument structure satisfaction and semantic role assignment take place, as well as morphosyntactic agreement processes. Violations during this phase result in a centro-parietal negativity, the N400 (Kutas & Hillyard, 1980) for argument structure violations, and a left anterior negativity (LAN) for morphosyntactic agreement violations (Friederici, Pfeifer, & Hahne, 1993, 1996). Finally, a third late phase is for processes of reanalysis and repair. The ERP associated with this stage is the P600, a large amplitude posterior positivity in the 500–700 ms range. The P600 appears to index phrase structure assignment errors and subsequent reanalysis in garden path sentences (Hagoort & Brown, 2000; Hagoort, Brown, & Groothusen, 1993; Kaan, Harris, Gibson, & Holcomb, 2000; Osterhout & Holcomb, 1992, 1993), as well as integration of a displaced phrase with the verb to which it is related (Felser, Clahsen, & Münte, 2003; Kaan et al., 2000).

Friederici's model can be mapped to specific predictions about the temporal and spatial nature of evoked potentials during violations of gap-filling, because of the way it associates distinct temporo-spatial ERPs with distinct types of parsing operations. Specifically, predictions can be derived from the model that can differentiate between direct association and trace construction.

1.3. The current study: Ungrammatical gap filling

We developed such a timing prediction by using a variation of the filled gap paradigm, by examining ERP responses to ungrammatically filled gaps, as in (3):

(3) [The zebra that the hippo kissed <u>the camel</u> on the nose] ran far away.

Under the trace theory, the construction of an empty category is part of phrase structure building operations, because an empty category is exactly like any other syntactic category except it is missing phonetic content. After analyzing the filler *the zebra* and the words up to and including *kissed*, the parser will hypothesize and build a trace immediately after the verb, and will therefore expect a structure following the verb that is consistent with this hypothesis. Subsequently, the parser reaches the NP *the camel*. This NP can only be analyzed as an object, but an object is highly unexpected in this position because the direct object position has already been occupied by the trace. The result is a violation of word category expectations. Such violations, arising from phrase structure knowledge, should consequently result in an eLAN response in Friederici's model.

Alternatively, under the direct association hypothesis, *the zebra* is integrated directly into the argument structure of the verb *kissed* as soon as the verb is encountered. Subsequently, *the camel* is encountered. At this point, there is no phrase structure violation per se, because the extra object NP fits in with allowable phrase structure rules for VP. During Phase 2, when argument structure satisfaction takes place, *the camel* cannot be assigned a theta-role, because the verb has already assigned it to the filler. In other words, the extraneous NP cannot be integrated into an argument structure, which should result in a violation of the Theta-criterion (Chomsky, 1981), which requires a one-to-one mapping between each semantic role and each syntactically present NP. The predicted electrophysiological response should be an ERP in the time range that Friederici's model associates with argument structure operations (i.e., LAN and/or N400 the 300–500 ms range). In fact, in a recent study, Frisch, Hahne, and Friederici (2004) argues specifically that argument structure violations are distinguished from word category violations by an N400. In other words, the trace model predicts an eLAN at the ungrammatically filled gap in (3), whereas direct association predicts a LAN and/or an N400.

It is important to note that the prediction of an eLAN under the trace model does not preclude the existence of subsequent ERPs. An incorrectly filled gap would result in a cascade of violations presumably having ERP effects at each of the three phases. For example, if a gap is prematurely filled, a second, "real" object NP would violate both phrase structure rules as well as argument structure constraints. It would therefore be consistent with the trace hypothesis to first observe an eLAN (reflecting the early stage filled gap effect), followed by an N400 or LAN (reflecting subsequent argument structure satisfaction problems), and possibly a P600 as a result of reanalysis and the search for a new analysis. The crucial question we are concerned with here is the temporal order of these language-related ERPs. If the earliest ERP to a filled gap is an N400 or a LAN, the conclusion would be that the extra NP simply causes an argument structure violation. If the earliest ERP is an eLAN, the conclusion would be that the filled-gap effect is caused by the parser trying to fit two NP arguments into a structure where only one is allowed, leading to a phrase structure violation.

2. Method

2.1. Participants

Twenty-four adults were recruited for the study and were reimbursed $10 per hour for participation. All subjects signed an informed consent form and filled out a self-report form on language, education, and health background. Four subjects were later excluded because of a history of head trauma, anti-depressant medication, recording difficulties or task non-compliance. Of the remaining 20 subjects, 11 were men and 9 were women (mean age 27 years, range 21–49 years). Two men were left handed. All subjects reported normal or corrected-to-normal vision, normal hearing and English as their first and native language.

2.2. Design

The filled gap condition (which we label *Ungrammatical Object*, abbreviated as *Ungramm* in figures) was constituted by sentences like (4a), where a relative clause in the subject position of a clause contained an ungrammatically filled object position. As a control condition for the Ungrammatical Object, we constructed a new sentence type (4b) by inserting a verb after the first noun, effectively turning the underlined substring in (4a) below into a grammatical sequence; this is the *Grammatical Object* control condition (abbreviated as *Object*):

(4) a. The zebra that the hippo kissed <u>the camel</u> on the nose ran far away.

b. The zebra said that the hippo kissed the camel on the nose and then ran far away.

Thus, *the camel* is expected as an object in (4b), but the same string is unexpected and ungrammatical in (4a).

The comparison between (4a) and (4b) is complicated by another ERP effect that might be independently elicited in (4a). Previous studies of gap-filling have focused on ERPs elicited by material intervening between the filler and the gap. These studies have observed a sustained anterior negativity between the filler and the gap in comparison with control structures (Fiebach, Schlesewsky, & Friederici, 2001, 2002; King & Kutas, 1995; Kluender & Kutas, 1993; Phillips, Kazanina, & Abada, 2005). This effect has been labeled "long negativity," and has been interpreted as reflecting the processing cost of keeping a filler in working memory over time. Long negativity would presumably be elicited by (4a), but not by (4b) (because a filler is not held in working memory in (4b)), and a negativity observed at the ungrammatically filled gap could therefore not be separated from long negativity. For this reason, we added a second control condition to determine whether long negativity interfered with our primary comparison. This control condition (labeled *Grammatical Trace*, abbreviated as *Trace*) is simply the grammatical version of the Ungrammatical Object sentences, constructed by replacing the filled gap (5a) with a grammatical gap (5b):

(5) a. The zebra that the hippo kissed the camel on the nose ran far away.
b. The zebra that the hippo kissed *t* on the nose ran far away.

By comparing ERPs at the offset of the verb in both cases, we can determine whether there is a residual of long negativity that differentiates the two conditions, and specifically, whether the Ungrammatical Object sentences elicit negativity over and beyond any long negativity observed at the Grammatical Trace. Inclusion of this condition also prevented subjects from associating every relative clause with ungrammaticality.

Note that the comparison between (5a) and (5b) will be based on processing of heterogeneous lexical items (e.g., *the camel on nose* vs. *on the nose*). This raises the question of whether the determiner–noun combination in (5a) independently elicits a negativity, in comparison to preposition–determiner–noun combinations. Some studies have reported that closed class words elicit different ERPs than open class words (Neville, Mills, & Lawson, 1992; Pulvermuller, Lutzenberger, & Birbaumer, 1995), although other studies have reported no differences across classes (Münte et al., 2001; Osterhout, Bersick, & McKinnon, 1997). Irrespectively, both articles and the prepositions in the current stimuli are closed class or functional categories, and we have no evidence that these lexical differences should yield independent ERP differences.

2.3. Materials

A set of 64 sentence triplets were constructed. Each triplet consisted of a sentence in the Ungrammatical Object condition and the two control conditions Grammatical Object and Grammatical Trace. The Grammatical Trace sentences were adapted from (Love, in press; Love & Swinney, 1997). Thirty-two unique verbs associated with the critical position of a trace/object were used, as well as 32 unique sets of animal nouns. Each verb was used twice, but with different animal noun sets, as shown in (6):

(6) a. The camel that the rhino kissed on the nose ran far away.
b. The zebra that the hippo kissed on the nose ran far away.

The resulting set of 64 triplets was divided into two lists so that no animal names were repeated in one list (but a verb was used twice within a list). Each list was then divided into three sub-lists, based on experimental condition. Each of the three sub-lists had 32 stimuli, resulting in a total of $6 \times 32 = 192$ trials. In addition, a set of 37 filler sentences were added. The fillers consisted of 15 declaratives and 21 relative clauses. The filler sentences were included both to increase the percentage of grammatically correct sentences, as well as to lower the predictability of the experimental condition sentences. The sentences were digitally recorded by a female speaker. Particular care was taken to ensure that there were no intonation cues differentiating the sentences across conditions, by pronouncing every sentence within a triplet with identical intonation structures in the region spanning the embedded verb and the following material, so that prosodic properties did not indicate presence or absence of trace. A written comprehension question was constructed for each sentence. Half the comprehension questions were Yes/No questions, counterbalanced for correct yes/no answer, and half were Wh-questions about one of the participants in the sentence. The questions for the ungrammatical sentences were related to the part of the sentence preceding the point of ungrammaticality.

2.4. Procedure

Subjects were seated in a comfortable chair in a sound- and electrically shielded booth, and participated in two consecutive sessions, each lasting approximately one hour. The sentence stimuli were presented over speakers. Subjects were instructed to try to not blink during the auditory presentation of the sentence. The stimulus presentation and behavioral response collection was controlled by a PC with E-Prime software and a Serial Response Box from Psychology Software Tools (Schneider, Eschman, & Zuccolotto, 2002).

One of the two main lists of experimental stimuli was presented in each of the two sessions. The order of the two lists was counterbalanced across subjects. Each session was further divided into three blocks of 70 trials. The first 6 trials in a block were always filler sentences. Subsequent to this, 32 experimental trials were randomly drawn from each of the three condition sub-lists in a given session list, as well as 32 filler items. Alternation of filler versus test item was also randomized, and filler sentences were repeated. This resulted in a total of 420 trials per subject.

Subjects were not told in advance that some sentences would be ungrammatical, but simply to listen for content in order to answer comprehension questions. A random 2/3 of the trials in each session were selected for a comprehension question, presented in written form on a computer screen. Subjects responded with button presses within 5 s, and accuracy feedback was provided after each question, as well as the cumulative accuracy. A single trial proceeded as follows: First, a cross appeared on the center of the computer screen 1000 ms before onset of the sentence and remained there during the auditory presentation of the sentence. Following the sentence presentation, the question would appear; if no comprehension question was selected, a 2 s pause ensued before the next trial.

2.4.1. Data acquisition

EEG data was collected using an Electrical Geodesics 200 system, with a 65 channel Geodesic Sensor Net with silver/silver-chloride (Ag/AgCL) plated electrodes contained in electrolyte-wetted sponges. One electrode was placed under each eye to monitor eye movements and eye blinks. EEG was continuously recorded with a sampling rate of 200 Hz, referenced to Cz. Electrode impedances were kept below 60 kΩ, which is acceptable for high impedance amplifiers (Ferree, Luu, Russell, & Tucker, 2001). EEG was amplified using a hardware band-pass filter (0.1–41.3 Hz) and digitized using 12 bits. After recording, the continuous EEG was segmented into 1000 ms epochs, using a 100 ms pre-stimulus baseline and a 900 ms segment time. ERPs were time-locked to the onset of the first word following the relative clause verb (i.e. "the camel" in (4a,b) and "on the nose" in (5b)). The 100 ms pre-stimulus period included the end of the verb and the silence between the verb offset and the following word.

2.4.2. Artifact decontamination

The 192 experimental trials per subject were then submitted to artifact decontamination procedures. Using *Netstation* software, a channel in a single recording was marked as a bad channel if the fast average amplitude exceeded 200 μV; if the differential amplitude exceeded 100 μV; or if it had zero variance. A channel was considered to be a bad channel in *all* trials if it was a bad channel in 20% of trials. A trial was excluded if it contained more than 10 bad channels, or if it contained lateral eye movements resulting in amplitudes greater than ±70 μV. Bad channels were deleted and replaced with data using the spherical spline interpolation, as long as they were surrounded by channels with good data. The data were then submitted to a procedure which performed Independent Component Analysis (Bell & Sejnowski, 1995; Glass et al., 2004) and automatically subtracted eye blink components that correlated at $r = 0.9$ with an eye blink template (Dien, 2004). This step also baseline corrected the data based on the 100 ms pre-stimulus period. After this procedure, no subject had more than 8% of trials lost due to eye-blink activity. An average of the remaining trials per condition was then computed for each subject's remaining data, and referenced to the average voltage.

2.4.3. Statistical analysis procedures

High density recordings require that the electrode factor be reduced in dimensionality before analysis and interpretation. For repeated measures ANOVAs, we followed the recommendations in Dien and Santuzzi (2005) and grouped electrodes on the basis of ANTERIORITY (anterior vs. posterior electrodes), LATERALITY (left vs. right hemisphere, excluding the midline electrodes), and DORSALITY (inferior vs. superior electrodes). Fig. 1 shows the resulting eight electrode sets for the 64 electrodes used in the recording (see Luu & Ferree (2000) for the correspondence between electrode placements and the International 10-10 system).

Mean amplitudes were computed for 100 ms time windows in each of the eight electrode regions (cf. Section 2.4.3) and three conditions per subject, and the resulting means were used as dependent measures in repeated measures ANOVAs. For all analyses involving factors with more than two levels, we report *p*-values based on ε-adjusted degrees of freedom (Greenhouse & Geisser, 1959) along with the original *F*-values. Interactions between the experimental conditions and temporal and/or spatial factors were followed up by planned orthogonal contrast analyses when

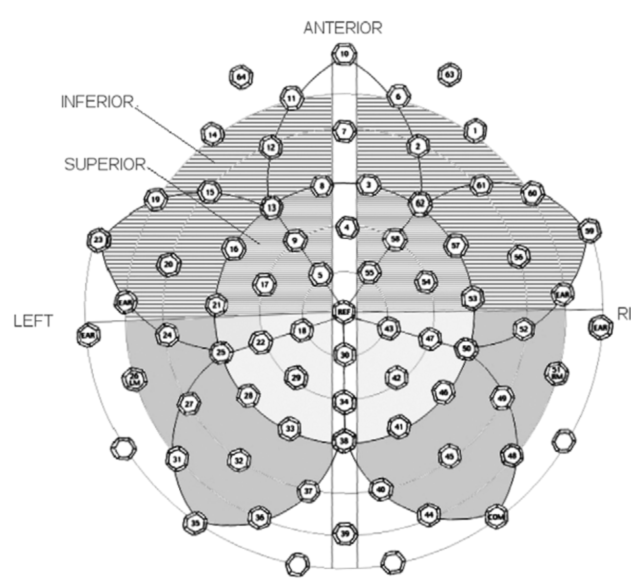

Fig. 1. Layout of Electrical Geodesics 64 channel electrode net. The eight shaded regions indicate averaged electrodes. For example, left anterior inferior region = 11, 12, 14, 15, 19, 20, 23; left anterior superior region = 5, 8, 9, 13, 16, 17, 21.

we had predictions about differences between conditions. All reported t-statistics use 19 degrees of freedom, and reported p-values are based on two-tailed probabilities.

Averaging over electrode regions relates the current findings to the analysis practice of the previous literature, which has mostly been based on lower-dimensionality EEG recordings. However, the use of predefined symmetrical scalp regions may lead to inaccurate modeling of the physical distribution of the ERP variance, and also "undoes" the high spatial resolution obtained with high-density electrode recordings. Similarly, mean amplitudes of pre-defined time regions lose some of the fine temporal grain inherent in EEG recordings. To sharpen the description of the spatial and temporal properties of the observed ERPs, we followed up the average-based analysis with a Principal Component Analysis (PCA) (Dien, 1998; Dien & Frishkoff, 2005; Dien, Frishkoff, Cerbone, & Tucker, 2003; Dien, Spencer, & Donchin, 2003, 2004, 2005; Spencer, Dien, & Donchin, 1999, 2001). PCA makes full use of the increased spatial resolution afforded by the high-density recordings and can provide a more objective and precise description of the spatial and temporal distribution of ERPs. According to (Dien & Frishkoff, 2005), spatial PCA should be used if the focus of analysis is on the time-course of ERPs, whereas temporal PCA should be used if topographic analysis of ERPs is the goal; furthermore, temporal PCA is in principle more accurate than a spatial PCA. We here followed the approach of first conducting a temporal PCA, followed by further spatial decomposition of latent topographical factors within each temporal factor. This method is termed sequential or temporo-spatial PCA (Dien & Frishkoff, 2005; Spencer et al., 1999, Spencer, Dien, & Donchin, 2001). All PCA analyses were carried out using *MatLab* software (Dien, 2005; Frank, 2005).

A general problem in PCA analysis concerns how many factors to retain. Rather than relying on the visual scree test (Cattell, 1966), we used a combination of Rule N (a version of the parallel test, (Dien, 1998)), Rule A4 (Preisendorfer & Mobley, 1988), and North's rule (North, Bell, Cahalan, & Moeng, 1982). The factors were then rotated using the covariance matrix (without Kaiser normalization) to simple structure, using PROMAX ($k = 3$) (Hendrickson & White, 1964; Richman, 1986; Tataryn, Wood, & Gorsuch, 1999).

The time-course of a given ERP may be defined by the rotated loadings (or weights) associated with a specific temporal factor, whereas the scalp topography of that same ERP may be defined by the rotated loadings associated with a specific spatial factor. The rotated loadings associated with a specific temporal factor define the extent to which a specific ERP activation was registered at particular time points (e.g., with higher loadings indicating stronger registration). Likewise, the rotated loadings associated with a specific spatial factor define the extent to which a specific ERP activation was registered at particular electrodes. Filtering the raw data by the weights associated with a specific temporal factor, and then by the weights associated with a specific spatial factor, results in a set of factor scores for each subject and experimental condition, which summarize the ERP variance associated with that time window and scalp region. These scores were used as dependent measures in repeated measures ANOVAs, for analyzing condition effects in the PCA components (Dien & Frishkoff, 2005; Spencer et al., 2001).

3. Results

3.1. Comprehension questions

Subjects responded to comprehension questions on 2/3 of the 420 trials, and roughly half of these trials were filler sentences. For the remaining 180 experimental trials with comprehension questions, each subject responded to an average of 42 of the 64 trials in each condition. The mean accuracy was 78% for Grammatical Object sentences, 73% for Grammatical Trace sentences, and 63% for Ungrammatical Object sentences. A one-way ANOVA with three levels of experimental conditions revealed a main effect of condition ($F(2,38) = 13.7$, $p < .0001$). Bonferroni-protected pairwise comparisons ($\text{MSE} = .00865$, $\text{df} = 38$) showed that this was due to Ungrammatical Object differing from both Grammatical Object ($p < .0001$) and Grammatical Trace ($p < .001$).

3.2. Time-window and region analysis

Inspection of the grand average waveforms showed that the Ungrammatical Object condition was more negative than control conditions in the 100–400 ms time window in the anterior region. (The reader is referred to Appendix A for a topographical plot of the grand average.) This negativity was most pronounced on the left side but also present frontally and on the right side. The negativity had a corresponding inversion at centro-parietal electrodes. In addition, a late positivity was seen in the posterior region in the 500–800 ms time window, without a corresponding anterior inversion. The statistical significance of these effects was examined with separate analyses for the anterior region during the early time window, and for the posterior region during the late time window.

3.2.1. 0–500 ms in the anterior region

The analysis of the first five 100 ms time windows in the anterior region resulted in a main effect of Condition ($F(2,38) = 4.3$, $\varepsilon = 0.77$, $p = .03$), a Time × Condition interaction ($F(8,152) = 7.33$, $\varepsilon = 0.47$, $p < .001$), and a Time × Condition × Dorsality interaction ($F(8,152) = 2.88$, $\varepsilon = 0.47$, $p = .03$). Planned comparisons showed that the main condition effect was caused by the Ungrammatical Object being more negative than both the Trace ($t = 3.8$, $p = .001$) and the Grammatical Object condition ($t = 2.3$, $p = .032$). The Time × Condition interaction was due to the Ungrammatical Object condition being more negative than both control conditions during the 100–400 ms than during the first and last 100 ms period. The Time × Condition × Dorsality interaction was due to this effect being of greater magnitude at inferior electrodes than superior electrodes, cf. Fig. 2.

Because there was no direct interaction between Condition and Dorsality, and no main effects or interactions involving Laterality, planned comparisons were computed for each time window using the mean amplitudes of the entire anterior region. This showed that the Trace condition and the Ungrammatical Object condition did not differ during the 0–100 ms time window, but differed significantly during the 100–200 ms ($t = 3.0$, $p = .007$), the 200–300 ms ($t = 6.23$, $p < .0001$) and the 300–400 ms ($t = 4.48$, $p = .0002$) time windows. The Ungrammatical Object and the Grammatical Object differed significantly in the 0–100 ms ($t = 2.14$, $p = .045$), 100–200 ms ($t = 4.22$, $p < .001$) and marginally in the 200–300 ms ($t = 2.01$, $p = .058$) time window.

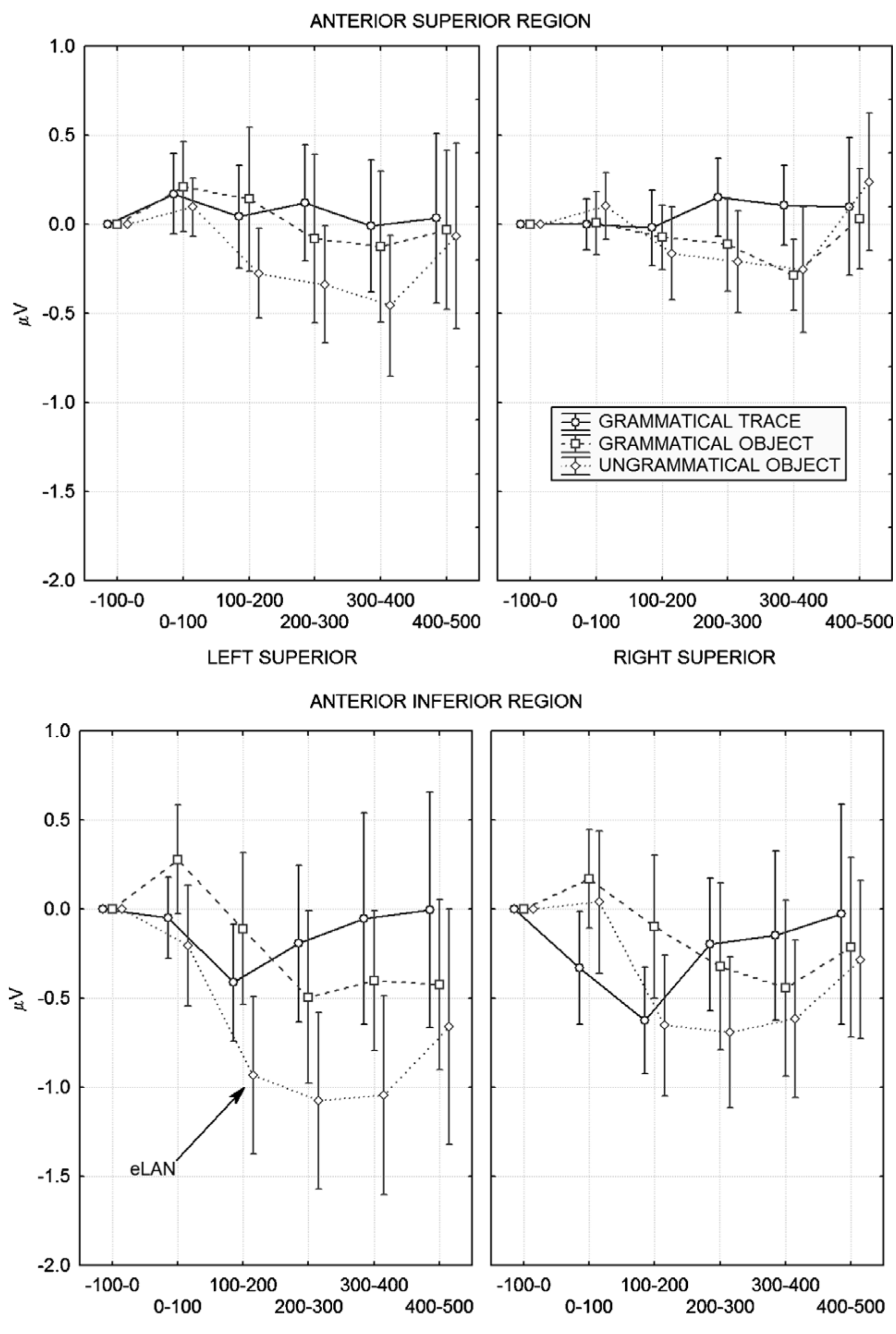

Fig. 2. Mean amplitudes per condition in the four anterior quadrants during the first 500 ms, including baseline period. Error bars indicate 95% confidence intervals for the means.

3.2.2. 500–900 ms in the posterior region

The analysis of the four posterior quadrants (cf. Fig. 3) during the 500–900 ms period resulted in a Time × Condition interaction ($F(6,114) = 3.19$, $\varepsilon = 0.46$, $p = .03$), and a marginally significant Time × Laterality × Dorsality × Condition interaction ($F(6,114) = 2.29$, $\varepsilon = 0.65$, $p = .069$). The Time × Condition interaction was followed up with planned comparisons, which showed that the Ungrammatical Object was significantly more positive than the Trace condition in the 500–600 ms ($t = -2.15$, $p = .04$) and the 600–700 ms time window ($t = -2.13$, $p < .01$), whereas the Ungrammatical and Grammatical Objects did not differ significantly.

The marginally significant four-way interaction involving both spatial factors was due to the Ungrammatical Object being more positive than both control conditions in the right superior quadrant, in comparison to the other three quadrants.

Because we had expectations about a P600 in the centro-parietal region, this interaction could be interpreted with a

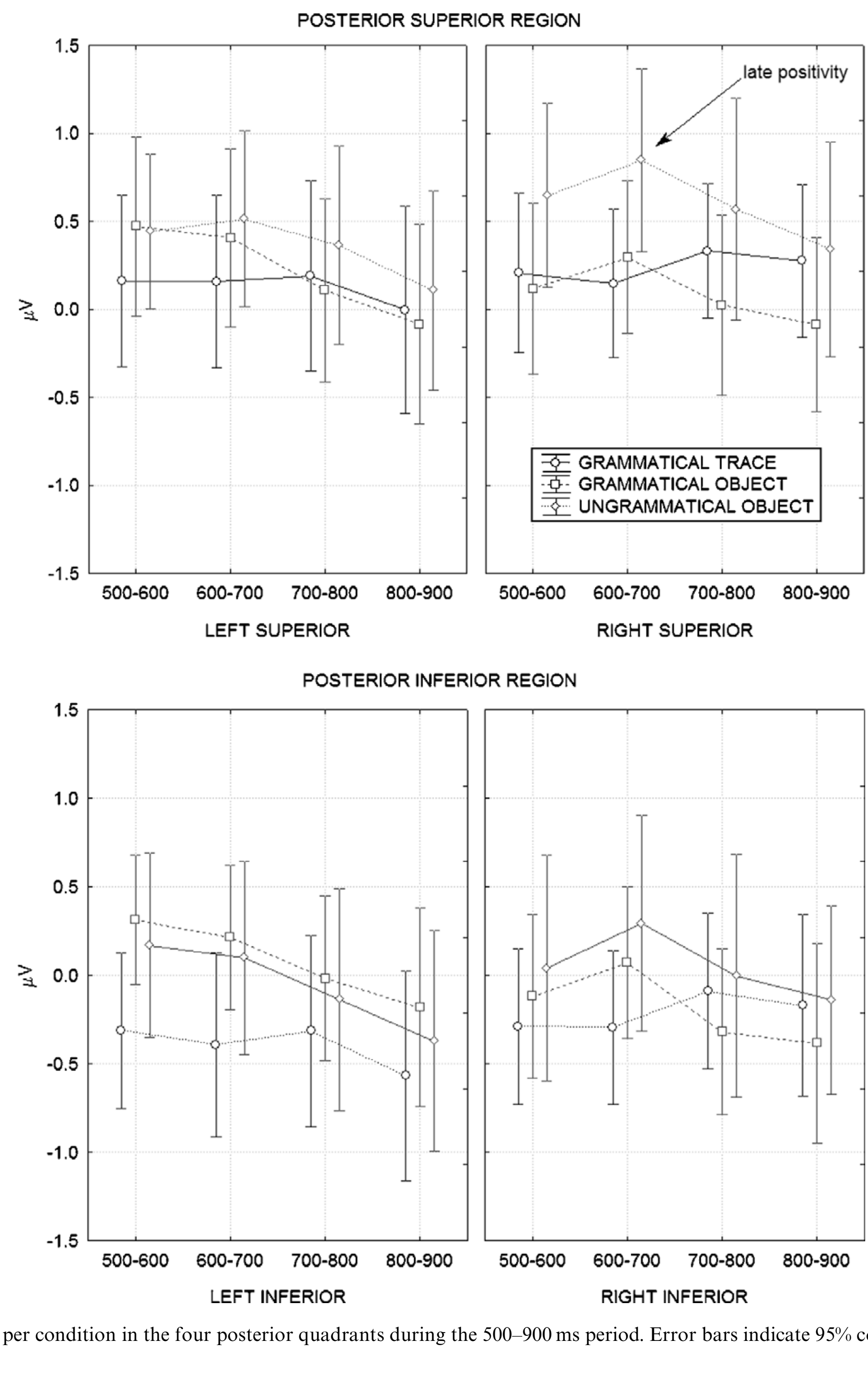

Fig. 3. Mean amplitudes per condition in the four posterior quadrants during the 500–900 ms period. Error bars indicate 95% confidence intervals for the means.

one-tailed probability, and was therefore followed up with planned comparisons. The complex contrast between Ungrammatical Object vs. both control conditions was significant in the 600–700 ms window ($t = -2.09$, $p = .049$); as was the contrast between Ungrammatical Object and Trace in the same time window ($t = -2.43$, $p = .025$). However, the simple contrast between Ungrammatical Object and Grammatical Object could only be interpreted as marginally significant in the 600–700 ms time window with a one-tailed probability ($t = -1.63$, $p = .12$, two-tailed).

3.3. Principal component analysis

We next conducted a temporo-spatial PCA analysis to sharpen the results of the previous analysis. The input to the initial temporal PCA was a data matrix consisting of 200 columns, one for each time point. The rows were 20 subjects × 3 conditions × 65 channels = 3900 cells for each of the 200 time points. The covariance among time points was computed, and the resulting relationship matrix was decomposed using PCA (eigenvalue decomposition). Our rules for factor retention resulted in eight temporal factors. After rotation, the eight factors accounted for 73.6% of the original variance.

Only those factors that have a time-course and topography consistent with previous findings should be interpreted (Kayser & Tenke, 2003; Spencer et al., 1999). Upon inspection of the temporal factor loading patterns, only three factors had clear time courses and peak amplitudes in the same time range as expected ERP components: Temporal factor 2 had high loadings during the 100–400 ms interval (peak latency 220 ms), temporal factor 4 had moderate loadings in the 300–600 ms range (peak latency 425 ms), and temporal factor 6 had the smallest loadings, extending through the 500–700 ms range (peak latency 595 ms). These time courses matched the latencies of the eLAN, the LAN/

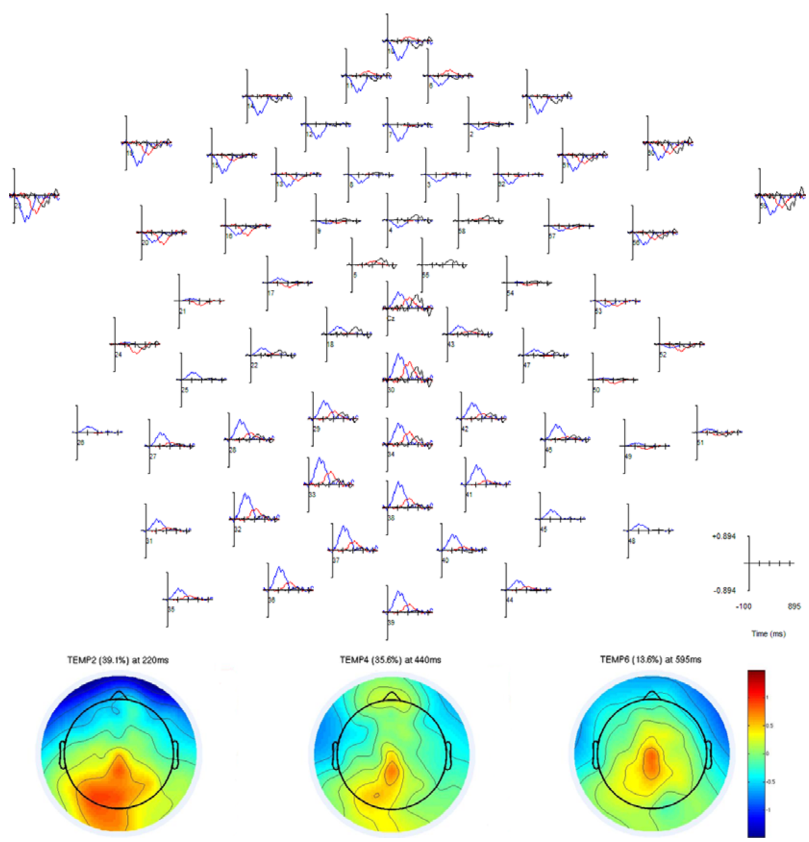

Fig. 4. Upper panel: backprojection into electrode space of temporal factors. Lower panel: topographical map of each factor at their respective peak latencies. Percentages indicate amount of variance accounted for by each factor.

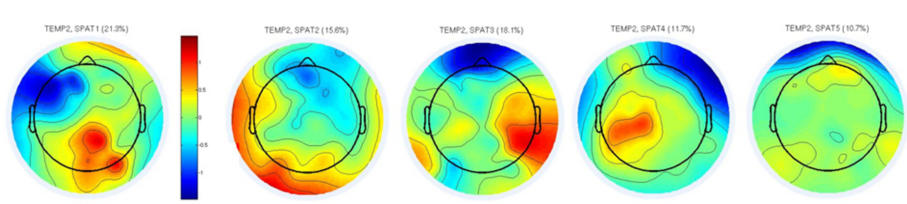

Fig. 5. Back-projection into topographical maps of five spatial factors within temporal factor 2. Percentages indicate amount of variance accounted for by each factor.

N400 and the P600, respectively. Visual inspection of the factor loadings back-projected into electrode space and scaled in microvolts, showed that temporal factor 2 had a consistent pattern of activation across anterior electrodes, with inversion at posterior electrodes. Factors 4 and 6 had a much smaller and less homogeneous pattern of activation, cf. Fig. 4.

The scores for the temporal factors were then submitted to spatial PCA decomposition. Only for temporal factor 2 did this result in temporo-spatial factors with significant condition effects. Temporal factor 2 also had the highest factor loadings, and would therefore be most likely to be replicated in future studies (Gorsuch, 1983). The rest of this discussion is therefore limited to this factor.

The input to the spatial PCA was a data matrix with 65 columns (representing electrodes) and 60 rows (20 subjects × 3 conditions per channel). Five spatial sub-factors were retained according to our rules. After rotation, the 5 spatial factors accounted for 64.5% of the original variance in temporal factor 2 (see Fig. 5 for back-projections into electrode space of the five temporo-spatial factor combinations).

Experimental effects within each of these five temporo-spatial factors were then analyzed by repeated measures ANOVA of each subject's factor score per condition. Only the first two spatial factors showed condition effects. Temporal factor 2, spatial factor 1 contained a statistically significant main effect of Condition ($F(2,38) = 7.99$, $p = .001$). Bonferroni-protected pair-wise comparisons showed that the Ungrammatical Object condition differed from both the Grammatical Trace ($p = .007$) and Grammatical Object ($p = .012$); the two control conditions did not differ from each other. Fig. 6 illustrates the condition effect in the peak electrode for the factor (left anterior inferior electrode #15).

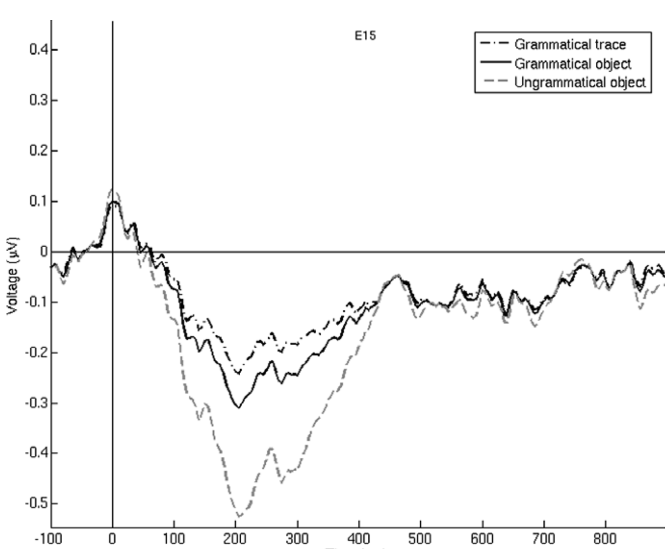

Fig. 6. Condition effects in the peak electrode (channel 15, left anterior inferior region) for Temporal factor 2, spatial factor 1 (eLAN temporo-spatial component).

Temporal factor 2, spatial factor 2 also contained a significant effect of Condition ($F(2,38) = 5.12$, $p = .011$). Bonferroni-protected pair-wise comparisons revealed a statistically significant difference between the Grammatical Trace and the Grammatical Object condition ($p = .001$), such that the Trace condition was more negative at right inferior sites and more positive at left posterior sites.

4. Discussion

4.1. Behavioral data

Subjects had some difficulties with answering comprehension questions, as indicated by the mean accuracy of 75% on the grammatical sentences. This general difficulty was probably due to fact that the sentences were center-embedded, with an object relative clause in the subject of a declarative clause. The lower accuracy in the Ungrammatical Object condition is likely due to the fact that it is hard to compute an answer to a question about an ungrammatical sentence. The primary purpose of the comprehension questions was to ensure that subjects kept their attention on the semantic contents of the sentences, trying to interpret "who did what to whom" while listening. The relative difficulty of answering questions suggested that subjects would have to pay close attention to the sentences, confirming the effectiveness of this control. ERP analysis could not be limited to only those trials with correct answers to comprehension questions, because not every trial received a question.

4.2. Early anterior negativity

The main finding of the repeated measures ANOVAs was that the Ungrammatical Object condition resulted in a bilaterally distributed anterior negativity in comparison to control conditions. The effect was larger at inferior than superior electrodes sites, but there was no interaction between Condition and Dorsality. Descriptively, the effect is largest in the left inferior quadrant, but the difference between left and right hemisphere was not significant. The preliminary conclusion based on the ANOVAs would be that we observed a bilaterally distributed anterior negativity to the filled gap. To evaluate the time course of this ERP we first turn to a discussion of long negativity.

As noted in Section 1, the Ungrammatical Object condition is likely to generate long negativity caused by the fact that the relativized noun is put in working memory during the search for a gap. This therefore confounds the comparison of Grammatical and Ungrammatical Object with respect to an eLAN-related negativity. Comparison of Ungrammatical Object and Trace allows for a control of this confound. The Grammatical Trace condition and Ungrammatical Object stimuli sentences were identical in structure and content up to the relative clause verb; therefore, both conditions should generate the same long negativity. The pair-wise comparisons of the Trace and Ungrammatical conditions in the entire anterior region showed that the two conditions did not differ significantly during the 0–100 ms time window, but differed significantly during the subsequent time windows. This can be interpreted as showing that long negativity "turns off" around 100–200 ms from the verb offset, and that the continuing negativity in the Ungrammatical Object condition after this point in time must be attributed to the filled gap ungrammaticality itself. Consequently, we isolate the difference between the Ungrammatical Object and the Grammatical Object during the 100–200 ms and the 200–300 ms time window as the crucial negativity, which places the effect in the 100–300 ms time range. This puts the effect in the same family as the eLAN.

The Ungrammatical and Grammatical Object conditions differed already during the 0–100 ms time window. Inspection of the anterior quadrants (cf. Fig. 2) shows that this effect was driven primarily by the left inferior quadrant. We speculate that this is a baseline effect caused by long negativity. Even though all trials are baseline corrected, if the Ungrammatical and Trace conditions are already negative going, the voltages should then keep going negative immediately after the baseline period. Again, we note that the Trace condition then turns more positive than even the Object condition after the 100–200 ms time window. Therefore, any baseline effect plays no role after this period, and the additional difference between the Ungrammatical and Grammatical Object after this point in time must be due to the ungrammatical status of the filled gap.

4.3. eLAN

The analysis so far only places the anterior negativity in the 100–300 ms time range. In order to determine the exact latency of the ERP, we turn to the PCA. The time course of the main temporal factor identified by the PCA extended from 100 to 400 ms with a peak amplitude at 220 ms. The spatial distribution of this factor, as illustrated by the topographical plot in the lower left panel of Fig. 4, showed a pattern similar to that observed in the ANOVA, with a bilaterally distributed negativity most pronounced at inferior electrode sites, and a corresponding positive inversion at centro-parietal sites (cf. the grand average topoplot). This convergence suggests that temporal factor 2 can be interpreted as closely corresponding to the anterior negativity identified by the initial time-window analysis. The temporal factor peak latency of 220 ms can therefore be interpreted as representing the peak latency of the 100–300 ms anterior negativity.

The next question concerns the exact spatial characterization of this component. Based on the average analysis, we could only conclude that the anterior negativity was bilateral. Other researchers have observed a frontally distributed anterior negativity to syntactic computations, and concluded that it is the same effect as the LAN (Steinhauer, Pancheva, Newman, Gennari, & Ullman, 2001). However, the spatial decomposition of the eLAN temporal factor allows us to conclude that the broadly distributed negativity observed in temporal factor 2, as well as in the grand average data, results from the typical superimposition of multiple spatial ERP components within the same temporal factor (Dien & Frishkoff, 2005). In particular, we interpret only temporal factor 2, spatial factor 1 as corresponding to the pure eLAN signal in the data. This was the only spatial factor in temporal factor 2 with a statistically significant condition effect in the predicted direction, and its peak electrode (cf. Fig. 6) coincides with the site where the eLAN has been observed by other researchers (e.g., AF7 in (Friederici et al., 1996; Hahne & Friederici, 1999)).

This shows that the repeated measures ANOVA only provides a rough approximation to the underlying latent ERP components, and that the temporo-spatial decomposition helps to isolate the effect from overlapping components. The PCA also helps to interpret other aspects of the data. For example, it is evident that the Trace condition turns negative very early, especially in right inferior electrodes (cf. Fig. 2, lower right hand panel). This is probably due to an unintended property of the stimuli sentences. We interpret the significant condition effect in temporal factor 2, spatial factor 2 as corresponding to this effect. The advantage of the PCA is that this effect is then factored out and separated from the true eLAN component, improving the interpretation of the latter.

4.4. N400

No centrally distributed negativity (i.e., N400) in the 300–500 ms time range was evident in the grand average topographical plot. A reviewer suggested that an N400 effect may suffer a reduction in effect size when shifting from linked mastoids reference to average reference; but the N400 was absent also when using linked mastoids reference. Furthermore, for the current data, this would have meant that much of the effect were at the mastoids. Including the mastoid data in the statistical analysis allowed for this to be examined. For the PCA analysis, all the data were used, and therefore it should not matter which reference is used because the difference in amplitude between any pair of sites is the same no matter what reference. (Appendix B demonstrates the difference between linked mastoid reference and average reference for the current data.)

More recent developments in syntactic theory model the incremental build-up of syntactic structure as integrated with and inseparable from theta-role assignment (via the operation "external merge" (Chomsky, 2001, 2005)). If theta-roles are assigned at the same time as constituents are formed, then structural incorporation of the NP in the filled gap position should necessarily lead to a concomitant violation of the Theta-criterion, because the verb's theta-role has already been assigned to the trace of the filler. As discussed above, violations of the Theta-criterion should lead to an N400 in Friederici's model. The absence of an N400 in the current paradigm could be interpreted as evidence against this interpretation of the "merge" operation, because it suggests that no theta-role is being assigned to the filled gap NP. Although this conclusion rests on a null result, it agrees with the findings of Frisch et al. (2004) that argument structure violations in isolation results in an N400, whereas double violations of both word category and argument structure requirements only results in a eLAN.

4.5. P600

The experiment did not result in the same, large P600 effect of the type previously reported to syntactically complex sentences and garden path sentences (Hagoort, 1993; Kaan et al., 2000; Osterhout & Holcomb, 1992; Osterhout, Holcomb, & Swinney, 1994). A small but significant positivity to the Ungrammatical Object condition was observed around 600 ms. This effect, however, primarily separated the Ungrammatical Object from the Trace condition, although it was marginally different from the Object condition in the right superior quadrant. The marginally significant late positivity that separated the Ungrammatical Object from the Grammatical Trace condition in the average analysis may correspond to temporal factor 6 in the PCA, but this factor contained no spatial factors with statistically significant condition effects. This suggests that the marginality of this effect in the average data analysis did not have sufficient statistical power to result in a PCA factor with condition effects, and that the ANOVA results should be interpreted conservatively.

There are several possible explanations for the absence of a clear P600. This component has been related to reanalysis and recovery of garden-path sentences, as well as to the complexity of syntactic processing (Kaan et al., 2000; Kaan & Swaab, 2003a, 2003b). However, the ungrammatical sentences in the current study were “terminally” ungrammatical and not just temporarily ungrammatical (as in classical “filled gap” effects). No grammatical analysis could be constructed after encountering the filled gap, which could explain the relative attenuation of this component.

As a case in point, note that there are grammatical continuations of sentences such as (3) with *the camel* immediately following the verb, as in *The zebra that the hippo kissed the camel for* or *The zebra that the hippo kissed the nose of* (Janet Fodor and Ray Jackendoff, personal communication). Such sentences would be analogous to the classical filled gap paradigm, in the sense that the unexpected phrase following the prematurely filled gap position is part of an eventually grammatical parse. Given the low probability of such continuations and the fact that ERPs are triggered by probabilistic expectations, we would expect the same early ERPs to be elicited by such sentences as the “terminally ungrammatical” sentences we used in the experiment. On the other hand, these grammatical sentences might have resulted in a clearer P600 response, because a grammatical parse is available via repair and reanalysis. The fact that our stimuli sentences had no available reanalysis could account for the lack of an clear P600 response.

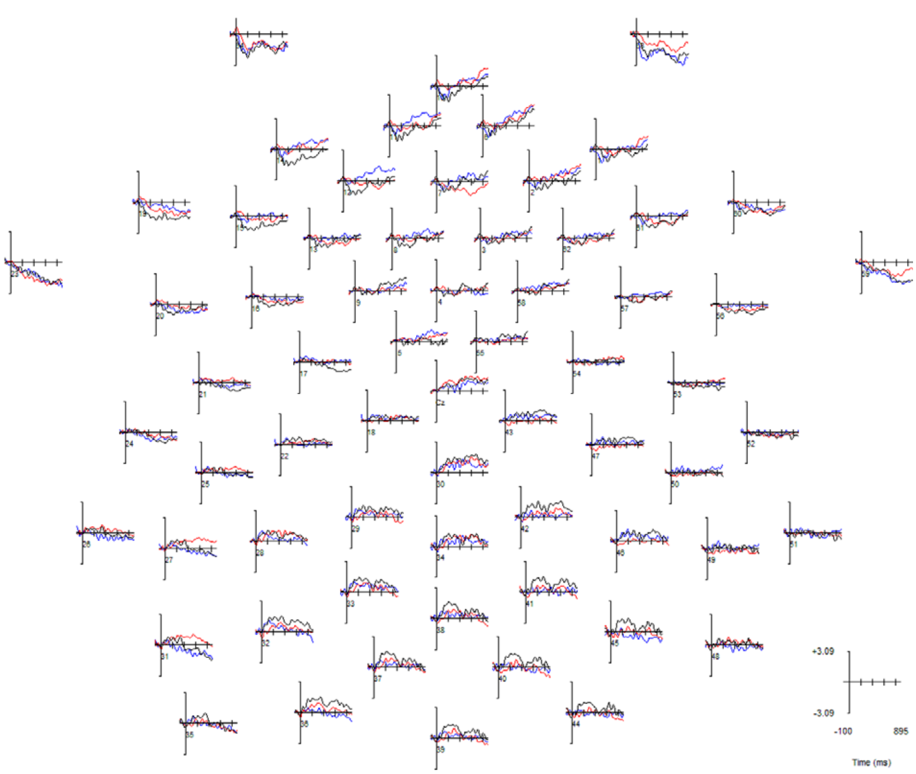

Fig. 7. Grand average topoplot, average referenced. Positive is plotted up; lowpass filtered at 15 Hz for display purposes only.

5. Conclusion

We conclude that the parser constructs syntactically present traces as part of representing displacement. When the parser processes the ungrammatical sentences used in the current experiment, it generates the expectation that the verb should be followed by a syntactic structure consistent with a trace. The presence of an extraneous NP object in this position leads to a violation of word category expectations. This in turn results in the eLAN evoked potential, which correlates with "rapidly detectable word category errors" (Friederici et al., 1993, 2002; Hahne & Friederici, 1999; Hahne & Jescheniak, 2001; Neville, Nicol, Barss, Forster, & Garrett, 1991). On the other hand, if gap-filling were primarily an operation relating displaced fillers directly with argument structure, then the ungrammaticality should have resulted in an N400 response or a LAN, which it did not. This provides new evidence that gap-filling is first mediated by the construction of an abstractly represented syntactic object, and that the construction of traces is part of the early, "first-pass" syntactic analysis by the parser (Friederici, 1995).

Further experimental evidence points to a dissociation of argument structure and gap-filling. For example, Friedmann, Taranto, Shapiro, and Swinney (2003), using cross-modal lexical priming experiment showed that subjects of unaccusative verbs reactivate immediately after the verbs, in contrast to subjects of unergative verbs. This is predicted by the trace theory assuming the classic theory of unaccusativity (Burzio, 1986), which models unaccusatives (but not unergatives) as having a trace of the subject in the object position. Direct association with argument structure does not seem to predict this distinction. In addition, prosodic cues to structure have been shown to cancel temporary

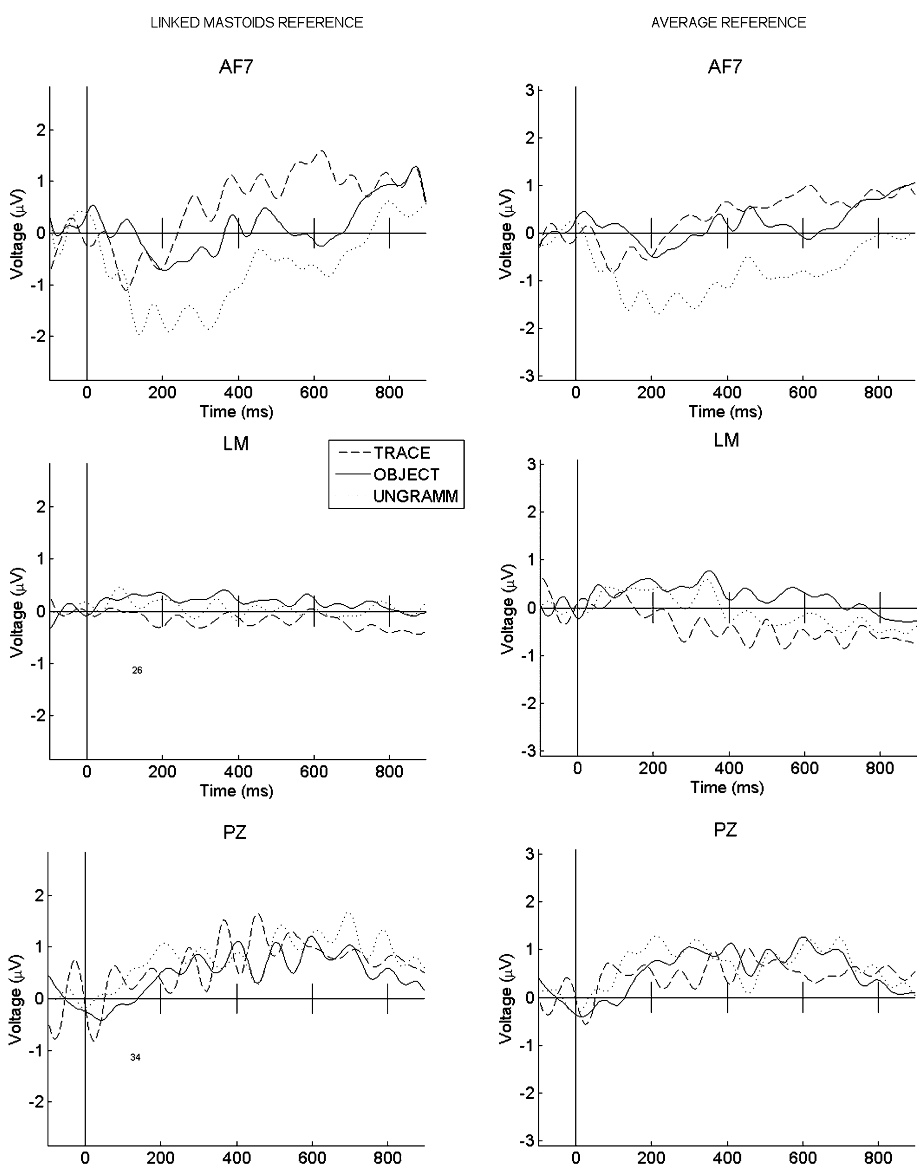

Fig. 8. Comparison of linked mastoid reference and average reference.

Garden Path effects in sentences like (2) (Nagel, Shapiro, & Nawy, 1994, 1996); this is not immediately reconcilable with direct association, which presumably is automatically activated by processing of the relevant verb. Finally, the long-standing account of Broca's aphasics as able to use argument structure information, but not to perform gap-filling (Grodzinsky, 2000), by itself argues for the independence of gap-filling from argument structure. The current finding adds to this body of evidence that argument structure satisfaction and gap-filling are related but separate processes.

Acknowledgments

This research was supported by the following grants from the National Institutes of Health, National Institute on Deafness and Other Communication Disorders: T32DC000039 (R. Schwartz, P.I.), 5R03DC006175 (A. Hestvik, P.I.), and 5R01DC003885 (R. Schwartz, P.I.). We thank Joseph Dien for assistance with PCA, and two anonymous reviewers for their helpful comments.

Appendix A

Grand average topoplot, average referenced. Legend: black, Ungrammatical Object; red, Grammatical Object; blue, Grammatical Trace. Tick marks at every 200 ms. Readers of the printed version of the journal are referred to the web version for the color coding. Note that since Cz was used as reference electrode during recording, average referencing effectively puts the average of all electrodes back into this electrode (see Fig. 7).

Appendix B

Comparison of AF7 (left inferior anterior region), left mastoid, and PZ (for N400 or P600), using linked mastoids vs. average reference (see Fig. 8).

References

Bell, A. J., & Sejnowski, T. J. (1995). An information-maximization approach to blind separation and blind deconvolution. *Neural Computation, 7*(6), 1129–1159.

Bever, T., & McElree, B. (1986). Empty categories access their antecedents during comprehension. *Linguistic Inquiry, 19*, 35–43.

Bresnan, J. (2001). *Lexical-functional syntax*. Oxford: Oxford University Press.

Burzio, L. (1986). *Italian syntax: A Government-binding approach*. Dordrecht: Reidel.

Cattell, R. B. (1966). The scree test for the number of factors. *Multivariate Behavioral Research, 1*(2), 140–161.

Chomsky, N. (1981). *Lectures on government and binding*. Dordrecht, Holland: Foris Publications.

Chomsky, N. (1995). *Prospects for democracy*. Edinburgh: AK Distribution Retail Press.

Chomsky, N. (2001). Beyond explanatory adequacy, MIT Occasional Papers in Linguistics, Vol. 20. Cambridge, MA: Department of Linguistics and Philosophy, MIT.

Chomsky, N. (2005). Three factors in language design. *Linguistic Inquiry, 36*(1), 1–22.

Clahsen, H., & Featherston, S. (1999). Antecedent priming at trace positions: evidence from German scrambling. *Journal of Psycholinguistic Research, 28*(4), 415.

Clifton, C., Jr., & Frazier, L. (1986). The use of syntactic information in filling gaps. *Journal of Psycholinguistic Research, 15*(3), 209–224.

Clifton, C., Jr., & Frazier, L. (1989). Comprehending sentences with long-distance dependencies. In G. Carlson & M. K. Tanenhaus (Eds.), *Linguistic structure in language processing* (pp. 273–317). Dordrecht: Kluwer Academic Publishers.

Crain, S., & Fodor, J. D. (1985). How can grammars help parsers? In D. Dowty, L. Karttunen, & A. Zwicky (Eds.), *Natural language parsing: psychological, computational and theoretical perspectives*. Cambridge: Cambridge University Press.

Crocker, M. W. (1996). Computational psycholinguistics: an interdisciplinary approach to the study of language(Vol. 20). Dordrecht: Kluwer.

Dien, J. (1998). Addressing misallocation of variance in principal components analysis of event-related potentials. *Brain Topography, 11*(1), 43–55.

Dien, J. (2004). ICAblink Toolbox [Computer Software] (Version 1.21). Lawrence, KA. Available from http://www.people.ku.edu/~jdien/downloads.html.

Dien, J. (2005). PCA Toolbox [Computer software] (Version 1.93). Lawrence, KA. Available from http://www.people.ku.edu/~jdien/dowloads.html.

Dien, J., Beal, D. J., & Berg, P. (2005). Optimizing principal components analysis of event-related potentials: Matrix type, factor loading weighting, extraction, and rotations. *Clinical Neurophysiology, 116*(8), 1808–1825.

Dien, J., & Frishkoff, G. A. (2005). Principal components analysis of event-related potential datasets. In T. Handy (Ed.), *Event-related potentials: a methods handbook*. Cambridge: MIT Press.

Dien, J., Frishkoff, G. A., Cerbone, A., & Tucker, D. M. (2003). Parametric analysis of event-related potentials in semantic comprehension: evidence for parallel brain mechanisms. *Brain Research. Cognitive Brain Research, 15*(2), 137–153.

Dien, J., & Santuzzi, A. M. (2005). Application of repeated measures ANOVA to high-density ERP datasets: A review and tutorial. In T. Handy (Ed.), *Event related potentials: a methods handbook*. Cambridge, MA: MIT Press.

Dien, J., Spencer, K. M., & Donchin, E. (2003). Localization of the event-related potential novelty response as defined by principal components analysis. *Brain Research. Cognitive Brain Research, 17*(3), 637–650.

Dien, J., Spencer, K. M., & Donchin, E. (2004). Parsing the late positive complex: mental chronometry and the ERP components that inhabit the neighborhood of the P300. *Psychophysiology, 41*(5), 665–678.

Felser, C., Clahsen, H., & Münte, T. F. (2003). Storage and integration in the processing of filler-gap dependencies: An ERP study of topicalization and wh-movement in German. *Brain and Language, 87*(3), 345.

Ferree, T. C., Luu, P., Russell, G. S., & Tucker, D. M. (2001). Scalp electrode impedance, infection risk, and EEG data quality. *Clinical Neurophysiology, 112*(3), 536–544.

Fiebach, C., Schlesewsky, M., & Friederici, A. D. (2001). Syntactic working memory and the establishment of filler-gap dependencies: insights from ERPs and fMRI. *Journal of Psycholinguistic Research, 30*(3), 321–338.

Fiebach, C., Schlesewsky, M., & Friederici, A. (2002). Separating syntactic memory costs and syntactic integration costs during parsing: the processing of German WH-questions. *Journal of Memory and Language, 47*(2), 250.

Frank, R. (2005). PCAtoRAW [Computer software] (Version 1.6). Available from http://homepage.mac.com/rmfrank/Filesharing23.html.

Frazier, L., & Clifton, C. (1995). *Construal*. Cambridge, MA: MIT Press.

Frazier, L., & Flores d'Arcais, G. B. (1989). Filler driven parsing: A study of gap filling in Dutch. *Journal of Memory and Language, 28*(3), 331.

Frazier, L., & Fodor, J. (1978). The sausage machine: A new two-stage parsing model. *Cognition, 6*, 291–325.

Friederici, A. D. (1995). The time course of syntactic activation during language processing: A model based on neuropsychological and neurophysiological data. *Brain and Language, 50*, 259–281.

Friederici, A. D. (2002). Towards a neural basis of auditory sentence processing. *Trends in Cognitive Sciences, 6*(2), 78–84.

Friederici, A. D., Hahne, A., & Mecklinger, A. (1996). Temporal structure of syntactic parsing: early and late event-related brain potential effects. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22*(5), 1219–1248.

Friederici, A. D., Hahne, A., & von Cramon, D. Y. (1998). First-pass versus second-pass parsing processes in a Wernicke's and a Broca's aphasic: Electrophysiological evidence for a double dissociation. *Brain and Language, 62*, 311–341.

Friederici, A. D., Pfeifer, E., & Hahne, A. (1993). Event-related brain potentials during natural speech processing: effects of semantic, morphological and syntactic violations. *Brain Research. Cognitive Brain Research, 1*(3), 183–192.

Friedmann, N., Taranto, G., Shapiro, L.P., & Swinney, D. (2003). The vase fell (the vase): the online processing of unaccusatives. In *Paper presented at the 19th IATL conference*.

Frisch, S., Hahne, A., & Friederici, A. D. (2004). Word category and verb-argument structure information in the dynamics of parsing. *Cognition, 91*(3), 191–219.

Gibson, E., & Hickok, G. (1993). Sentence processing with empty categories. *Language and Cognitive Processes, 8*, 147–161.

Glass, K., Frishkoff, G. A., Frank, R. M., Davey, C., Dien, J., Maloney, A. D., et al. (2004). A framework for evaluating ICA methods of artifact removal from multichannel EEG. In C. G. Puntonet & A. Prieto (Eds.), *ICA 2004, LNCS 3195* (pp. 1033–1040). Berlin, Heidelberg: Springer Verlag.

Gorsuch, R. L. (1983). *Factor analysis*. Hillsdale, NJ: Erlbaum.

Greenhouse, S. W., & Geisser, S. (1959). On methods in the analysis of profile data. *Psychometrika, 24*, 95–112.

Grodzinsky, Y. (2000). The neurology of syntax: language use without Broca's area. *Behavioral and Brain Sciences, 23*(1), 1–21 discussion 21–71.

Hagoort, P. (1993). The syntactic positive shift as an ERP measure of syntactic processing. *Language and Cognitive Processes, 8*, 439–483.

Hagoort, P., & Brown, C. M. (2000). ERP effects of listening to speech compared to reading: the P600/SPS to syntactic violations in spoken sentences and rapid serial visual presentation. *Neuropsychologia, 38*(11), 1531–1549.

Hagoort, P., Brown, C. M., & Groothusen, J. (1993). The syntactic positive shift as an ERP-measure of syntactic processing. *Language and Cognitive Processes, 8*, 439–483.

Hahne, A., & Friederici, A. (1999). Electrophysiological evidence for two steps in syntactic analysis. Early automatic and late controlled processes. *Journal of Cognitive Neuroscience, 11*(2), 194–205.

Hahne, A., & Jescheniak, J. D. (2001). What's left if the Jabberwock gets the semantics? An ERP investigation into semantic and syntactic processes during auditory sentence comprehension. *Cognitive Brain Research, 11*(2), 199–212.

Hauser, M. D., Chomsky, N., & Fitch, W. T. (2002). The faculty of language: what is it, who has it, and how did it evolve? *Science, 298*(5598), 1569–1579.

Hendrickson, A. E., & White, P. O. (1964). Promax: A quick method for rotation to oblique simple structure. *British Journal of Statistical Psychology, 17*(1), 65–70.

Kaan, E., Harris, A., Gibson, E., & Holcomb, P. (2000). The P600 as an index of syntactic integration difficulty. *Language and Cognitive Processes, 15*(2), 159–201.

Kaan, E., & Swaab, T. Y. (2003a). Electrophysiological evidence for serial sentence processing: a comparison between non-preferred and ungrammatical continuations. *Brain Research. Cognitive Brain Research, 17*(3), 621–635.

Kaan, E., & Swaab, T. Y. (2003b). Repair, revision, and complexity in syntactic analysis: an electrophysiological differentiation. *Journal of Cognitive Neuroscience, 15*(1), 98–110.

Kayser, J., & Tenke, C. E. (2003). Optimizing principal components analysis (PCA) methodology for ERP component identification and measurement: Theoretical rationale and empirical evaluation.

King, J. W., & Kutas, M. (1995). Who did what and when? Using word- and clause-level ERPs to monitor working memory usage in reading. *Journal of Cognitive Neuroscience, 7*, 376–395.

Kluender, R., & Kutas, M. (1993). Bridging the gap: Evidence from ERPs on the processing of unbounded dependencies. *Journal of Cognitive Neuroscience, 5*, 196–214.

Kutas, M., & Hillyard, S. A. (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science, 207*, 203–205.

Love, T. Real-time processing of object-relative constructions by pre-school children. *Journal of Psycholinguistic Research*, in press.

Love, T., & Swinney, D. (1997). Real-time processing of object-relative constructions by pre-school children. In *Paper presented at the 10th annual CUNY conference on human sentence processing*, Los Angeles, CA.

Luu, P., & Ferree, T. C. (2000). Determination of the Geodesic Sensor Nets' Average Electrode Positions and Their 10-10 International Equivalents: Electrical Geodesics, Inc.

Münte, T. F., Wieringa, B. M., Weyerts, H., Szentkuti, A., Matzke, M., & Johannes, S. (2001). Differences in brain potentials to open and closed class words: class and frequency effects. *Neuropsychologia, 39*(1), 91.

Nagel, H. N., Shapiro, L. P., & Nawy, R. (1994). Prosody and the processing of filler-gap sentences. *Journal of Psycholinguistic Research, 23*(6), 473–485.

Nagel, H. N., Shapiro, L. P., Tuller, B., & Nawy, R. (1996). Prosodic influences on the resolution of temporary ambiguity during on-line sentence processing. *Journal of Psycholinguistic Research, 25*(2), 319–344.

Nakano, Y., Felser, C., & Clahsen, H. (2002). Antecedent priming at trace positions in Japanese long-distance scrambling. *Journal of Psycholinguistic Research, 31*(5), 531–571.

Neville, H. J., Mills, D. L., & Lawson, D. S. (1992). Fractionating language: different neural subsystems with different sensitive periods. *Cerebral Cortex, 2*(3), 244–258.

Neville, H. J., Nicol, J., Barss, A., Forster, K., & Garrett, M. F. (1991). Syntactically based sentence processing classes: Evidence from event-related brain potentials. *Journal of Cognitive Neuroscience, 3*, 151–165.

Nicol, J., Fodor, J. D., & Swinney, D. (1994). Using cross-modal lexical decision tasks to investigate sentence processing. *Journal of Experimental Psychology: Learning Memory and Cognition, 20*(5), 1229–1238.

North, G. R., Bell, T. L., Cahalan, R. F., & Moeng, F. J. (1982). Sampling errors in the estimation of empirical orthogonal functions. *Monthly Weather Review*(110), 699–706.

Osterhout, L., Bersick, M., & McKinnon, R. (1997). Brain potentials elicited by words: word length and frequency predict the latency of an early negativity. *Biological Psychology, 46*(2), 143–168.

Osterhout, L., & Holcomb, P. (1992). Event-related brain potentials elicited by syntactic anomaly. *Journal of Memory and Language, 31*, 785–806.

Osterhout, L., & Holcomb, P. (1993). Event-related potentials and syntactic anomaly: Evidence of anomaly detection during the preception of continuous speech. *Language and Cognitive Processes, 8*, 413–438.

Osterhout, L., Holcomb, P. J., & Swinney, D. (1994). Brain potentials elicited by garden-path sentences: evidence of the application of verb information during parsing. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 20*(4), 786–803.

Phillips, C., Kazanina, N., & Abada, S. H. (2005). ERP effects of the processing of syntactic long-distance dependencies. *Cognitive Brain Research, 22*(3), 407.

Phillips, C., & Wagers, M. Relating structure and time in linguistics and psycholinguistics. In G. Gaskell (Ed.), Oxford Handbook of Psycholinguistics. Oxford: Oxford University Press, in press.

Pickering, M. J. (1993). Direct association and sentence processing: A reply to Gorrell and to Gibson and Hickok. *Language and Cognitive Processes, 8*, 163–196.

Pickering, M. J., & Barry, G. D. (1991). Sentence processing without empty categories. *Language and Cognitive Processes, 6*, 229–259.

Pollard, C., & Sag, I. (1993). *Head-driven phrase structure grammar*. Stanford, CA: CSLI and University of Chicago Press.

Preisendorfer, R. W., & Mobley, C. D. (1988). *Principal component analysis in meteorology and oceanography*. New York: Elsevier.

Pulvermuller, F., Lutzenberger, W., & Birbaumer, N. (1995). Electrocortical distinction of vocabulary types. *Electroencephalography and Clinical Neurophysiology, 94*(5), 357.

Richman, M. B. (1986). Rotation of principal components. *Journal of Climatology, 6*, 293–335.

Roberts, L., Marinis, T., Felser, C., & Clahsen, H. Antecedent priming at trace positions in children's sentence processing. *Journal of Psycholinguistic Research, 35*, in press.

Sag, I., & Fodor, J. D. (1995). Extraction without traces. In *Paper presented at the west coast conference of formal linguistics 13*, Stanford, CA.

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime Reference Guide*. Pittsburgh: Psychology Software Tools, Inc.

Shapiro, L. P., Swinney, D., & Borsky, S. (1998). Online examination of language performance in normal and neurologically impaired adults. *American Journal of Speech-Language Pathology, 7*, 49–60.

Spencer, K. M., Dien, J., & Donchin, E. (1999). A componential analysis of the ERP elicited by novel events using a dense electrode array. *Psychophysiology, 36*(3), 409–414.

Spencer, K. M., Dien, J., & Donchin, E. (2001). Spatiotemporal analysis of the late ERP responses to deviant stimuli. *Psychophysiology, 38*(2), 343–358.

Steinhauer, K., Pancheva, R., Newman, A. J., Gennari, S., & Ullman, M. T. (2001). How the mass counts: an electrophysiological approach to the processing of lexical features. *Neuroreport, 12*(5), 999–1005.

Stowe, L. A. (1986). Parsing WH-constructions: evidence for on-line gap location. *Language and Cognitive Processes, 1*(3), 227–245.

Stowe, L. A., Tanenhaus, M. K., & Carlson, G. (1991). Filling gaps on-line: Use of lexical and semantic information in sentence processing. *Language and Speech, 34*(4), 319–340.

Swinney, D., Ford, M., & Bresnan, J. (1989). On the temporal course of gap-filling and antecedent assignment during sentence comprehension. In B. Grosz, R. Kaplan, M. Macken, & I. Sag (Eds.), *Language structure and processing*. Stanford, CA: CSLI.

Swinney, D., & Osterhout, L. (1990). Inference generation during auditory language comprehension. In A. Graesser & G. Bower (Eds.), *The psychology of learning and motivation* (Vol. 25, pp. 17–33). New York: Academic Press.

Swinney, D., & Zurif, E. (1995). Syntactic processing in aphasia. *Brain and Language, 50*, 225–239.

Tataryn, D. J., Wood, J. M., & Gorsuch, R. L. (1999). Setting the Value of K in Promax: A Monte Carlo Study. *Educational and Psychological Measurement, 59*(3), 384–391.

Traxler, M. J., & Pickering, M. J. (1996). Case-marking in the parsing of complement sentences: evidence from eye movements. *Quarterly Journal of Experimental Psychology (Section A), 49*(4), 991–1004.