Waves and Words

Waves and Words:
Oscillatory activity and language processing

INAUGURAL-DISSERTATION
zur
Erlangung des akademischen Grades
eines Doktors der Philosophie (Dr. phil.)
dem
Fachbereich Germanistik und Kunstwissenschaften
der Philipps-Universität Marburg

vorgelegt von
Dietmar Roehm
aus Backnang

Marburg, Mai 2004

Vom Fachbereich Germanistik und Kunstwissenschaften der Philipps-Universität Marburg als Dissertation angenommen am 12. Mai 2004

Tag der Disputation: 08. November 2004

Erstgutachter: HD Dr. Matthias Schlesewsky

Zweitgutachter: Prof. Dr. Hubert Haider

Acknowledgements

Although this thesis bears only my name as author, it would not have been possible without the generous help of a number of people whose contributions I would like to acknowledge. There are three persons above all others who deserve my deepest thanks and respect for their continued support during the writing of this thesis: my first advisor Matthias Schlesewsky, Ina Bornkessel, and Hubert Haider. Nearly two and a half years ago, I first met Ina and Matthias in the course of a talk which they gave on behalf of an invitation of Hubert Haider at the Linguistics Department of the University of Salzburg. Matthias and Ina's keen insight and thoughtful reflection on the issues associated with psycholinguistic research are abilities to which I aspire. In every sense, none of this work would have been possible without them. Of course, despite all the assistance provided by them, I alone remain responsible for the content of the following, including any errors or omissions which may unwittingly remain.

I want to thank Matthias especially for the many thought-provoking conversations we have had concerning cognitive linguistics, the detailed comments and suggestions on this and other work, and his support and advice in other areas of academic life. He fostered a working relationship which was crucial to the completion of this work. I am especially indebted to Ina for the Sisyphean task of repeatedly reading the manuscript and suffering the torments of Tantalus to vulgarise my outlandish English. Thank you Ina for being so generous with your time and knowledge.

To Hubert Haider, I would like to express my deepest appreciation for his patient, friendly, and unfailing support over the past years. About six years ago, I set out from Stuttgart to accomplish my studies under his supervision at the University of Salzburg. Since then, he has been instrumental in ensuring my academic, professional, financial and personal wellbeing. I have benefited tremendously from his profound knowledge and his help.

In the Psychophysiological Laboratory of the University of Salzburg I am very grateful to Wolfgang Klimesch for his continuous help and numerous discussion whenever 'EEG questions' arose. His views and theories with regard to EEG dynamics and analysis deeply coined my understanding of EEG research.

Many thanks also to Walter Gruber for his invaluable patience in answering all my technical questions and particularly in helping me through the mysteries of the application and interpretation of wavelet analysis.

Parts of the present research were generously supported by the Austrian 'Fond zur Förderung der wissenschaftlichen Forschung', Project P16281-G03.

I would like to thank my family who have waited ever so patiently for me to graduate, and especially my mother, Ilse Roehm, who never gave up the hope that I would finally succeed.

My final, and most heartfelt, acknowledgment must go to Peggy for ten thousand considerations large and small. Her love and constant support sustained me through the many hard times when my confidence and enthusiasm had waned. For all that, and for being everything I am not, she has my whole love.

Table of Contents

Wissen Sie mir auch wenig Dank für das,
was ich ihnen erzähle, so wissen Sie
mir ihn wenigstens für das, was ich ihnen
nicht erzähle!

Denis Diderot (Jacques der Fatalist)

Es ist fast unmöglich,
die Fackel der Wahrheit durch ein Gedränge zu tragen,
ohne jemandem den Bart zu sengnen.

Lichtenberg

Introduction

Successful language comprehension depends not only on the involvement of different domain-specific linguistic processes, but also on their respective *time-course*. Therefore, a large part of the recent work in psycholinguistics has focused on trying to determine which processes play a role and how these processes interact in time.

Whereas in our own everyday experience, language comprehension is an imperceptible and apparently effortless process, the human language processing system nevertheless is continually confronted with unexpected, conflict engendering events that must be resolved if comprehension is to proceed successfully. An example of an ambiguity leading to difficulties in comprehension is given in (1) (from Osterhout & Holcomb, 1992, 1993).

(1) The broker persuaded to sell the stock was sent to jail.

When sentence (1) is processed sequentially, the verb *persuaded* is initially analysed as a main verb (as in *The broker persuaded the manager to sell the stock*), a decision that must be revised when *to* is encountered and it becomes clear that *persuaded* is actually the verb in a reduced relative clause. Thus, the difficulty associated with (1) results from an ambiguity - and subsequent misanalysis - pertaining to properties of syntactic structure. This type of enhanced processing cost has long been used to gain insights into the architecture and mechanisms of the language processing system (Kimball, 1973; Fodor, Bever, & Garrett, 1974; Frazier, 1987; Clifton, Frazier, & Rayner, 1994). As in the investigation of other cognitive domains (e.g. memory, attention etc.), the simplest characterisation of ‘processing difficulty’ in this sense may be achieved via the measurement of reaction times or accuracy of comprehension. However, the use of these types of behavioural measures as a means of characterising underlying mechanisms of linguistic analysis presupposes that the locus of the processing problem can be straightforwardly established. Thus, an implausible sentence such as (2) also gives rise to longer reaction times in the critical region and lower acceptability ratings in comparison to a minimally differing plausible sentence (e.g. ending with *butter* rather than *socks*).

(2) He spread the warm bread with *socks*.

In contrast to (1), the enhanced processing costs in (2) are due to semantic oddness or a mismatch between the critical item and the preceding sentence context. Thus, the observed processing difficulty has to be attributed to the lexical-semantic processing domain. In this way, behavioural measures as pure quantitive measures of processing difficulty cannot dissociate underlyingly different linguistic domains from one another, but rather provide unspecific global measures of processing difficulty. Additionally, by merely measuring the end result of a comprehension process, either locally, i.e. on the word level (as for example in reading time methods; cf. Haberlandt, 1994) and/or globally (i.e. on the sentence level), behavioural measures (like e.g. self-paced-reading, speeded-grammaticality judgments or lexical decision) do not allow conclusions about the precise time course of underlying processes (Schütze, 1996).[1]

Therefore, to tackle issues pertaining to underlying linguistic processing domains and their temporal processing characteristics, comprehension measures are needed that not only provide quantitive estimations but furthermore allow qualitative differentiations as well as a continuous record of the underlying processing characteristics. Functional imaging methods like functional magnetic resonance imaging (fMRI) or positron emission tomography (PET) provide a very good spatial resolution of underlying brain processes (by imaging the hemodynamic activity of the brain) and therefore might provide enhanced insights into the spatial organisation of functionally distinct underlying cognitive processes. Unfortunately, this benefit of good spatial resolution is accompanied by poor (in the case of PET even very poor) temporal resolution (i.e. in the second range). Although the temporal resolution of the fMRI-method has been substantially improved in recent times through the use of event-related fMRI (e.g. Rosen, Buckner, & Dale, 1998; Menon & Kim, 1999), it still exceeds by far the time ranges relevant to language processing (and, in principal, cannot be improved; cf. Ogawa, Lee, Nayak, & Glynn , 1990; Ogawa, Tank, Menon, Ellermann, Kim, Merkle, & Ugurbil, 1992).[2] FMRI therefore offers only few insights into the temporal dynamics of language processing. However, a method which provides a direct reflection of underlying brain processes and furthermore provides an excellent time resolution in the millisecond range is the recording of the human electroencephalogram (EEG), i.e. the acquisition of a reflection

---

[1] An exception is the speed-accuracy tradeoff (SAT) procedure, which allows for a precise characterisation of the time course of sentence processing (McElree, 1993; McElree & Griffith, 1995) as well as a functional characterisation by distinguishing between processing speed (dynamic behaviour) and processing accuracy (non-dynamic behaviour).

[2] For example due to the delayed blood flow response.

of the summed (and damped) electrophysiological activity of the brain by means of electrodes applied to the surface of the human scalp. During the performance of cognitive tasks, the respective task- or event-related electrical activity can be acquired with the event-related brain potentials (ERPs) technique. In particular, ERPs can be measured throughout the presentation of words/sentences and thus can potentially provide a continuous record of language comprehension processes as they unfold.[3] Moreover, ERPs are not only an ideal time-sensitive measure, but also provide a multi-dimensional characterisation of processing difficulties during language comprehension, in which various language-related effects ('components') can be differentiated on the basis of parameters such as polarity, latency and topography.[4] Furthermore, ERPs as a physiological measure of mass neural activity can be used to examine the functional organisation of the brain for language and language processing (e.g. Friederici, 1999, 2002; Kutas & Van Petten, 1994; Rugg & Coles, 1995). In fact, through the application of the ERP methodology it became clear that the syntactic processing difficulty in (1) and the semantic violation in (2) indeed elicit distinct ERP components, namely a parietal positivity (Osterhout & Holcomb, 1992, 1993) with a maximum at approx. 600 ms (P600 or 'syntactic positive shift', SPS) vs. a centro-parietal negativity with a maximum at approx. 400 ms post critical word onset (N400; Kutas & Hillyard, 1980). On the basis of findings such as these, the N400 came to be regarded as an unambiguos general marker of lexical-semantic processes (Kutas & Federmeier, 2000).[5] This functional allocation is particularly important not only because the N400 thereby provided neurophysiological evidence for the involvement of qualitive different processes for syntactic and lexical-semantic processing aspects which consequently aligns with the postulated linguistic distinction of unique syntactic/semantic processing domains (i.e. modulary organisation). As a result, the N400 has even been used as 'diagnostic tool' in cases where the nature of the observed processing difficulty could not be established straightforwardly.

However, recent findings from ERP experiments revealed that precisely the N400 with its seemingly unequivocal functional interpretation, has been found in a number of areas which

---

[3] Indeed, they provide continuous data over time, so that the timing of parts of the waveform may provide valuable information about the timing of underlying processes (cf. Kutas & Van Petten, 1994).

[4] In addition, 'real' on-line measures in principle allow for an abandonment of extraneous secondary task demands, although for pragmatic reasons behavioural responses provide the experimenter with an easy way to monitor subject's alertness and performance.

[5] The P600/SPS has been associated with syntactic anomalies in ambiguous and ungrammatical sentences as well as attempts at reanalysis and/or repair (Osterhout & Holcomb, 1992; Friederici, 1999).

are not only *not* confined to language-related processes (e.g. Niedeggen & Rösler, 1996) but clearly independent of the lexical-semantic domain (e.g. Bornkessel, Schlesewsky, & Friederici, 2002; Osterhout, 1997).

The fact that the N400 component cannot be attributed to a single specific language processing domain therefore shows that the desired one-to-one mapping between ERP components and linguistic processes cannot be upheld. The present approach attempts to resolve this interpretative uncertainty by means of *frequency-analytical* dissociations of different ERP components.

Thereby, the primary aim of this thesis is to present a fundamentally new analysis technique for EEG research on human language comprehension, which can address the vagueness of interpretation associated with traditional language-related ERP components. It is argued that this new method, which supplements ERP measures with corresponding frequency-based analyses, not only allows for a differentiation of ERP components on the basis of activity in distinct frequency bands and underlying dynamic behaviour (in terms of power change and/or phase locking), but also provides further insights with regard to the functional organisation of the language comprehension system and its inherent complexity. To this effect, the thesis focuses on the investigation of the following three questions:

(A) Is it possible to dissociate two language-related ERP components that are indistinguishable on the surface on the basis of their respective underlying frequency characteristics?

(B) Is it possible to characterise the processing nature of the ‘classical’ semantic N400 effect by means of its underlying frequency characteristics, i.e. in terms of power (evoked and whole) and phase-locking differences in specific frequency bands?

(C) If question (A) and (B) can be answered in the affirmative: Is it possible to employ frequency-analytical analyses to distinguish the semantic N400 effects from N400-like effects that appear in contexts which cannot readily be characterised as semantic-interpretative processes (e.g. structure dependent N400 effects)?[6]

---

[6] Note that this question does not necessarily presuppose that two N400s are indistinguishable from a surface perspective.

Whereas question (A) addresses the vagueness of interpretation associated with traditional language-related ERP components (in particular with the N400), question (B) deals with the interpretative allocation of the N400 effect with regard to the underlying neuronal dynamics. Furthermore, (C) addresses the question of domain specificity of the N400 (with regard to its functional significance). Questions (A) and (B) are insofar independent from each other, because it is absolutely conceivable that it is possible to specify corresponding frequency characteristics of the N400 without being able to dissociate two from superficially indistinguishable components from each other. On the other hand, it might be possible to dissociate apparently indistinguishable N400 components on the basis of supplemental information from the frequency domain without being able to reliably codify its underlying frequency characteristics. Nevertheless, a close interdependence between (A) and (B) is expected.

The thesis is roughly divided into two parts. In the first two chapters, the methodological grounds for the following experimental part are provided. In Chapter 1, we first briefly introduce the ERP methodology and give a short overview of the current heterogenous interpretation of the N400 and the consequences thus arising. Chapter 2 presents existing language-related findings from analyses in the frequency domain and outlines the frequency-analytical methods that will be employed in the experimental part. Chapters 3, 4 and 5 report experiments designed to suggest an answer to the three questions raised in the thesis (see above). Finally, Chapter 6 provides a summary of the reported experimental findings and evaluates the results in the light of the above mentioned questions. Moreover, implications arising from the new analysis technique proposed here for (language-related) EEG research will be discussed.

Chapter 1
Theoretical Prerequisites

As already outlined in the introduction, the present thesis deals with an approach that attempts to resolve the uncertainty associated with the interpretation of language related event-related brain potentials (ERPs), in particular with the N400 as a hitherto undisputed reflection of semantic processing. Therefore, in the present chapter, we will first briefly introduce the ERP methodology (section 1.1). Then we will give a short overview of some generally accepted language-related ERP components in the light of Friederici's (1999, 2002) neurocognitive model of language comprehension (section 1.2), before presenting a more detailed discussion of the interpretation of the N400 (section 1.3 and 1.4). Finally, we will examine more closely some criticism of the ERP analysis method (section 1.5).

1.1 Event-related brain potentials (ERPs)

ERPs represent scalp-recorded changes in the ongoing EEG which are time locked to some specific event such as the presentation of a word or the onset of a behavioural response. The magnitude of these changes is small in comparison to the amplitude of the 'background' EEG. It is commonly assumed that the background EEG is in effect *noise* from which the ERP *signal* has to be extracted. This necessitates the use of signal averaging ('summation method') to improve the signal-to-noise ratio of the event-related response (Dawson, 1951, 1954).[1] Thus, ERP waveforms represent the average of EEG samples obtained on a number of trials (typically, between 30 and 40) belonging to the same experimental condition. The averaged waveforms represent estimates of the time-locked neural activity engendered by the presentation of stimuli belonging to different experimental conditions. Differences between ERP waveforms derived from different conditions therefore represent differences in the neural activity engaged by the items belonging to each condition.

---

[1] Since the invention of the summation method (averaging) through Dawson (1954) and the deployment of digital computer techniques (Barlow 1957; Brazier 1960; Clark 1987), ERPs are calculated by means of computer programs and mostly expressed as time dependent functions. However, there are no fundamental arguments to prefer and vindicate a time dependent ERP-analysis against a frequency-analysis; both reflect the same 'reality' (Lopes da Silva 1999a).

ERPs are especially useful for the investigation of language processing because of their excellent temporal resolution (usually in the millisecond range).[2] In addition, each averaged waveform is a multidimensional measure (in contrast to behavioural measures). In this way, ERP components are characterisable in terms of the following qualitatively different parameters: polarity (positive or negative deflection), topography (site of the effect dependent on electrode position), latency ('timing' relative to the onset of the critical item), and amplitude ('strength' of the effect; for a more comprehensive description of the method see e.g., Lopes da Silva, 1999a; Rugg & Coles, 1995; Picton, Lins, & Scherg, 1995; Kutas & Van Petten, 1994).

1.2 Language-related ERP components

In the following section, the most important language-related ERP components will be briefly described.

ELAN

A number of ERP studies have observed an early left anterior negativity between 150-200 ms, when the brain is confronted with phrase structure violations due to outright word category violations with either regular words such as (1) (Neville, Nicol, Barrs, Forster, & Garrett, 1991; Friederici, Pfeifer, & Hahne, 1993; Hahne & Friederici, 1999; Hahne, 2001; Hahne & Friederici, 2002) or even morphologically marked pseudowords such as (2) (Hahne & Jescheniak, 2001).

(1) * The man admired Don's <u>of</u> sketch the landscape.

(2) * Das Fiehm wurde im <u>gerottert</u>. (The ploker was being in-the <u>rished</u>.)

This early left anterior negative component was labelled ELAN (Friederici, 1995). The ELAN is typically interpreted as a highly automatic correlate of initial structure-building processes (first-pass parsing processes responsible for local phrase structure building; Friederici, 1995, 1999; Hahne & Friederici, 1999).

---

[2] In principle, the lower time resolution boundary is solely determined by the selected sampling rate (e.g. a sampling rate of 250 Hz gives a resolution of 4 ms).

Gunter, Friederici, & Hahne (1999) showed that the latency of the ELAN depends on input conditions: whereas the ELAN is early (150 ms) when the sentence is presented as normal connected speech or in reading conditions with a rapid presentation rate and/or a high visual contrast (Neville et al., 1991; Friederici et al., 1993; Hahne & Friederici, 1999), it appears only after about 450 ms when the stimuli are of low visual contrast or are presented in a slow word-by-word fashion (Gunter et al., 1999).[3]

LAN

Many studies in which the violation condition was realized as a morphosyntactic (i.e., inflectional) error have quite systematically observed left-anterior negativities (LANs) with a maximum between approx. 300 and 500 ms after onset of the critical item. LAN effects have been reported for agreement violations with legal words (e.g. subject-verb agreement as in 3, or wrong pronoun case as in 4, from Coulson, King, & Kutas, 1998; Kutas & Hillyard, 1983; Osterhout & Mobley, 1995: Gunter, Stowe, & Mulder, 1997) as well as with morphologically marked pseudowords (as in 5, from Münte, Matzke, & Johannes, 1997).

(3) * They <u>suns</u> themselves on the beach.

(4) * The plane took <u>we</u> to paradise and back.

---

[3] It has been argued that the latency difference between ELAN and LAN effects is also a function of when the relevant word category information is available. When available early, as in short function words (**Max's <u>of</u> proof the theorem*; Neville et al., 1991) or as in a prefix of the main verb (**Das Eis wurde im <u>ge</u>gessen*; *The ice cream was in-the eaten*; Hahne & Friederici, 1999) the ELAN occurred early (critical word and prefix are underlined), whereas for morphologically complex words in which the word category was marked only on the suffix (**Das Metall wurde zur vere<u>delt</u>* vs. *Vere<u>delung</u>*; *The metal was by the refined* vs. *refinement*; Friederici, Hahne, & Mecklinger, 1996), the left anterior negativity started 50 ms after the mean word category uniqueness point (corresponding to 370 ms after the word onset). This line of argumentation could also explain the late frontal negativity observed for pronoun-verb mismatches (*you <u>spend</u>* vs. *your <u>write</u>*) from the word pair study of Münte, Heinze, & Mangun (1993). Although the authors claim that their observed late negativity for *your <u>write</u>* is due to a morphosyntactic mismatch (and hence interpreted as a LAN), it could be argued that this pronoun-verb mismatch is in fact a clear word category violation. Because the possessive pronoun *your* requires a nominal argument like in *your writing*, the verbal argument *write* induces a structural violation. Similar to the example above (Friederici et al., 1996) the word category information becomes available not before the suffix (thereby eliciting a delayed ELAN). Furthermore, in the same experiment, Münte et al. investigate a pronoun-noun violation (*my laughter* vs. *you <u>administration</u>*). Unfortunately, this type of construction could also be understood as a structure analogous to: *you idiot*, thereby inducing a sort of semantic violation or implausibility.

(5) * Das Klenck$_{sg}$ frunen$_{pl}$ den Wech. (A mizzel quanch the plurr)[4]

Furthermore, it has been observed for gender violations (as in 6, from Gunter, Friederici, & Schriefers, 2000).

(6) * Sie bereist den Land auf einem kräftigen Kamel.
She travels the$_{masc}$ land$_{neuter}$ on a strong Camel.

It has been suggested (e.g. Münte et al., 1997) that the LAN specifically reflects the actual detection of a morphosyntactic mismatch. However, because a LAN can also be found in grammatically correct sentences, others have claimed that it indexes some aspect of working memory usage (Kluender & Kutas, 1993a,b; King & Kutas, 1995; Rösler, Pechmann, Streb, Röder, & Hennighausen, 1998; for a review see Vos, Gunter, Kolk & Mulder, 2001).[5] For example, in filler-gap constructions like (7b), the direct object of the verb *coerce* has been moved to the initial position of the embedded sentence via *wh*-movement (leaving its gap behind), whereas in (7a) it stays in its base position.

(7a) What did he wonder that he could coerce her into …

(7b) What did he wonder who$_i$ he could coerce t$_i$ into …

Kluender & Kutas (1993a) found that a LAN is elicited at the position of the moved *wh*-element *who* as well as at the preposition *into* (directly following the gap). They argued that

---

[4] Note that the sentence initial argument *Das Klenck* in (5) is case ambiguous between accusative and nominative and therefore also ambiguous with regard to its grammatical function. Because German allows object-initial structures like *den Jungen*$_{ACC,\ sg}$ *mögen*$_{pl}$ *die Mönche*$_{NOM,\ pl}$ (*the boy*$_{ACC,\ sg}$ *like*$_{pl}$ *the monks*$_{NOM,\ pl}$), the plural-marked verb *frunen*$_{pl}$ in (5) doesn't lead to an agreement violation per se (i.e. the sentence is still grammatical at the verb position). Therefore, the observed negativity cannot straightforwardly be interpreted as a correlate of a morphosyntactical mismatch, but instead might reflect a reanalysis N400 in the sense of Bornkessel (2002), i.e. reflecting a reanalysis (of the subject preference of the initial case ambiguous NP) that does not involve any modifications of the syntactic structure. However, beim Graben, Saddy & Schlesewsky (2000) found a P600 in response to the revision of a subject preference in interrogative sentences with case ambiguous *Wh*-phrases as in *Welche Frau sahen die Männer?* (*which woman*$_{ACC,\ sg}$ *saw*$_{pl}$ *the men*$_{NOM,\ pl}$*?*).

[5] It should be mentioned that, although the LAN appears in roughly the same time window as the late ELANs, both negativities show quite a different topographical distribution. Whereas the ELAN can be found bilaterally (especially at electrode sites F7 and F8), the LAN clearly has a more left anterior distribution (Friederici & Meyer, in press).

the critical constituent has to be identified as a moved element and subsequently held in working memory until the identification of its trace in the base position, so that it can be integrated into the current phrase structure. Hence, the first LAN effect would reflect the storing of the filler in working memory, whereas the second LAN would indicate its retrieval to fill the gap. Therefore, they interpreted their findings as presumable evidence that the LAN is a reflection of working memory load (but see the critical discussion in Fiebach, 2001, and the findings from Fiebach, Schlesewsky, & Friederici, 2001; Schlesewsky, Bornkessel & Frisch, 2003). King & Kutas (1995) compared the processing of object (8b) vs. subject relative clauses (8a) and found a LAN at the position of *sued* in object relative clauses (8b) but not in subject relative clauses (8a).

(8a) The fireman who$_i$ t$_i$ speedily rescued the cop <u>sued</u> the city over working conditions.

(8b) The fireman who$_i$ the cop speedily rescued t$_i$ <u>sued</u> the city over working conditions.

Furthermore, King & Kutas calculated multiword ERPs over the entire relative clause. They observed a sustained frontal negativity starting at the onset of the *wh*-filler and spanning the complete relative clause. They argued that this frontal slow-wave negativity reflects the increasing demand on working memory during the processing of object relative clauses, due to the maintenance of the *wh*-filler in working memory until the syntactic relation between filler and gap can be established.[6]

N400

As discussed in the Introduction, a centro-parietal negativity with a maximum at approx. 400 ms post critical word onset (=N400; Kutas & Hillyard, 1980) has hitherto been regarded as an unequivocal general index of a whole range of lexical-semantic processes (for a review see Kutas & Federmeier, 2000). This component will be discussed in more detail in sections 1.3 and 1.4.

---

[6] See Fiebach et al. (2001) and Fiebach, Schlesewsky, & Friederici (2001) for a similar interpretation with regard to long object *wh*-questions in German (Thomas fragt sich, <u>wen</u>$_i$ am Mittwoch nachmittag nach dem Unfall der Doktor <u>*t$_i$*</u> verständigt hat; Thomas asks himself, who$_{(ACC)}$ on Wednesday afternoon after the accident the$_{(NOM)}$ doctor called has).

P600/SPS

A late positive component with a broad parietal distribution and a typical latency between 600 and 900 ms post critical word onset, termed the P600 (Osterhout & Holcomb, 1992) or, on the basis of its functional characteristics, the Syntactic Positive Shift (SPS; Hagoort, Brown, & Groothusen, 1993), was first observed as a correlate of outright syntactic violations (following the ELAN and interpreted as an index of repair processes) in sentencences such as (9) (from Osterhout & Holcomb, 1992) and (1) (from Neville et al, 1991), as well as in so called 'garden-path' sentences that require a syntactic revision due to a temporal structural ambiguity (as in 10, from Osterhout & Holcomb, 1992).[7]

(9) * The broker hoped to sell the stock <u>was</u> sent to jail.

(10) The broker persuaded <u>to</u> sell the stock was sent to jail.

Furthermore, the P600 has also been found in sentences with a higher syntactic complexity (11a vs. 11b, from Kaan, Harris, Gibson, & Holcomb, 2000), thereby presumably reflecting higher syntactic integration costs.

(11a) Emily wondered *who* the performer in the concert had <u>imitated</u> for the audience's amusement.

(11b) Emily wondered *whether* the performer in the concert had <u>imitated</u> a pop star for the audience's amusement.

Friederici, Hahne, & Saddy (2002) argue that the P600 is not a unitary phenomenon. Based on topographical differences, they suggest that there are at least two types of positivity reflecting different aspects of syntactic processing: a more frontally distributed positivity related to syntactic complexity, and a more centroparietally distributed one related to syntactic repair mechanisms.

---

[7] Garden-path sentences are fully grammatical but require syntactic reprocessing due to a temporal structural ambiguity, i.e. the initial preferance-guided syntactic structure assignment (first-pass) has to be reanalysed (second parse) when conflicting information (e.g. word category, case) is met.

Latency differences have also been observed with regard to the P600. Friederici, Mecklinger, Spencer, Steinhauer, & Donchin (2001) investigated subject vs. object relative clauses (12a vs. 12b) with case ambiguous arguments and observed a positivity with a shorter latency between 300-400 ms (P345) followed by a small P600 for object relative clauses only (measured at the position of the disambiguation auxiliary).[8]

(12a) Das ist die Direktorin, die $_{\text{NOM/ACC,sg}}$ die Sekretärinnen $_{\text{NOM/ACC,pl}}$ gesucht hat $_{\text{sg}}$.
This is the director that the secretaries sought has.

(12b) Das ist die Direktorin, die $_{\text{NOM/ACC,sg}}$ die Sekretärinnen $_{\text{NOM/ACC,sg}}$ gesucht haben $_{\text{pl}}$.
This is the director that the secretaries sought have.

They concluded that the early P345 is a reflection of a process of diagnosis (diagnosing the need for reanalysis) and immediate recovery from a nonpreferred structure (Mecklinger, Schriefers, Steinhauer, & Friederici, 1995) whereas the P600 reflects the actual reanalysis itself.[9]

The temporal sequence of the components described above (ELAN, LAN/N400, P600/SPS) led Friederici (1995) to propose that they may reflect a temporal hierarchy in the availability or use of the different types of information encoded in the lexical entry, with word category information being processed earlier than other types of syntactic information (Friederici, 1995, 1999). These considerations with regard to a functional hierarchical mapping of ERP components resulted in the proposal of a three phase neurocognitive model of language comprehension (Friederici, 1995, 1999, 2002). In phase 1 (100–300 ms), the initial syntactic structure is formed on the basis of word category information. During phase 2 (300–500 ms), lexical-semantic and morphosyntactic processes take place with the goal to assign thematic roles and to establish semantic relations. Finally, during phase 3 (500–1000 ms), different types of information are integrated and reanalysis and/or repair processes set in when integration difficulties are encountered (e.g. unsuccessful mapping). Whereas the syntactic-phrase structure building is taken to be an autonomous process preceding semantic processes

---

[8] In addition, they observed a late positivity between 600 and 900 ms for object-first *complement* clauses.

[9] The processes associated with the P345 are assumed to be fast and automatic, because the P345 seems to be uninfluenced by semantic aspects (Mecklinger et al., 1995), probability variation (Steinhauer, Mecklinger, Friederici, & Meyer, 1997) and additional working memory load (Vos, Gunter, Schriefers, & Friederici, 2001).

(in phase 1), it is assumed that syntactic/semantic processes can interact in the late-time window.

A more comprehensive description of Friederici's neurocognitive model can be found in Friederici (1999; 2002). In addition, Bornkessel (2002) proposes an extension and refinement of the model in her 'argument dependency model' (especially with regard to phase 2; see also Schlesewsky & Bornkessel, in press).

1.3 The 'semantic' N400

It is still generally assumed, even in new text-books dealing with psycholinguistics or the neurocognitive bases of language (e.g. Brown & Hagoort, 1999), that the N400 is a language-related component reflecting lexical-semantic integration in the broadest sense.[10] In this section, we will first give an overview of some of the experimental findings that gave rise to the belief that the N400 is a unique reflection of lexical-semantic processes. Then we will show on the basis of recent findings that this belief in fact is a misbelief because the N400 can also be found in manipulations clearly outside the lexical-semantic domain. Furthermore, we address the consequences arising from these findings, namely the resulting uncertainty with regard to the functional interpretation.

Early attempts in the sixties and seventies, which were undertaken to use event-related potentials as markers of the well-known hemispheric lateralisation of language phenomena, remained without consistent results (e.g. Morrell & Salamy, 1971; Wood, Goff, & Day, 1971). It was the merit of Kutas & Hillyard (1980) to show that event-related potentials can be used to study the physiological correlates of semantic associations. Words that didn't fit into the preceding sentence context elicited a broad negativity between 300 and 500 ms post onset of the critical word depending of their degree of violation, i.e. strong context violations

---

[10] For example, Brown & Hagoort take the N400 for "…a marker of lexical processing", "…related to the processing costs of integrating the meaning of a word into the overall meaning representation that is built up on the basis of the preceding language input…", "…N400 amplitude modulations have been reliably linked to the processing of conceptual/semantic information." (Hagoort, Brown, & Osterhout, 1999:280/1).

(as in 14) showed a more pronounced N400 than moderate violations (as in 13).[11] In contrast, a pure physical deviance like in (15) elicited only a late positivity (P560).[12]

(13) He took a sip from the waterfall (moderate violation)

(14) He took a sip from the transmitter (strong violation)

(15) She put on her high heeled SHOES (physical deviance)

Since then, numerous studies have demonstrated a bilateral centro-parietal negative ERP component peaking at about 400 ms after stimulus onset, which can be reliably evoked in experiments contrasting semantically congruent with semantically incongruent sentence completions. This so-called N400 component has proved responsive to the manipulation of a whole range of different linguistic variables (for a review see Kutas & Federmeier, 2000). Although the N400 is especially pronounced in response to semantic violations, it is not simply an index of anomaly, but a part of the brain's normal response to meaningful stimuli. With regard to the processing of sentence context information, N400 amplitude was shown to be modulated by the 'cloze probability' that is, the degree of expectedness of sentence-final words (Taylor, 1953; Bloom & Fischler, 1980). The more unlikely a given completion for a sentence fragment, the more pronounced is the N400, so that its amplitude is an inverse function of cloze probability (Kutas & Hillyard, 1984; Kutas, Lindamood, & Hillyard, 1984). Furthermore, it was shown that predictability (based on sentence context) and semantic priming (through lexical context) are separate effects (Van Petten, 1993).[13] In addition, the N400 is sensitive to discourse-level constraints (Van Berkum, Hagoort, & Brown, 1999) and even to thematic level associations and constraints (St. George, Mannes, & Hoffman, 1994).[14] Several authors (e.g. Bentin, McCarthy, & Wood, 1985; Holcomb, 1988; Holcomb & Neville, 1990) have obtained similar results for semantic processing of single words presented in a

---

[11] Originally, Kutas & Hillyard interpreted the N400 as a reflection of 'reprocessing' that occurs when people seek to extract meaning from senseless sentences (Kutas & Hillyard, 1980:204).

[12] This late positivity (P560) seems to belong to the P3 family, i.e. it seems to be an instance of a so called P3b which can for example be found in visual oddball tasks.

[13] Words that were associated with a preceding word (prime) but embedded in an anomalous sentence (lexical priming) elicited a smaller N400 than unassociated words in congruent sentences (sentential context).

[14] St. George et al. (1994) investigated the word by word reading of ambiguous paragraphs. They not only showed that a disambiguating title helped readers to interpret a paragraph, but also that identical words yielded smaller N400s in paragraphs with disambiguating titles than when no title was given.

paired stimuli paradigm. For various other lexical-semantic manipulations reflected in the N400 see the overview in Kutas & Federmeier (2000).

It therefore appears that the N400 is a reflection of 'contextual integration', i.e. words that are easier to process because they are expected in a context or are semantically related to recently presented words elicit a smaller N400 than unexpected or unrelated words. However, the N400 is not only a reflection of the relative ease of semantic integration. For example, N400 amplitudes also vary as a function of even non-semantic factors like frequency (Van Petten & Kutas, 1990) and repetition (Rugg, 1990; Van Petten, Kutas, Kluender, Mitchiner, & McIsaac, 1991). Furthermore, the N400 amplitude has been found to be sensitive to category membership relations (based on semantic associations) regardless of the truth value of the sentence (Fischler, Bloom, Childers, Roucos, & Perry, 1983; Fischler, Bloom, Childers, Arroyo, & Perry, 1984; Kounios & Holcomb, 1992).[15] In (16) and (17), the same N400 is elicited regardless of the plausibility of the item in the local context (Kounios & Holcomb, 1992).

(16) All apples are <u>fruits</u>

(17) No apples are <u>fruits</u>

These results are taken as evidence for the involvement of long-term semantic memory processes in the elicitation of the N400. This link between the N400 and long-term memory processes is supported from findings with intracranial recordings (Nobre & McCarthy, 1995; Nobre, Allison, & McCarthy, 1994). Notably, the N400 response is not restricted visual word stimuli, but is also elicited for auditory presentations (i.e. modality independent), and even for pictures and line drawings (Nigam, Hoffmann, & Simons, 1992; Ganis, Kutas, & Sereno, 1996), photographs (McPherson & Holcomb, 1999), faces (Jemel, George, Olivares, Fiori, & Renault, 1999), and environmental sounds (Van Petten & Rheinfelder, 1995).

In summary, a great number of different types of potentially meaningful stimuli elicit N400s which are temporally coincident and also seem to be functionally similar.[16] Moreover, it is generally believed that the N400 is neither affected by language-irrelevant changes in the

---

[15] For a more extensive discussion of semantic and contextual or expectancy based priming see Chapter 4.

[16] Although it is likely that they are anatomically non-identical (Kutas & Federmeier, 2000).

physical attributes of words (cf. Example 3 above; Kutas & Hillyard, 1980) nor by non-linguistic symbolic mismatch (e.g. processing of music, cf. Besson & Macar, 1987; Patel, Gibson, Ratner, Besson, & Holcomb, 1998). However, most important in the context of the present thesis is the belief that the N400 is *not* sensitive to manipulations in language that are non-semantic in nature such as grammatical violations (cf. Kutas & Federmeier, 2000).

1.4 'Non-semantic' N400s

Unfortunately, more recent findings have shown that the hope of establishing a one-to-one correspondence between ERP components and linguistic sub-domains cannot be upheld. Particularly the N400, which was associated with an undisputedly uniform interpretation in terms of lexical-semantic processing for almost two decades, has now been observed in a number of heterogeneous areas. Firstly, studies examining incongruity processing with regard to faces (Jemel et al., 1999) and environmental sounds (Van Petten & Rheinfelder, 1995), for example, have shown that this component is not confined to language-related processes. Furthermore, an arithmetic N400 has been elicited by incongruous solutions in multiplication problems (Niedeggen & Rösler, 1996, 1999). Even more gravely, the N400 also has been elicited by a number of linguistic manipulations that are more or less independent of the lexical-semantic domain. For example, Praamstra & Stegeman (1993) report a phonological N400 in an auditory rhyming task (cf. also Rugg & Barrett, 1987). It is hard to see how these results could be incorporated into a lexical-semantic N400 approach. Furthermore, Weckerly & Kutas (1999) report an N400 effect for inanimate grammatical subjects (e.g. 'the poetry' in *The editor that the poetry depressed …*) in comparison to animate subjects (e.g. 'the editor' in *The poetry that the editor recognized …*). Whereas findings such as the latter (Weckerly & Kutas, 1999) could still be described within a broader sense of interpretive processes, the crucial reference to grammatical functions shows that these effects should at least be considered as phenomena at the semantics-syntax interface rather than as a part of semantics proper.[17]

---

[17] Several studies have suggested that the N400 effect reflects activity in a superordinate semantic-conceptual system which is language independent and can be accessed by several input codes like pictures, line drawings or environmental sounds (e.g., Barrett & Rugg, 1990; Nigam et al., 1992; Van Petten & Rheinfelder, 1995).

Yet, in a series of experiments, N400-like components have also been observed in domains which do not show this type of proximity to interpretive properties, for example for word order variations (Bornkessel, Schlesewsky, & Friederici, 2002), structures requiring a syntactic reanalysis (Osterhout, 1997; Bornkessel 2002), and conflicts of case (Frisch & Schlesewsky, 2001). Viewed under the perspective of the knowledge system 'grammar', these domains belong to different subsystems of syntax.

In this way, the component known as the N400 requires an interpretation that is much more heterogeneous in nature than previously assumed. Therefore, the question arises whether the observed N400-effects have to be associated with a global reflex of undifferentiated language-related conflict processing activity or if it is possible to gain more specific processing correlates by providing a more fine-grained characterisation of the N400s on the basis of additional information. Whereas the first option would lead to an aggravating loss of utility with regard to the indicator function of the N400 (i.e. the use of the N400 as a diagnostic tool for revealing the involvement of lexical-semantic processes)[18] the latter one presupposes that there are more fine grained analytical techniques which might allow further disentanglement of the association between linguistic sub-domains and the N400 (or ERP components in general).

1.5 Criticism of the ERP analysis method

The most accepted model of ERP analysis in the time domain is based on the general assumption that ERPs are signals generated from neural populations which become active time-dependent to a stimulus. These signals are summed up to the ongoing EEG activity (Rugg & Coles 1995). Hence, the following basic premises underlie ERP-analyses (although, for the most part, they remain implicit):

i) the evoked electrical activity (response) is time invariant with regard to a stimulus
ii) the ongoing EEG activity is basically constant stationary noise

---

[18] For example, in cases where the locus of the encountered processing difficulties cannot be established unamabiguously (e.g. in the case of structures where a negative polarity item is not in the scope of a negation, such as "*A telephone was ever sold*" which were shown to elicit an N400 and therefore categorised as an instance of semantic, rather than syntactic processing problems; cf. Saddy, Drehnhaus, & Frisch, in press).

Therefore ERPs are regarded as a signal (S_k), contaminated through additional noise ($\underline{N}_k$) which consists of the ongoing background activity (with *k* as discrete time variable):

$\underline{X}_k = S_k + \underline{N}_k$ (the underlined variable is stochastic)

Consequently, the measurement of ERPs becomes largely a matter of improving the signal-to-noise ratio, for example by means of averaging (cf. Basar 1980).

However, a completely different view is hidden behind the hypothesis that ERPs are – at least partly - due to a reorganisation of already existing ongoing EEG activity (Basar, 1998, 1999). Such a model is supported by a number of recent findings. Already at the beginning of the seventies, Sayers, Beagley, & Hanshall (1974) showed with the help of Fourier-analysis applied to single EEG segments, that auditory stimuli with either high or low intensity could be distinguished from prestimulus activity on the basis of their respective phasic spectral values (depending on stimulus intensity), whereas this was not possible on the basis of their respective amplitude values. They concluded that auditory stimuli primarily generate an ERP due to a reorganisation of the phase-spectrum of existing ongoing EEG activity. According to such a view, ERPs are the result of a process comprising phase control.[19] Recent findings strongly support the hypothesis that at least some ERP components are due to phase resetting mechanisms in specific frequency bands (Makeig, Westerfield, Jung, Enghoff, Townsend, Courchesne, & Sejnowski, 2002; Basar, 1999). Furthermore, it was shown repeatedly that ERP components are strongly dependent on ongoing prestimulus EEG activity (Basar, 1998, 1999; Schürmann, Basar-Eroglu, Kolev, & Basar, 2001). In addition, recent findings from Truccolo, Ding, Knuth, Nakamura, & Bressler (2002) impressively showed that the assumption of a stereotype time-invariant ERP signal is not warranted. Their findings revealed a large trial-to-trial variability of the evoked response with regard to latency as well as amplitude (although they mainly take their results as a possible objection against certain analysis methods in the frequency domain and the misleading interpretations thereof, e.g.

---

[19] Thus, Sayers et al. already concluded "…that the notion of signal-to-noise ratio (…) applied to a response waveform and its apparent noise background, is inapplicable to a situation in which a phase-control mechanism operates." (Sayers et al., 1974:483)

induced band power =*IBP*; cf. Bastiaansen, Van Berkum, & Hagoort, 2002a,b; Klimesch, Russegger, Doppelmayr, & Pachinger, 1998).[20]

Consequently, none of the above stated premises underlying the calculation of ERPs can be upheld. In this way, a simple additive model, as in the case of the averaging-method, in which ERPs are regarded as the sum of a deterministic signal and uncorrelated background noise, can merely be valid in ideal cases (Lopes da Silva, 1999a; Basar 1980). Notwithstanding, it is indisputable that the application of the ERP methodology not only led to a vast number of important experimental findings in language-related research, but also entailed crucial insights with regard to psycholinguistic theory (e.g. Kutas & Van Petten, 1994) and neurocognitive model building (e.g. Friederici, 1999, 2002; Bornkessel, 2002). Nevertheless, it should already become clear on basis of the above examples that complementary analyses in the frequency domain seem to be a valuable and recommendable supplementation of common ERP analyses. Therefore, in the following chapter, an analysis paradigm will be introduced which lies in the description of EEG frequency characteristics as correlates of corresponding cognitive processes.[21]

Such an approach is already well established in other domains of higher-level cognition (Basar, 1998, 1999; Klimesch, 1996, 1997, 1999). Furthermore, various studies have provided a first indication that the investigation of frequency band characteristics in relation to language comprehension processes indeed represents a new and promising methodological access (e.g. Roehm, Winkler, Swaab, & Klimesch, 2002; Pulvermüller, 1999; Pulvermüller, Preissl, Lutzenberger, & Birbaumer, 1996; Eulitz, Eulitz, Maess, Cohen, Pantev, & Elbert, 2000). More specifically, Roehm, Klimesch, Haider, & Doppelmayr (2001) showed a correspondence between activity in different frequency bands and linguistic sub-domains, thereby paving the way for a dissociation of language-related sub-components in terms of frequency band characteristics. Further supporting evidence in favour of pursuing such an approach was provided by Bastiaansen et al. (2002a,b) and Roehm, Winkler, Swaab, &

---

[20] "… inter-trial variability of the evoked response may appear as intra-trial stimulus- or task-related modulation of intrinsic parameters in the neural system. To overlook this possibility, as is commonly done, may result in the erroneous interpretation of trial-to-trial non-stationary as intra-trial task-related changes in functional connectivity." (Truccolo et al., 2002:207)

[21] An alternative approach, pursued by a number of researchers is, for example, the attempt to dissociate sub-components of the N400 by distinguishing their underlying neural generators via source-localisation (e.g. Schmidt, Arthur, Kutas, & Flynn, 1989; Simos, Basile, & Papanicolaou, 1997).

Klimesch (2002). Nevertheless, a direct association between the ERP components and the frequency band characteristics elicited by a *specific linguistic* phenomenon has hitherto not been reported.[22]

However, with regard to the question of whether it is possible to resolve the interpretative uncertainty of the N400 (and possibly also of other ‘fuzzy’ language related ERP components) by providing a more fine-grained characterisation of the N400 on the basis of additional information, the frequency-analytical investigation of the N400 seems to be a technique which might allow for a further clarification of the issue. Thus, in the following chapter, the basic frequency-analytical paradigm will firstly be shortly depicted before we introduce the analysis methods applied in the subsequent experiments.

---

[22] Although there is evidence from other cognitive domains for a successful application of such an approach, e.g. Basar (1998) and recently Klimesch, Schack, Schabus, Doppelmayr, Gruber, & Sauseng (2004).

Chapter 2

A Frequency-analytical Approach

> "From the perspective of Occam's razor, ERPs make good scientific sense, especially as entry points or precursors to more sophisticated methods." (Nunez, 2000:420)

2.1 Historical remarks

Although the observation that rhythmic electrophysiological brain activity might play an important role in the basic functioning of mammal brains can be traced back to findings from the late nineteenth century (Caton, 1875; Danilewsky, 1877; Beck, 1890a,b), it was not before 1929 that the German Hans Berger reported the first successful recording of electrical activity from the intact *human* skull (Berger, 1929).[1] He thereby not only confirmed and extended prior findings from animal research to human brain functioning, but furthermore provided an extensive description of the conditions under which these human rhythmic EEG activities can be observed. Berger validated the experimental results from Práwdicz-Neminski (1913), who had previously identified two different types of rhythmic activities (in the EEG of dogs), that were initially termed 'waves of the first order' (≈alpha) and 'waves of the second order' (≈beta).[2] Furthermore, Berger also noted that there is an inverse relation between amplitude and frequency of EEG rhythms. However, most importantly, he was the first to find an objective correlate of mental states by observing and describing the well-known alpha-blocking effect during cognitive processing.[3] Therefore, the so-called 'Berger-effect' (alpha-blocking) is regarded as the crucial starting point of psychophysiological EEG-research (Altenmüller & Gerloff, 1999).

Subsequently, research in this 'new' discipline focused on the relation between EEG-frequencies (natural brain rhythms) and behaviour. In 1951, the 'summation method'

---

[1] For a more comprehensive historical review see for example Coenen, Zajachkivsky, & Bilski (1998) and Niedermeyer (1999), as well as the references cited there.

[2] These waves were later called A- and B-waves; Berger (1938) termed them *alpha*- and *beta*-waves, a terminology which is still in use nowadays, although in Berger's notion the term beta-waves was a collective term for the whole frequency range between 20-100 Hz.

[3] However, Adolf Beck (1890a,b) had already observed oscillatory blocking phenomena during the investigation of rabbit and dog brains. When the eyes were stimulated with light, the ongoing rhythmical oscillations disappeared (Berger, 1938).

(superimposition method) as an averaging-technique was introduced into EEG-research by Dawson. This method led to the improvement of the signal to noise ratio, which subsequently led to the discovery of small endogenous event-related potentials (ERPs).[4] When the psychophysiological significance of these ‘endogenous’ potentials was recognised in the mid-sixties, research concentrated on the investigation of ERP-components and, as a consequence, frequency analysis receded more and more (Altenmüller & Gerloff, 1999). This tendency was reinforced by the deployment of digital computer techniques (Barlow 1957; Clark, Brown, Goldsetin, Molnar, O’Brian, & Zieman, 1961; Brazier 1960)[5] which allowed for ERPs to be calculated by means of computer programs and expressed as time-dependent functions (i.e. computerised averaging methods).[6]

Whereas the phenomenon of alpha-blocking and the accompanying appearance of higher frequency rhythms (‘beta-waves’) can be observed with the naked eye, a more thorough analysis of the involved frequency components (or the underlying frequency dynamics) is in need of appropriate computational techniques of wave analysis. Computational approaches to analysis in the frequency domain started early in the history of EEG. First attempts were already made by Berger (1932) and Dietsch (1932). The physicist Dietsch, who assisted Berger, applied Fourier analysis to short EEG sections (cf. Berger, 1938:193/4). In the year 1965, Cooley and Tukey invented and introduced the ‘Fast Fourier Transform’ algorithm (FFT) as the basis of power spectral analysis. The FFT not only facilitated the data analysis substantially, but furthermore contributed to a wider utilisation of frequency analysis in psychophysiological research. Investigations focussed mainly on the question of whether hemispheric differences in alpha-power could be related to tasks requiring predominant processing in one hemisphere (e.g. McKee, Humphrey, & McAdam, 1973). However, overall, the results obtained were disappointing.[7] As a consequence, many researchers switched over to the developing field of endogenous event-related potentials (Altenmüller & Gerloff, 1999).

Nonetheless, in recent years the frequency-analytical approach has experienced a renaissance. On the one hand, this “return to the neurobiological roots of psychophysiology” (Altenmüller & Gerloff, 1999:637) was due to the development of new analytical techniques based on the

---

[4] Thereby, Dawson can be regarded as the ‘father of evoked potential studies’ (Niedermeyer, 1999).

[5] Actually, the first Average Response Computer (ARC) was already completed in early 1958 (Clark, 1987).

[6] For an overview of the early history of EEG data-processing see Barlow (1997).

[7] The results exhibited only small effects which often could not be replicated by other investigators (Donchin, McCarthy, & Kutas, 1977).

calculation of FFT (Basar, 1980), as for example event-related desynchronisation or synchronisation (ERD/ERS) which allow for a calculation of the percentage of event-related power changes for different frequency bands (for the caluculation of ERD/ERS see the subsequent section and e.g. Pfurtscheller & Aranibar, 1977 or Pfurtscheller, 1999). On the other hand, the finding that coherent periodic neural activity in the high-frequency gamma band (40 Hz range) accompanies information processing in the olfactory bulb (Freeman, 1975) and visual cortex of vertebrates (Freeman & van Dijk, 1987; Gray & Singer, 1987; Eckhorn, Bauer, Jordan, Brosch, Kruse, Munk, & Reitbeck, 1988) led to a tidal wave of experiments searching for gamma oscillations as a correlate of cognitive processes in animals and humans (for an overview see Tallon-Baudry & Bertrand, 1999a). The significance of oscillatory brain activity in different frequency bands was emphasized in Basar's monograph *EEG-Brain Dynamics* (1980),[8] in which he proposed the working hypothesis that EEG is not simply 'background noise' or 'idling of the brain', but a crucial signal for the understanding of brain function (i.e. oscillations as brain codes). Furthermore, he suggested that evoked potentials (EPs) should be defined as the result of a superposition of induced or evoked oscillations in various frequency bands.[9]

---

[8] See also Galambos, Makeig, & Talmachoff (1981), who observed a 40 Hz auditory potential recorded from the human scalp.

[9] Bullock & Achimowicz (1994) pointed out that one should clearly distinguish between the terms oscillation or rhythm on the one hand, and wave on the other. They state that an oscillation is a rhythm or fairly regular fluctuation in some measure of activity. On the contrary, waves might simply be a portion of broadband activity isolated by a bandpass filter or caused by the ringing of a filter transient. Therefore, filtered waves could well be true oscillations. However, unless there is no clear and narrow power peak observable in the wideband spectrum, Bullock & Achimowicz suggest that these waves should merely be called components of the power spectrum, instead of rhythms. The same line of argumentation stems from Pfurtscheller & Lopes da Silva (1999). With respect to ERD (ERS), they argue that the term ERD is only meaningful "…if the baseline measured some seconds before the event represents a rhythmicity seen as a clear peak in the power spectrum" (1999:1843). However, Bullock, McClune, & Enright (2003) showed that quite often a clear peak in the power spectrum accompanied no periodicity peak and some periodicity peaks had no power spectral peak. Consequently, they concluded that the Fourier spectrum is not a reliable indication of rhythms. Hence, to circumvent the problematic issue whether we deal with true oscillations (rhythms) or merely with waves, and for the sake of simplicity, we will use both terms interchangeably. That is, oscillations and waves both simply refer to the outcome of the applied wavelet transform.

2.2 Basic concepts

In accordance with Galambos' (1992) classification scheme, which was originally proposed for the gamma frequency band (30-70 Hz), the following three general types of oscillations can be distinguished:[10]

1) Spontaneous oscillations (not stimulus-related; *background noise*)
2) Evoked oscillations (time *and* phase-locked to stimulus)
3) Induced oscillations (time-locked but *not* phase-locked)[11]

From a purely functional perspective (i.e. apart from possible effective neurophysiological realisations), it is still a matter of debate whether the proposed types of oscillations can be regarded as independent phenomena or must be treated as instances of one common denominator (i.e. with a common provenience). In the latter case, the originator for evoked and induced oscillations must necessarily be spontaneous (ongoing) oscillations which are somehow modulated or reorganised as a consequence or in preparation of stimulus processing.

The concept of synchronisation (desynchronisation)

Increases and decreases in spectral power are generally taken as a reflection of increases and decereases in synchrony of the underlying neuronal populations, respectively (Singer, 1993). Since the first descriptions of oscillatory EEG activity, it is well known that the frequency of brain oscillations is negatively correlated with their amplitude. Because the amplitude of oscillations is proportional to the number of synchronously active neural elements (Elul, 1972), slow oscillations (as a reflection of the activity of underlying cell assemblies) are due

---

[10] Galambos (1992) furthermore discriminates *emitted* gamma rhytms. These emitted gamma rhythms are anticipatory time-locked gamma waves which follow emitted stimuli in a train of regular stimuli. However, because emitted waves are time- but not phase-locked, they will be treated just as a special case of induced oscillations.

[11] Basar (1999:331) cites Brazier (1960:351), who presumably observed the first instance of a phase-locked alpha rhythm in humans (due to onset of light flashes): "This finding of a rhythm phase-locked to stimulus shows that the brain now has a rhythm that has been imposed on it through a sensory system. Has this imposed rhythm supplanted 'the endogenous' one; or is it the same rhythm with a shift in phase to carry the message; or is the basic rhythm still there and this one added? …"

to the activity of a larger population of neurons than fast oscillations (Singer, 1993).[12] Lopes da Silva & Pfurtscheller (1999) point out that synchronisation and oscillatory behaviour, although no doubt related, are nevertheless distinct concepts.[13] However, under the present hypothesis that ERPs can be explained by the superposition of evoked oscillations (e.g. Basar, 1998), both concepts will be treated as equivalent. Therefore, two types of changes in the EEG may occur upon sensory stimulation: one change is time-locked *and* phase-locked (evoked) and can be extracted from the ongoing activity by simple linear methods such as averaging; the other one is time-locked but *not* phase-locked (*induced*) and can only be extracted through some non-linear method such as power spectral analysis (Pfurtscheller & Lopes da Silva, 1999). The former type we will call *evoked oscillations*, and the latter *induced oscillations*. Whereas phase-locked activity can be easily captured with the most common method of calculating event-related potentials, spectral power changes have been investigated mainly with the measurement of event-related desynchronisation or synchronisation (ERD/ERS). With this approach, power changes within identified frequency bands that occur in response to stimulus processing can be calculated relative to (as a percentage of) a reference or baseline period (Pfurtscheller, 1999).[14] The classical method to compute ERD/ERS includes the following steps (cf. Pfurtscheller, 1999): (1) bandpass filtering of all event-related trials; (2) squaring of the amplitude samples to obtain power samples; (3) averaging of power samples across all trials; (4) averaging over time samples to smooth the

---

[12] Von Stein & Sarnthein (2000b) provided experimental evidence that led them to infer an inverse relationship between the size of an active neuronal assembly and the frequency of interactions. However, Nunez (2000) pointed out that very high excitatory firing rates generally cause reduction of EEG frequencies since frequency is predicted to decrease with increased amplitude at large amplitudes, although *moderate* increases in firing rates do not affect EEG frequencies.

[13] That is, they do not necessarily depend on one another (Singer, 1993). As an example of synchronous behaviour of neuronal populations that is not necessarily oscillatory, Lopes da Silva & Pfurtscheller cite transient components of sensory evoked potentials or interictal epileptiform spikes. However they also note, that "…there is a tendency for neuronal populations to display oscillatory behavior when synchronously active." (1999:3)

[14] A modification of the measurement of ERD/ERS is the calculation of event-related band power (ERBP; Klimesch, Russegger, Doppelmayr, & Pachinger, 1998). Whereas ERD/ERS displayes relative power changes (i.e. percentage activity changes in a critical time interval relative to a reference period which at best spans a rest or baseline condition), ERBP comprises the *z*-transformed absolute values. In this way, z-transformed ERD/ERS equals ERBP.

data and reduce variability.[15] According to this procedure, the obtained power measures (ERD/ERS, ERBP) include phase-locked as well as non phase-locked power changes, and therefore give an estimate of whole power changes in a specific frequency band. However, one major problem with regard to these measures is the determination of frequency bands and their bandwith. Although the suggestion to adjust frequency bands individually according to the *individual alpha frequency* (IAF) has been proved fruitful (see discussion in the subsequent section; Klimesch, 1999), the determination of frequency bandwith, especially outside the traditional alpha range like in the delta or subdelta range, is still an unsolved issue.[16] However, the wavelet transform (which will be used for the analysis in the experimental part of this thesis), circumvents much of these problems (at least at single-subject level) and furthermore gives a more accurate picture of power distributions as a function of time by means of time-frequency plots.

The concept of phase resetting

In Chapter 1, it was argued that the general conception that averaged ERPs are the result of a set of discrete stimulus-evoked brain events cannot be uphold. Sayers et al. (1974) already showed in a study of auditory ERPs that auditory stimuli reorganise spontaneous activity in the EEG by changing the distribution of phase. More recent studies provide further evidence that at least some ERP components might be generated by stimulus-induced changes in the phase of ongoing brain oscillations. There is ample evidence from animal studies that a phase resetting mechanism could be operative in hippocampal theta (e.g. Givens, 1996).[17] In human

---

[15] A further step in ERD/ERS computation would be the calculation of the percentage of power increase or decrease, respectively, according to the expression ERD% = (A – R)/R x 100 (where A = critical interval and R = reference interval).

[16] A possible solution to this problem would probably be the adjustment of frequency bands as a percentage of IAF. Doppelmayr, Klimesch, Pachinger, & Ripper (1998) showed that percentage adjustment is superior to methods that are based on fixed frequencies and fixed bandwiths (and also to individually adjusted frequencies but fixed bandwith). However, such an approach still presumes that there exists a linear relationship between frequency bands and IAF.

[17] Givens (1996) showed that task-relevant sensory stimuli elicited a resetting of rhytmic theta activity in the dentate gyrus of rats performing a working memory task, but not in rats performing a reference memory task with identical stimuli. He suggests that, as a consequence of the phase-locking of dentate theta activity, sensory information would more readily activate hippocampal circuits, increase synaptic efficacy, and organise the ensemble patterning of neural activity. Furthermore, he proposed that the phase-locking of the theta rhythm with sensory input might ultimately result in synaptic potentiation.

EEG, Brandt (1997) showed that, after the presentation of a visual or auditory stimulus, alpha waves undergo a partial phase resetting. This phase resetting was coincident with the visual and auditory evoked N1 component. Makeig et al. (2002) showed that the visual evoked N1 component arises from stimulus-induced partial phase resetting of multiple ongoing EEG rhythms. By analysing frequencies between 2 and 20 Hz, these authors found that theta and alpha oscillations exhibited non-random phase distributions following the presentation of visual stimuli in a visual selective attention task. The uniform phase distribution across trials present before and during stimulus presentation was replaced by a phase distribution weighted toward a dominant phase in the N1 time window. As there was no concurrent alpha power increase in single trials during the N1 interval, in contrast to a large power increase in the averaged ERP, Makeig et al. concluded that the poststimulus ERP has to be accounted for by phase resetting of ongoing EEG activity.

Klimesch, Schack, Schabus, Doppelmayr, Gruber, & Sauseng (2004) investigated the P1-N1 components during memory performance. In comparison to a prestimulus reference, they found a significant increase in phase locking for the alpha and theta band during the time windows of the P1 and N1. More importantly, the significant phase locking for alpha was accompanied by a decrease in power, which clearly suggests oscillatory phase resetting. It is important to stress that an enhanced phase locking does not per se mean that phase resetting was effected. A fixed-polarity, fixed-latency component superimposed on (random) oscillations would also lead to a transient reduction in the intertrial phase variability and, thus, would mimic phase resetting (cf. Klimesch et al., 2004). However, while phase locking can only occur with a concurrent amplitude increase in an evoked model, in an oscillatory model, phase resetting can occur independently of the type of amplitude modulation (cf. Klimesch et al., 2004 for more details). Therefore, phase locking without simultaneous amplitude increase or even with an amplitude decrease is clear evidence for phase resetting.

The above findings are further corroborated by a recent study from Rizzuto, Madsen, Bromfield, Schulze-Bonhage, Seelig, Aschenbrenner-Scheibe, Kahana (2003). These authors recorded intracranial EEG from the human cortex and hippocampal areas while subjects performed a short-term recognition memory task.[18] In response to all three stimulus classes (orienting stimuli, list items, and memory probes), they found a broadband increase in phase

---

[18] Each trial consisted of the presentation of an orienting stimulus (asterisk), followed by four list items (consonants) and a subsequent memory probe.

locking.[19] In addition, they showed that the peak in phase locking to probes, which was observed in the 7-16 Hz frequency range, was not associated with increased power in the post-probe interval.[20] Consequently, they concluded that the observed phase locking in the 7-16 Hz range had to be due to a reset of ongoing oscillations.

It should be mentioned that there also exists preliminary evidence for phase resetting in the delta band with regard to language processing. In a cloze probability task, Roehm, Winkler, Swaab, & Klimesch (2002) not only found a close correlation between the observed N400 effect for low-cloze probability items and increased evoked delta (delta response). They also found that the increase in evoked delta power was due to stronger phase locking *without* concurrent power enhancement in single trials (whole power).

It has been suggested that there is a basic distinction between amplitude modulation (AM) and phase modulation (PM) (Penny, Kiebel, Kilner, & Rugg, 2002). An example for amplitude modulation (AM) would be the ERP generation under its ‘classical’ conception, i.e., as a stimulus-related amplitude enhancement due to fixed-latency, fixed-polarity brain activities (enhancement of neuronal firing rate). On the other hand, the concept of *phase resetting* or *partial phase resetting* refers to the phenomenon that, following each stimulus presentation, the phase of an ongoing oscillation is shifted towards a particular value in relation to the stimulus (Tass, 1999). Therefore, considering the distribution of phases over many stimulus-related trials, one finds a pre-stimulus distribution that is approximately uniform, whereas the post-stimulus distribution shows a culmination at a dominant value due to phase modulation (PM). To decide whether an AM or a PM mechanism underlies the ERP, one needs to look at the spectral characteristics of their single-trial EEG. If there is no stimulus-induced increase in the power of a specific frequency band, then PM is the more likely mechanism.[21]

---

[19] Whereas most of the recording sites in various brain areas showed a preferential reset to all three stimulus classes, recording sites in the inferior temporal lobe, occipital lobes (bilaterally), and right posterior lobe exhibited a preferential reset to probes *only* in the 7-12 Hz band. However, list items and orienting stimuli also elicited a preferential reset in several brain locations.

[20] In fact, there was *negative correlation* between phase locking and post-probe power increase in this frequency range.

[21] However, as Penny et al. (2002) point out, both *AM* and *PM* mechanisms are likely to underlie real ERP data.

Taken together, the above findings provide ample evidence that electrophysiological recordings are not purely amplitude-modulated, but rather arise from an interaction between sensory input and ongoing brain oscillations. Hence, in the light of these findings and with regard to the primary aim of the present thesis, namely to address the vagueness of interpretation associated with traditional language-related ERP components by means of a differentiation of ERP components on the basis of activity in distinct frequency bands and their underlying dynamic behaviour (in terms of power change and/or phase locking), we need frequency based measures, which allow us to capture and keep apart the two confounding aspects of amplitude and phase modulations. To this end, in section 2.5 of the present chapter, we will introduce three frequency based measures (in supplementation to the calculation of averaged ERPs), which permit us to quantify (1) the degree of evoked power (EPow), (2) the degree of phase modulation independently of amplitude (phase locking index, PLI), (3) and an estimate of the degree of amplitude modulation (by means of whole power, WPow). Furthermore, the introduced measures form the basis for the analysis of the experiments in the remaining part of the present thesis.

2.3 Physiological basis and functional interpretation of oscillatory brain activity

Oscillatory brain waves, which are evoked or event-related (induced) to a sensory or cognitive event are usually classified according to the ‘natural frequencies’ of the brain (delta: 0.5-4 Hz, theta: 4-7 Hz, alpha: 8-13 Hz, beta: 14-30 Hz, and gamma: 30-70 Hz).[22] Unfortunately, the electrophysiological basis of the brain wave generation is not completely clarified (Altenmüller & Gerloff, 1999; for a comprehensive overview of the cellular substrates of brain rhythms see Steriade, 1999). Although, with regard to sleep spindle oscillations (low voltage bursts of distinctive 7-14 Hz sinusoidal waves) and slow oscillations (<1 Hz), there is already detailed knowledge about the intrinsic neuronal properties and network synchronisation, other types of oscillations (e.g. gamma oscillations) are far from being understood.[23] Surprisingly, this also holds for the well-studied alpha oscillations (even though the first description of alpha waves dates back more than 60 years), i.e. little is known about

---

[22] Note that beta oscillations will be discussed within the scope of gamma oscillations.

[23] For example, spindle oscillations characterise the state of light sleep; they are generated in the thalamus and their widespread synchronisation is determined by corticothalamic projections (Steriade, McCormick, & Sejnowski, 1993).

the precise site of production and virtually nothing about the underlying neuronal mechanisms (Steriade, 1999). Furthermore, most of the current knowledge stems from animal research or from *in vitro* studies.

Alpha oscillations

Despite sparse knowledge about the electrophysiological basis of alpha wave generation, there is general agreement that synchronous discharges of cortical cell assemblies driven by afferent thalamocortical inputs play an important role in alpha oscillations. Thalamic pacemakers are controlled by inhibitory inputs from the substantia reticularis in the midbrain (Steriade, 1999). Activation of the reticular system leads to *disinhibition*[24] of the thalamic pacemaker and might thereby cause alpha-desynchronisation of the EEG.[25] This hypothesis is supported by the observation that alpha-blocking – as measured via the method of event-related desynchronization (ERD) – is related to arousal mechanisms mediated by the reticular activating system (Moruzzi & Magoun, 1949). Although some researchers attempted to understand the mechanisms underlying alpha wave generation by refering to sleep spindle oscillations, which occur in the same frequency range (8-13 Hz) and for which the underlying generation mechanisms are already known in detail, both wave types are quite different oscillations with regard to their origins and their function (i.e. their behavioural context).[26] Whereas sleep spindle oscillations are associated with *unconsciousness* and with the *blockage* of synaptic transmission through the thalamus from the very onset of sleep, alpha oscillations have been taken as a correlate of cognitive processing since the time of Berger's first description. Experimental data from Lopes da Silva, van Lierop, Schrijer, & Storm van Leuwen (1973; alpha rhythm recorded from dog cortex) showed that cortico-cortical alpha coherence (i.e. coherence between adjacent cortical alpha rhythms) is larger than any thalamocortical coherence measured.[27] This observation led to the conclusion that a system of

---

[24] Disinhibition is the 'release' of inhibition. An inhibitory neuron which is inhibited by a second neuron reduces its inhibitory influence on a third neuron which leads to an enhanced firing rate of this third neuron.

[25] It has been shown that arousal mechanisms are mediated by the reticular activating system; however, arousal is related to alpha-blocking which again is reflected in a general alpha desynchronisation measured for example by event-related desynchronisation (ERD) method (Pfurtscheller & Aranibar, 1977).

[26] "Thus the idea of an alpha-to-spindle continuum, or alpha viewed as an embryo of spindle oscillations, is untenable." (Steriade, 1999:69)

[27] Andersen & Andersson (1968) advanced the hypothesis that facultative pacemakers in the thalamus induce activity in corresponding cortical areas, thus giving rise to a correspondence between thalamic and cortical

surface-parallel intracortical connections is mainly involved in the spread of alpha activity, while the influence of thalamic nuclei over the cerebral cortex is only moderate (Steriade, 1999).

The classical alpha suppression (Berger effect) can be described as follows: When a healthy individual is in a relaxed state, with eyes closed, one can observe the appearance of a rhythmic activity around 10 Hz located mainly at occipito-parietal leads. This occipital alpha rhythm is suppressed (or at least attenuated) when the eyes are opened and perceptual and/or mental activities are performed. Since the very first descriptions of alpha oscillations (Berger, 1929) it was suggested that alpha suppression reflects attentional processes (Mulholland, 1969; Ray & Cole, 1985). However, more recent evidence indicates that different frequency bands within the extended alpha frequency range reflect quite different cognitive processes.[28] Furthermore, it has been proposed that, besides a global cortical 10 Hz rhythm, there are several local cortical 10 Hz rhythms that can be functionally distinguished from one other on the basis of differences in both scalp distribution and reactivity to experimental manipulations (Nunez, 1995; Williamson, Kaufman, Lu, Wang, & Karron, 1997).[29] In a series of experiments, Klimesch and colleagues showed repeatedly that activity changes in the alpha frequency band, which are clearly functionally different can only be detected if (1) the alpha band is subdivided into several frequency bands with a small bandwith and (2) the respective frequency bands are individually adjusted in relation to the individual alpha frequency (IAF).[30] Results obtained from principal component analyses have shown that power values in the alpha band load on two different and orthogonal components, roughly corresponding to the upper and lower alpha bands (Mecklinger, Kramer, & Strayer, 1992). Together, these data

---

rhythmicity. However, the findings from Lopes da Silva et al. (1973) are not predicted under the assumption of a deterministic pacemaker which imposes its rhythm upon other systems and therefore would imply absolute thalamocortical correlation.

[28] For an overview see e.g. the special issue of the *International Journal of Psychophysiology*, **26**, 1997.

[29] Grey Walter (in Evands & Mulholland, 1969) already proposed that there is no single alpha rhythm but, rather, a variety of different alpha rhythms. Note that we will confine our description of 10 Hz rhythms to alpha rhythms in correlation with cognitive events. However, there are at least three 10 Hz rhythms which are aligned with sensory modalities: an alpha rhythm which is closely linked to the primary visual system (Berger, 1929), a mu rhythm corresponding to the somatosensory modality (and partly to the motor system; Pfurtscheller, 1999; Pfurtscheller, Neuper, Andrew, & Edlinger, 1997) and a tau rhythm corresponding to the primary auditory system (Tilhonen, Hari, & Kajola, 1991; Hari, Salmelin, Mäkelä, Salenius, & Helle, 1997).

[30] For a detailed description of the calculation of IAF and the determination of individually adjusted frequency bands see Klimesch, Russegger, Doppelmayr, & Pachinger (1998).

indicate that power values of the lower and upper alpha band vary largely independently from each other and that resting alpha frequency (as measured with IAF) marks the overlap between the two alpha bands. This fits well with the assumption of Nunez (1995) that there are different alpha populations that operate largely independently from each other.[31] With regard to the individual alpha frequency, it has been shown repeatedly that IAF is directly related to memory performance (Klimesch, 1997). For example, Alzheimer subjects with good memory showed an alpha frequency which was approximately 1.12 Hz higher than that of Alzheimer subjects with bad memory (Klimesch, Schimke, Ladurner, & Pfurtscheller, 1990). Generally, IAF tends to decrease with increasing task demands (Klimesch, 1997).[32] Furthermore, it has been found that there is a strong positive correlation between alpha power and intelligence (Doppelmayr, Klimesch, Stadler, Pöllhuber, & Heine, 2002).[33] Several experiments supported the suggestion that the broad alpha band has to be subdivided into (at least) three distinct frequency bands with a small bandwith and clearly discriminative functional role. It is crucial that these alpha subbands are calculated on the basis of IAF because otherwise contrary effects in the different subbands might be canceled out. Therefore, the three alpha bands would comprise the lower-1 alpha (IAF-4 Hz to IAF-2 Hz), the lower-2 alpha (IAF-2 Hz to IAF), and the upper-alpha (IAF to IAF+2 Hz). Whereas desynchronisation in the upper alpha band (~10-12 Hz) is selectively associated with the processing of stimulus-related sensory-semantic information (e.g. Klimesch, Schimke, & Schwaiger, 1994; Klimesch, Doppelmayr, Schimke, & Ripper, 1997; Klimesch, Doppelmayr, Pachinger, & Russegger, 1997), desynchronisation in the two lower alpha bands (~6-10 Hz) reflects attentional processes (attention in the sense of allocating processing resources).[34] In addition, it has been proposed that induced lower-1 alpha desynchronisation (~6-8 Hz) reflects phasic *alertness* (e.g. in response to a warning signal or target), whereas lower-2 alpha

---

[31] On the basis of these assumptions, Klimesch (1997:330) suggests that a task-related decrease in IAF is due to a tendency towards an asymmetric desynchronisation which is more pronounced in the upper than in the lower alpha band. Therefore, a drop in IAF reflects a shift in alpha power towards lower frequencies.

[32] This inverse relation holds particularly for poor performers (Klimesch, Schimke, & Pfurtscheller, 1993).

[33] In addition, Doppelmayr et al. (2002) could show that the alpha bands responded selectively to the different requirements of the applied intelligence test. Whereas the upper alpha band showed the strongest correlation with the IST-70 (an intelligence test which has a strong emphasis on semantic memory demands), power in the two lower alpha bands tended to show a more consistent relationship with the LGT-3 (which focuses more on the ability to learn new material).

[34] Klimesch (1997) proposed that *attention* in the sense of *allocating processing resources* may reflect the monitoring function of thalamocortical feedback loops.

desynchronisation (~8-10 Hz) reflects *expectancy* of an upcoming stimulus (Klimesch, Doppelmayr, Russegger, Pachinger, & Schwaiger, 1998).[35]

Theta oscillations

Theta waves were first described in the rabbit hippocampus during arousal due to sensory stimulation. Nevertheless, it is the hippocampal theta rhythm in the rat which is probably the most well-studied biological rhythm. It reliably appears when the animal engages in exploratory behaviour (which includes movement, sniffing and orienting), and in rapid eye movement (REM) sleep (Bland, 1986). In addition, hippocampal theta (in animals) is clearly an oscillatory component of the EEG which is related to the encoding of new information and to *episodic memory* in particular (Miller, 1991).[36] It has also been shown that the activity of hippocampal theta appears to be phase locked to stimuli in a working memory condition (but not in a reference memory condition, which comprised a pure sensory discrimination task). Hence, it was suggested that the resetting of the theta rhythm may play an important role in working memory (Givens, 1996). Furthermore, theta appears to play a role in the neural coding of place (O'Keefe & Recce, 1993).[37]

Lesion studies with rabbits showed that the septum can be regarded as the pacemaker of the theta rhythm (Petsche, Stumpf, & Gogolak, 1962). In addition, lesioning the medial septum produces severe impairments in memory function.[38] Whereas the cellular bases of theta wave generation have been intensively investigated in rodents, the presence of this rhythm in

---

[35] For a more comprehensive description of alpha oscillations and their functional correlates see the overviews in Basar (1998; 1999), Klimesch (1997; 1999), Schürmann (1998), as well as Basar, Hari, Lopes da Silva, & Schürmann (1997).

[36] According to Tulving (2002), episodic memory is a neurocognitive system that enables human beings to remember past experiences. That is, it stores information about the timing of events and episodes in a person's life (e.g. personal knowledge, organised by time and place of occurrence).

[37] O'Keefe & Recce (1993) showed that the *spatially* specific firing of hippocampal place cells in rats also had a characteristic *temporal* relationship with the hippocampal theta field potential. As the rat entered the place field of a given cell, the initial spikes occurred late in the theta cycle. As the rat passed through the place field, the phase advanced progressively. O'Keefe & Recce called this phenomenon '*theta phase precession'*. They concluded that firing phase is highly correlated with spatial location and hence provides additional information about the animal's location beyond the information provided by firing rate.

[38] Although neither prior learning of spatial information nor hippocampal place representations are impaired by septal lesions, septal lesions do impair the acquisition of new spatial information (Leutgeb & Mizumori, 1999).

humans was denied until recently (Steriade, 1999).[39] However, the crucial role of theta oscillations in neural plasticity and information coding as shown in rodent studies led to an increased effort to investigate the role of theta oscillations in human cognition (e.g. Squire, Ojeman, Meizin, Petersem, Videen, & Raichle, 1992; Tesche, 1997).

Although the spectral properties of scalp-recorded EEG signals had been studied for many years, there was long little evidence that theta oscillations are reflected in the human scalp-recorded EEG.[40] Nevertheless, recent studies using implanted depth and cortical surface electrodes in humans have changed this situation by demonstrating a task-related theta activation. In these studies, it was shown that theta increases in power during different cognitive tasks (e.g. Burgess & Gruzelier, 2000; Krause, Sillanmäki, Koivisto, Saarela, Häggqvist, Laine, & Hämäläinen, 2000; for a review see Klimesch, 1999). For example, theta power increases with memory load during both verbal and spatial n-back tasks, which involve the simultaneous encoding, maintenance, and retrieval of information (Gevins, Smith, McEvoy, & Yu, 1997; Krause et al., 2000). Klimesch, Schimke, & Schwaiger (1994) found that theta band power responded selectively to the retrieval of information from episodic memory in an episodic recognition task just as hippocampal theta in animals does. It has also been proposed that theta synchronisation is related to the successful encoding of new information. In an incidental memory task, words which could be remembered later exhibited a significantly larger extent of theta synchronisation than not-remembered words (Klimesch, Doppelmayr, Russegger, & Pachinger, 1996). In a coherence analysis, a significant long-range theta-band coherence between prefrontal and posterior electrodes was found during the retention interval of both a verbal and a visuospatial working memory task but not during a perceptual control task (Sarnthein, Petsche, Rappelsberger, Shaw, von Stein, 1998). Furthermore, human theta does not appear to be restricted to hippocampal sites, but rather appears over widespread regions of the cortex. This led von Stein & Sarnthein (2000a) to suggest that theta synchronisation across distant brain regions is characteristic of *top down* processes (which use higher-level expectations and strategies to coordinate lower level perceptual and encoding processes), whereas gamma synchronisation, which was found

---

[39] Theta waves have also been observed in other brain regions like the hypothalamus, entorhinal cortex, cingulate cortex, superior colliculus and prefrontal cortex (Kahana, Seelig, & Madsen, 2001).

[40] One main objection was that scalp-recorded signals would not allow for the observation of oscillations in deep brain structures such as the hippocampus. Furthermore, theta oscillations couldn't be identified in raw traces of the human scalp EEG and didn't show clear theta peaks in spectral distributions.

between more local brain regions, reflects *bottom-up* processes (for an interpretation of gamma oscillations see below).

Theta oscillations have also been found in human intracranial recordings. In one such experiment, the finding of theta involvement in rat spatial functions could be extended by revealing prominent theta oscillations in the human brain during a virtual, 3D-rendered maze-learning task (Kahana, Sekuler, Caplan, Kirschen, & Madsen, 1999). This study with subdural recordings from epileptic patients demonstrated that, during maze navigation, theta oscillations appeared more frequently during longer (i.e. more complex) mazes, and also more frequently during recall trials than during learning trials. In a follow-up study, Caplan, Madsen, Raghavachari, & Kahana (2001) showed that the effect of maze length on theta does not reflect the increased difficulty of encoding or retrieval at individual choice points of the maze, but rather reflects a more global difference between long and short mazes.

There is also some evidence that theta oscillations are related to evoked potentials. It has been proposed that certain components of the evoked potential result from the superposition of oscillations that are phase locked to stimulus presentation (Basar, 1999; Rizzuto, Madsen, Bromfield, Schulze-Bonhage, Seelig, Aschenbrenner-Scheibe, Kahana, 2003). Klimesch and colleagues report data which indicate that early P1-N1 components of the event-related potential are due to the superposition of evoked theta and alpha oscillations (Klimesch, Schack, Schabus, Doppelmayr, Gruber, & Sauseng, 2004). They observed that theta and alpha show a significant increase in phase locking during the time window of the P1 and N1 as compared to a prestimulus reference. In addition, they found that theta phase locking is larger during encoding than recognition and that good memory performers show a larger increase in theta and alpha phase locking during recognition in the time window of the N1. Klimesch et al. concluded that the evoked alpha and theta oscillations, which are primarily related to the generation of the P1-N1 complex, reflect the synchronous activation of two different memory systems, a working-memory and a semantic memory system.

Gamma (& beta) oscillations

Berger (1929) already observed that cognitive processing demands lead to a suppression (desynchronisation) of alpha oscillations and a simultaneous appearance of high frequency oscillations (>20 Hz) which he regarded as a reflection of mental processes. Nonetheless, until the beginning of the sixties, *activation* was mainly thought to consist of negative events (i.e. suppression of synchronised EEG waves). In 1960, Bremer and colleagues reported that a flattening of the cortical EEG due to brainstem stimulation was accompanied by an enhancement in the amplitude of spontaneous rhythms and their regular acceleration to 40-45 Hz, simultaneously with the ocular syndrome of arousal (cited in Steriade, 1999). Since then, a series of studies in various cortical areas have reported the presence of high-frequency oscillations during different conditions of increased alertness in dog, cat, monkey and human, but also during dreaming in REM sleep (Llinás & Ribary, 1993).[41] It is generally accepted that cortical neurons play a major role in the genesis of high-frequency oscillations. However, only recent studies have demonstrated that 40 Hz oscillations also appear in thalamocortical cells (Steriade, Curró Dossi, Paré, & Oakson, 1991). Despite the fact that the fast oscillations can be generated by intrinsic properties of single cells, it is assumed that complex neuronal circuits are required for the synchronisation of cellular ensembles in order to be visible in multi unit and EEG recordings (Steriade, 1999). In this line of argumentation, neocortical excitatory-inhibitory circuits (as exclusively intracortical circuits) have been thought to underlie the 40 Hz rhythm recorded in the visual cortex (Gray, Engel, König, & Singer, 1990). In addition to intracortical circuits, it has been shown that subcortical structures (particularly the thalamus) are interposed in complex neuronal chains generating 40 Hz oscillations (via *specific* thalamocortical resonant loops).[42] The presence of 40 Hz oscillatory neurons in the intralaminar nucleus has led to the proposal of a second *unspecific* thalamocortical circuit.[43] Llinás & Ribary (1993) propose that both systems (the specific and unspecific thalamocortical circuits) are tightly connected and interact with each other.

With regard to the functional significance of gamma oscillations, there are meanwhile numerous studies with heterogeneous findings showing that gamma oscillations cannot

---

[41] Llinás & Ribary (1993) consider the dreaming condition as a state of *hyperattentiveness* in which "…sensory input cannot address the machinery that generates conscious experience." (1993:2081)

[42] It is hypothesised that 40 Hz oscillations of specific thalamocortical neurons can establish thalamocortical resonance via inputs from cortical layer IV, which resonates with inhibitory interneurons at the same level. Such oscillations can reenter the thalamus via layer VI pyramidal cells and can resonate with both the nucleus reticularis and in the specific thalamic nuclei (thereby forming a thalamocortical reentrant loop) (Llinás & Ribary, 1993).

[43] The second system is represented by the intralaminar cortical input to layer I of the cortex and its return-pathway projection via layer V and VI pyramidal systems to the intralaminary nucleus (Llinás & Ribary, 1993).

clearly be attributed to a unique set of sensory or even cognitive functions.[44] One main view, which is still very popular among neuroscientists, is that gamma oscillations reflect a mechanism of feature linking (e.g. in the visual cortex; Eckhorn et al., 1988) - thereby possibly offering a solution to the puzzling *binding problem*.[45] In addition to a spatial mapping that only allows a limited number of representations, gamma oscillations are thought to bring about a temporal component by synchronised oscillatory responses across spatially separate cortical columns (Eckhorn, Bauer, Jordan, Brosch, Kruse, Munk, & Reitbeck, 1988; Gray & Singer, 1987; Singer, 1993). It is this conjunction of spatial and temporal factors that allows functionally coherent cell assemblies to link spatially distributed elements, thus possibly providing the bases for global and coherent properties of distinct patterns (Singer, 1990). However, there are many empirical findings which cannot be straightforwardly classified or even subsumed solely under this aspect (Schürmann, Basar-Eroglu, & Basar, 1997).[46] Being related to multiple functions, gamma oscillations may: (i) occur in different and distant structures; (ii) act in parallel; and (iii) show phase locking, time locking or weak time locking. Therefore, it has been proposed that gamma oscillations represent a universal code of central nervous system (CNS) communication (Kirschfeld, 1992; Basar, 1998, 1999). Based on their distinction of a specific and unspecific thalamocortical system (see above), Llinás & Ribary (1993) suggested that 40 Hz resonant coactivation of at least these two systems would provide one possible basis (or requirement) of a temporal conjoining of cerebral cortical sites activated at or around 40 Hz (thereby potentially giving rise to consciousness). Thus, the specific system would provide the ‘content’, and the nonspecific system would provide the ‘temporal binding’ of such a content into a single cognitive experience (evoked either by external stimuli or intrinsically, e.g. during dreaming).[47]

---

[44] For an overview see for example Galambos (1992) or Tallon-Baudry & Bertrand (1999a).

[45] The term *binding problem* refers to the general problem of integrating information across time, space, attributes, and ideas (Treisman, 1999). Binding is thereby the process responsible for the functional linking of distributed information (i.e. neuronal activity). For example, in the case of visual perception, it is well known that processing streams in the visual system are segregated, so that different visual feature dimensions (e.g. shape, colour, location) are processed in separate brain regions. How is this information bound together spatially and temporally to provide a unified and coherent representation? For a recent discussion about the “binding problem” see for example the collection of articles in *Neuron*, **24**, Issue 1.

[46] For example, simple electrical stimulation of isolated invertebrate ganglia evokes gamma oscillations in the absence of perceptual binding or higher cognitive processes (Basar, Basar-Eroglu, Karakas, & Schürmann, 2001).

[47] Recent evidence for the claim that specific and nonspecific thalamocortical inputs sum at the cortical level in a time-sensitive fashion stems from Llinás, Leznik, & Urbano (2002). In their own words, their results suggest

Delta oscillations

Delta waves can be defined as slow waves between 0.5 and 4 Hz that prevail during the deep stage of normal, EEG synchronised sleep. It is assumed that the generator mechanisms of delta waves are different from those underlying sleep spindles and 10 Hz alpha rhythms. As Steriade (1999) points out, the term *delta* seems to comprise a heterogeneous group of rhythms, with different mechanisms and levels of genesis within the thalamus or neocortex. He proposes the existence of two different types of delta activity: one generated in the cortex, the other originating in the thalamus. Experimental animal studies have shown that spindles are absent in athalamic cats, whereas the delta rhythm persists at the cortical level (Villablanca, 1974; but see the critical remarks in Steriade, 1999). On the other hand, thalamic recordings have shown the presence of focal delta waves even after cortical disconnection (Steriade, 1999). It has been demonstrated by animal studies in cat and rabbit that cortical delta waves are generated in the cortex, between layers II-III and layer V (e.g. Petsche, Pockberger, & Rappelsberger, 1984). Ball, Gloor, & Schaul (1977) studied the extracellular microphysiological properties of delta waves produced by lesions of the subcortical white matter, the thalamus or the reticular formation. They demonstrated that cortical delta waves exhibit a dipolar profile across cortical layers. Tangential recording of delta activity over distances of the cortex comparable to its thickness did not show any evidence for a tangential component in the current flow underlying delta waves. These findings indicate that delta waves are generated by vertically arranged dipole layers lying parallel to each other. This makes the pyramidal neurons in the cortex the most likely candidates for the generation of EEG delta activity. With regard to the thalamic delta oscillation, it has been suggested that it is an intrinsic oscillation depending on two inward currents of thalamocortical cells (Steriade, 1999).[48]

"…that the basic coinage for cognition is the existence of thalamocortical-resonant columns that can support the complex thalamocortical synchronization and coherence required for global cognitive binding" (2002:454). The preferred operation mode thereby shows up as oscillatory activity in the gamma band frequency.

[48] Interestingly, corticothalamic volleys (e.g. due to cortical stimulation of a motor area which is not directly related to the recorded thalamic nucleus) are capable of synchronising delta-oscillating thalamic cells that were uncoupled prior to cortical stimulation (Steriade, 1999). This makes reticular thalamic cells a possible candidate for the exertion of a mediating influence between afferents from cortical areas and thalamic cells.

Some researchers believe that synchronisation in the low frequency band up to 4 Hz has no functional significance, because such states of global synchrony require the discharge of very large populations of cells in unison (e.g. Singer, 1993). Furthermore, it has been shown that large scale synchronisation in low frequency bands occurs during sleep and in coma and anesthesia. Therefore, delta waves have been assumed to be inappropriate for information processing (Singer, 1993). However, there are also proposals for a functional significance of low frequency oscillations (even in natural sleep). For example, delta waves during slow-wave sleep have been linked to processes of memory formation, especially with regard to consolidation processes (Buzsáki, 1998; Hobson, 1988). In a recent study, Bódizs, Kántor, Szabó, Szütilde, Erõss, & Halász (2001) report the discovery of a rhythmic slow wave oscillation (1.5–3 Hz), recorded from near the human hippocampal formation, that is specific to REM sleep. The oscillatory activity was analysed from electrodes implanted near the parahippocampal gyrus in 12 patients with medically intractable epilepsy. There is also neurological evidence that direct stimulation of the *brain-stem ascending reticular activating system* (BSARAS) produces a low frequency cortical response in the 0-4 Hz range (whereas stimulation of the diffuse thalamic projection system leads to a 10 Hz wave; Guyton, 1976). Furthermore, functional correlates of delta waves in humans have been found during different cognitive tasks. For example, the amplitude of the delta response is increased during oddball experiments. Therefore, it has been concluded that the delta response is related to signal detection and decision making (Basar-Eroglu, Basar, Demiralp, & Schürmann, 1992; Schürmann, Basar-Eroglu, Kolev, & Basar, 1995; Demiralp, Ademoglu, Schürmann, Basar-Eroglu, & Basar, 1999; Schürmann, Basar-Eroglu, Kolev, & Basar, 2001).[49] Whereas the delta response to visual oddball targets has its highest response amplitude in parietal locations, for auditory target stimuli the highest delta response amplitudes have been observed in central and frontal areas (Schürmann et al., 1995; Basar, 1998, 1999). In addition, it has been shown that delta oscillations respond to stimuli at the hearing threshold in human subjects (Parnefjord & Basar, 1995). These findings confirm the role of the delta response in signal detection and decision making (Basar, 1999). It has also been suggested that a power increase in delta is related to task difficulty or complexity (Harmony, Fernandez, Silva, Bernal, Diaz-Comas, Reyes, Marosi, Rodriguez, & Rodriguez, 1996). In a mental arithmetic

---

[49] Schürmann et al. (1995) and Schürmann et al. (2001) showed that the delta response (0.5-3.5 Hz) dominates the P300 elicited in a visual oddball experiment (checkerboard reversals). Furthermore, averaging subsets of trials with differences between the delta response showed different P300 responses. This result can be taken as evidence for the dependence of the P300 on delta oscillations and hence as support for the proposed superposition hypothesis from Basar (1980, 1998, 1999).

task as well as in a Sternberg task, Harmony et al. (1996) observed a selective power increase during both conditions in comparison to a control condition. Additionally, in the Sternberg task, this power increase was more pronounced for the larger memory set size (5 vs. 3 digits). On the basis of prior findings from Giannitrapani (1971) and experimental results from their own group, Harmony et al. propose that delta activity is an indicator 'of attention to internal processing' during the performance of mental tasks.[50]

As for theta oscillations, there is some evidence that delta oscillations can be correlated with ERP amplitudes. Robinson (1999) showed a strong correlation between the N1 component and 7 Hz and 4 Hz first negative deflection latencies. More importantly, the P2 component was highly correlated with a positive delta deflection. Furthermore, he obtained supportive evidence for the hypothesis that the 4 Hz averaged evoked potential is associated with the maintenance of behavioural arousal and that the 4 Hz slow waves might be generated by the *brain-stem ascending reticular activating system* (BSARAS). He also found a negative correlation between wakefulness (i.e. behavioural arousal) and 4 Hz latency: shorter 4 Hz latencies were associated with greater wakefulness. Robinson (1999) also observed a negative correlation between 4 Hz latency and sex (with shorter 4 Hz latencies in females) and a positive correlation between 4 Hz latency and age.

2.4 Language-related oscillatory activity

It is quite remarkable that only very few researchers have attempted to apply frequency-analytical EEG methods to the investigation of language processing mechanisms. The reasons for this neglect are not really obvious. On the one hand, there has been an overwhelming dominance of the ERP paradigm in psycholinguistic research since the seminal findings of language-related ERP effects (N400) from Kutas & Hillyard in 1980 (see section 2.1). On the other hand, early attempts to use spectral analysis in the investigation of language processing primarily focussed on gross hemispheric differences with regard to different language tasks.

---

[50] Giannitrapani (1971) investigated changes in spectral power during different mental tasks: listening to white noise, to music, to verbal contextual material, looking at a poster, looking through diffusing goggles and silently performing mental arithmetic. Only in the latter task, he observed a delta power increase, whereas in the other conditions, which demand attention to the external environment, he observed a decrease of delta power. Therefore, Harmony et al. (1996:169) draw the conclusion that "…delta power increases only in those tasks which require attention to internal processing."

Hence, findings that task-related changes in EEG power (at the lower end of the power spectrum, i.e. delta, theta) showed hemispheric differences were regarded as evidence for a hemispheric specialisation for language functions (e.g. Davidson, Chapman, Chapman, & Henriques, 1990). Power spectrum asymmetries associated with engagement in the performance of verbal as opposed to non-verbal tasks were also found with respect to the alpha band (e.g., McKee et al., 1973; Klimesch, Pfurtscheller, Mohl, & Schimke, 1990; Pfurtscheller & Klimesch, 1992).

In a more recent study, Bizas, Simos, Stam, Arvanitis, Terzakis, & Micheloyannis (1999) observed that power spectrum measures (calculation of absolute power) varied systematically with the type of linguistic operation. Subjects had to perform a visual, orthographical, phonological, and lexical-semantic target detection task. In general, a systematic increase in spectral power was observable as a result of overall increased task complexity. The lexical-semantic task especially was associated with increased delta power (1-3.5 Hz) as compared to the phonological task. However, increased delta power was also noted in the orthographic vs. the pure visual task. Furthermore, there was also an increased delta and theta power (3.5-7.5 Hz) for the lexical-semantic vs. the visual task. In addition, the authors found significant power differences in the left hemisphere between frontal and temporal electrode sites (more pronounced frontal delta power during the orthographical, phonological, and lexical-semantic tasks, in addition to an increased theta power for the lexical-semantic task), and between parietal and temporal sites (increased parietal theta power for all four conditions).

Despite the overall findings that language specific processes might be successfully captured with power spectrum analyses, the earlier studies suffered from substantial methodological problems.[51] One major problem concerns the temporal resolution of spectral power measures. For example, Bizas et al. (1999; see above) calculated absolute power estimates over 8 sec epochs in relation to different linguistic manipulations. Consequently, the entire temporal dynamics which underlie and reflect specific task-related processing characteristics are lost. Moreover, most of the studies calculated spectral power over a broad frequency range (and with fixed bandwith). This method affects especially the evaluation of the classical alpha band

---

[51] Apart from possible conceptual misconceptions with regard to the question of what is an appropriate linguistic task/manipulation to investigate language processing (instead of for example task complexity as presumably reflected in the study of Bizas et al., 1999).

(8-13 Hz) with respect to task-related activity modulations.[52] A better understanding of the functional meaning of different oscillations is provided by the method of ERD (Pfurtscheller & Aranibar, 1977). In the following, we will shortly summarise some results from several studies which report putative language-related processing correlates in the higher frequency range (gamma, beta), before returning to very recent findings which show that specific language processing mechanisms are reflected in lower frequencies (<13 Hz).

Gamma oscillations and language processing

Earlier findings from animal research that coherent periodic neural activity in the high-frequency gamma band range (40 Hz range) accompanies information processing (Freeman, 1975; Gray & Singer, 1987; Eckhorn et al., 1988) led to an increasing effort to show that gamma activity cannot only be detected in human scalp EEG, but can also be reliably linked to stimulus processing. Indeed, changes in gamma-band activity could be observed when accoustic or visual stimuli were perceived (Tallon, Bertrand, Bouchet, & Pernier, 1995) or when movements were carried out (Kristeva-Feige, Feige, Makeig, Ross, & Elbert, 1993; Pfurtscheller, Neuper, & Kalcher, 1993). These high-frequency activity changes sometimes showed task- as well as stimulus-specific topographical differences (e.g. Pfurtscheller et al., 1993). Furthermore, cortical gamma-band activity has even been related to higher cognitive processes like face perception or decision making (Rodriguez, George, Lachaux, Martinerie, Renault, & Varela, 1999; Haig, Gordon, Wright, Meares, & Bahramali, 2000). Findings such as these caused some researchers to interpret gamma activity in terms of the so-called *Hebbian framework*, that is, taking local gamma-band activities as evidence for the existence of cell assemblies. More specifically, it has been proposed that high-frequency activity changes are related to the activation of cell assemblies (Pulvermüller, 1996, 1999). Under a Hebbian view, it is suggested that every cognitive element (e.g. each *gestalt* or *word*) has its own cell assembly. Such an assembly should be active whenever the cognitive element is processed (Pulvermüller & Preißl, 1991; Pulvermüller, 1996, 1999). As a consequence, it is predicted that high-frequency gamma responses should be tightly linked to language processes (Pulvermüller, Preissl, Eulitz, Pantev, Lutzenberger, Elbert, & Birbaumer, 1994; Pulvermüller, Preissl, Lutzenberger, & Birbaumer, 1995).

---

[52] As discussed above, it has been shown that the alpha band cannot be regarded as a unitary phenomenon but that (at least) three functionally distinct alpha subbands have to be distinguished (cf. Klimesch, 1997, 1999).

Starting from the above assumption that gamma band activity as a reflection of cell assembly activation should be related to language processing, Lutzenberger, Pulvermüller, & Birbaumer (1994) presented words and pseudowords in a lexical decision task. They observed a general power reduction in the alpha (7.5-12.5 Hz; alpha desynchronisation) and beta band (12.5-17.5 Hz) in response to both stimulus types. However, the only band in which they found reliable stimulus-specific differences in spectral response was the lower gamma band (25-35 Hz). Whereas words engendered no attenuation of the ongoing 30 Hz activity over the left hemisphere, the presentation of pseudowords led to a pronounced reduction in spectral power at around 30 Hz, which paralled the concurrent alpha desynchronisation. The authors interpreted their results as evidence for different neuronal dynamics in the language-dominant hemisphere. They speculated that pseudoword stimuli (which are presumably not be cortically represented) would fail to activate a cortical cell assembly or alternatively would lead to a partial activation of several assemblies representing words. Crucially, in both scenarios, this would result in asynchronous activity which would finally show up as a signal reduction. Results from an MEG experiment (Pulvermüller, Eulitz, Pantev, Mohr, Feige, Lutzenberger, Elbert, & Birbaumer, 1996) with a similar experimental design also showed reduced lower gamma-band activity in response to pseudowords and therefore resembled and supported the previous findings. A further EEG-study from Pulvermüller, Lutzenberger, & Preissl (1999) showed topographically distinct 30 Hz (25-35 Hz) responses to concrete nouns (e.g. *rat*) in comparison to action verbs (e.g. *write*).[53] Whereas lower gamma responses to concrete nouns were stronger over visual cortices (electrode sites O1, O2), the responses for action verbs were more pronounced close to motor cortices (C3, C4). In addition, Pulvermüller et al. (1999) observed a significant ROI x Word interaction between 200-230 ms post stimulus onset. This interaction was due to a more positive deflection for verbs vs. nouns at central electrode sites (C3/4) and a more negative deflection for nouns vs. verbs at occipital sites (O1/2).[54] Based on these findings, the authors proposed that the initial ERP difference

---

[53] But see the contradictory results from Khader & Rösler (2004). In a visual semantic priming experiment comprising a minimal phrase ([verb-noun-noun], [noun-noun-verb]; subjects had to judge the semantic relatedness between primes [verb-noun], [noun-noun] and targets [noun], [verb]), the authors analysed the EEG in response to the first word of a minimal phrase (verb vs. noun). They found no significant differences between verb and noun processing in the gamma band, neither in absolute or relative power, nor in coherence. Note, however, that Khader & Rösler point out that word-class specific gamma-band effects might possibly be task-dependent (Pulvermüller et al., 1999, used a lexical decision task).

[54] The ERP findings are published in Pulvermüller, Preissl, Lutzenberger, & Birbaumer (1996). In a study from Khader, Scherag, Streb, & Rösler (2003), these ERP results were by and large confirmed.

between 200 and 230 ms might reflect the *ignition* of a word category specific cell assembly (i.e. the '…initial access to a representation'), whereas the high-frequency response might correspond to *reverberation* in the respective cell assembly (i.e. reflecting sustained activity due to the fact that '… the cognitive item is kept in *active memory*').[55] In an MEG study, Eulitz, C., Eulitz, H., Maess, Cohen, Pantev, & Elbert (2000) investigated the differential processing of words, false fonts, shapes, and dots in a nonlinguistic target detection task. They found a pronounced induced 60 Hz brain magnetic activity around 200 ms after stimulus onset for words in comparison to false fonts and shapes. These differences supported earlier findings (Eulitz, Maess, Pantev, Friederici, Feige, & Elbert, 1996), which suggested that the induced 60 Hz activity enhancement might reflect oscillatory patterns specific to the processing of words. However, the overall differences across all four stimulus classes in Eulitz et al. (2000) revealed a dependence of event-related oscillations in the 60 Hz band on the *familiarity* of the visual '*Gestalt*' and therefore the latter results did not support the proposed lexical hypothsis.

Jürgens & Rösler (1995) pointed out that the interpretation of high-frequency oscillations is seriously flawed by the observation that power changes in the gamma range can be ascribed to corresponding power changes in the alpha frequency.[56] In line with this objection, Jürgens, Rösler, Hennighausen, & Heil (1995) showed that, although the power spectra of their subjects indeed revealed power changes in the high frequency gamma range, these power modulations appeared only at harmonics of the individual alpha frequencies. Contrary to this claim, Bertrand & Tallon-Baudry (2000) argued for a clear functional separation of alpha and high-frequency oscillations.[57] In a visual delayed matching-to-sample task, they observed an increased perception-related gamma response (for a memory condition in comparison to a

---

[55] According to such a view, early ERP effects should always precede induced gamma activity. This, however, is clearly contradicted by other experimental findings which observed that the first stimulus-specific modulation shows up in the gamma activity (e.g. Tallon-Baudry, Bertrand, Delpuech, & Pernier, 1997; in a *Dalmatian dog* experiment). Therefore, the precedence of evoked-potentials effects in comparison to high-frequency modulations cannot be considered a general rule. That is, the initial access to a representation is not necessarily expressed in the evoked potential (Tallon-Baudry & Bertrand, 1999b).

[56] For various other objections with regard to the findings and interpretation of the data from Pulvermüller, Preissl, Eulitz, Pantev, Lutzenberger, Elbert, & Birbaumer (1994), see the commentaries to this target article in *Psycoloquy*.

[57] Interestingly, beta activities showed the same type of variation with the task as gamma.

control condition) without a concurrent *differential* alpha response.[58] Unfortunately, they calculated alpha activity in a broad frequency band with fixed bandwith (between 8-12 Hz). Therefore, the above findings that gamma responses can be functionally (and topographically) distinguished from alpha responses (e.g. Bertrand & Tallon-Baudry, 2000), or that high-frequency power changes in the lower gamma range are specifically related to word processing and not just reflections of alpha harmonics (e.g. Lutzenberger, Pulvermüller, & Birbaumer, 1994) have to be treated with caution. For instance, because reductions of spectral power in the lower alpha range (~6-10 Hz) were found as a correlate of increased attention demands and/or enhanced processing efforts, the observed gamma spectral power reduction for pseudowords could simply be a reflection (due to alpha harmonics) of the increased processing demands for pseudowords as opposed to words.

With regard to high-frequency gamma oscillations as presumed correlates of specific language processes, several critical annotations have to be made.

(i) Up to now, differential gamma responses have only been observed in studies examining single word processing (i.e. words vs. pseudowords, nouns vs. verbs). So, at best (on basis of the current findings), early gamma activation (ignition) might be a reflection of 'access' to different 'word-webs' whereas late gamma reflects 'reverberation' in the sense of active memory (cf. Pulvermüller, 2001).

(ii) If we assume that distinct gamma responses reflect activity of specific neuronal cell assemblies (e.g. ignition, reverberation) on the single word level, one has to ask how this finding relates to higher order language processes (e.g. syntactic structure building) and general cognitive processes (e.g. attention, memory). In other words, on a more abstract level, how can gamma responses be linked with well established language-related findings from other methods (e.g. ERPs or fMRI)?

(iii) It has been suggested that gamma waves reflect a much more general effect, as for example neuronal *gain-control* (Kirschfeld, 1992, 1995), and are therefore independent of feature binding or other higher order functional implications (e.g. consciousness, awareness). According to this hypothesis, larger-amplitude

---

[58] The alpha resonse had also a distinct topographical distribution.

oscillations in the gamma range in response to meaningful words (as opposed to pseudowords, cf. Lutzenberger et al., 1994; Pulvermüller et al., 1999) would appear because meaningful words excite attention, and hence only they cause an increase in gain and in oscillation amplitude (Kirschfeld, 1995).

Low frequency correlates of language processing

In earlier findings from category judgment tasks, it was already demonstrated that there is a specific relationship between upper alpha ERD and semantic task demands (Klimesch, Pfurtscheller, & Schimke, 1992; Klimesch, Schimke, & Schwaiger, 1994). In two (more recent) experiments from Klimesch, Doppelmayr, Pachinger, & Ripper (1997) and Klimesch, Doppelmayr, Pachinger, & Russegger (1997), subjects had to judge whether sequentially presented feature-concept word pairs (*claws - eagle*, *wings - banana*) are semantically congruent. In both experiments, they observed a significant increase in upper alpha desynchronisation during the time interval in which the semantic judgement task had to be carried out (i.e. during the presentation of the second word).[59] Additionally, upper alpha desynchronisation was significantly larger for good semantic memory performers as compared to bad performers (with regard to a subsequent semantic memory task; cf. Klimesch, Doppelmayr, Pachinger, & Russegger, 1997). Hence, it has been suggested that upper alpha desynchronisation is sensitive to the encoding and processing of semantic information and, more specifically, reflects search and retrieval processes in semantic long-term memory.

Roehm, Klimesch, Haider, & Doppelmayr (2001) were the first to report low-frequency activity changes in response to a sentence processing task. Subjects had to perform either a reading or a semantic task. Whereas, in the first task, subjects simply had to read the sentences such as (1), in the second (semantic) task, an additional process had to be carried out.

(1) [Ein Kaninchen] [hat sich] [in der Kiste] [versteckt.]
[a rabbit] [has itself] [in the box] [hiding]
A rabbit is hiding in the box.

---

[59] By contrast, the theta band did not respond to semantic task demands at all.

In the semantic task, subjects were instructed to find the superordinate concept to the noun of the third chunk (which would be *container* in response to *box* in the present example). Thus, two linguistic processes were involved: sentence comprehension, which was common for both tasks, and, finding a superordinate concept, which was of importance in the semantic task only. Whereas both tasks elicited a similar increase in theta event-related band power, the semantic task showed a significant enhanced upper alpha desynchronisation in comparison to the reading task during the presentation of the second, third, and fourth chunk. Roehm et al. concluded that the findings for the theta band support the notion that theta reflects general processing demands of a complex working memory system and not linguistic processes per se, whereas the upper alpha band reflects semantic retrieval processes. Furthermore, the findings suggested that semantic processing does not draw selectively on the capacity of working memory. This conclusion was apparently weakend through findings from Bastiaansen, van Berkum, & Hagoort (2002a). In a sentence reading task, these authors observed a phasic induced power increase in the lower frequency bands (theta, lower-1 alpha), and a concurrent power decrease in higher bands (lower-2 alpha, upper alpha) in response to the presentation of individual words (but averaged over word positions *and* word categories).[60] More importantly, there was a slow gradual increase in induced theta power as the sentence unfolded. The authors speculated that this induced theta effect might reflect "…the formation of an episodic memory trace as the individual words in a sentence gradually converge into overall understanding of the 'episode' described by the sentence", or alternatively "… incremental verbal working memory load as the sentence unfolds." (2002a:16).[61] In a second study, Bastiaansen, van Berkum, & Hagoort (2002b) investigated the processing of syntactic violations in Dutch sentences such as (2) and (3).[62]

(2) Ik zag een donker <u>wolk</u>* aan de horizon (grammatical gender violation)
I saw a dark$_{\text{NEU}}$ cloud$_{\text{COM}}$* on the horizon

(3) Ik zaag enkele donkere <u>wolk</u>* aan de horizon (number agreement violation)
I saw several dark cloud* on the horizon.

---

[60] The authors propose that the phasic theta increase might reflect the activation of a cell assembly corresponding to the representation of the lexical item (Bastiaansen et al., 2002a).

[61] Note, however, that Bastiaansen et al. (2002a) presented their stimulus material in a word-by-word manner whereas Roehm et al. (2001) presented chunks. Of course, this difference is mirrored in the calculation of band power changes over single words vs. chunks. This, however, might have led to different results.

[62] Abbreviations used: COM ('common gender'), NEU ('neutral gender').

They observed a significant power increase in the delta and theta frequency bands between 300-500 ms after the onset of the critical word.[63] However, only the theta band revealed significant differences between correct sentences and sentences containing a violation. Furthermore, the two types of violations led to a different scalp distribution of the induced theta power increase. While grammatical sentences elicited bilaterally symmetrical induced theta power increases at frontal electrodes, number agreement violations were followed by induced theta power increases with a left-frontal maximum, whereas gender agreement violations led to increases with a right-frontal maximum.

However, there are some basic objections with regard to the findings of the two Bastiaansen et al. (2002a,b) studies and their interpretation. In both studies, induced band power (IBP; see Klimesch, Russegger, Doppelmayr, & Pachinger, 1998) was calculated as the percentage power increase or decrease in a particular frequency band with regard to a reference interval.[64] Unfortunately, the selected reference interval for the calculation of IBP sentence level-effects (Bastiaansen et al., 2002a) was between an auditory warning tone and the onset of the first word of the sentence. In the syntactic violation study (Bastiaansen et al., 2002b), the reference interval was choosen from 300 to 0 ms preceding the onset of the critical word (gender or number violation), that is in the middle of the sentence. Above all, this might have led to a heavy distortion of relative power changes in the lower alpha bands. As previous work indicates, the presentation of a warning stimulus already leads to a pronounced and sustained power decrease in lower alpha.[65] Hence, taking exactly this period of alpha desynchronisation as a reference interval for alpha IBP calculation implicates that a decrease of alpha desynchronisation will erroneously show up as alpha power synchronisation (cf. Fig. 1 & 2, in Bastiaansen, van Berkum, & Hagoort, 2002a).[66] Furthermore, Bastiaansen et al. assume that IBP reflects induced frequency-band-specific modulations *devoid* and *independent* of evoked

---

[63] Additionally, there was a phasic increase in induced theta power for each word between 300-500 ms after word onset (cf. Bastiaansen et al., 2002a).

[64] Note that the original proposal for the calculation of IBP from Klimesch, Russegger, Doppelmayr, & Pachinger (1998) is not based on percentage power, but on absolute power values. This is crucial because percentage power can only be calculated in relation to a reference interval.

[65] See, for example, Figure 1 in Klimesch, Russegger, Doppelmayr, & Pachinger (1998). Of course, the same argumentation holds for the presentation of words preceding the critical stimuli in the syntactic violation study.

[66] A further problem is that, for IBP calculation, Bastiaansen et al. (2002b) filtered the epoched EEG data (from 300 ms preceding to 1300 ms following the onset of the critical word). However, this might lead to unpredictable boundary effects.

activity (i.e. phase locked activity).[67] However, Truccolo, Ding, Knuth, Nakamura, & Bressler (2002) showed that, when the averaged ERP is subtracted from single-trial epochs, a stimulus phase-locked component remains in the residual time series (due to latency and/or amplitude jitter). Hence, the interpretation that IBP reflects induced rhythms which are independent of the occurrence of ERPs cannot be upheld. Instead, IBP has to be understood as a measure of inter trial variability showing the degree of latency and amplitude jitter (as in the original proposal of Kaufman, Schwartz, Salustri, & Williamson, 1989). Finally, IAF was determined through a spectral analysis on the EEG segments either ranging from 500 ms preceding sentence onset to 4800 ms after sentence onset (Bastiaansen et al., 2002a) or in a 2350 ms window ranging from 750 before to 1600 ms after the onset of the critical word (Bastiaansen et al., 2002b). In both cases, this is exactly during the processing of critical lexical-semantic information (either the whole sentence or critical word plus sentence ending). However, it has been shown repeatedly that lexical-semantic processing leads to a strong desynchronisation in the upper alpha band (IAF to IAF+2 Hz), with an additional power decrease in the lower alpha bands (IAF to IAF-4 Hz) (Klimesch, Doppelmayr, Pachinger, & Russegger, 1997). Therefore, calculation of IAF during cognitive (lexical-semantic) performance instead of during pure baseline demands (e.g. rest with eyes closed) artificially displaces the IAF towards the lower alpha bands (Klimesch, 1997; Pfurtscheller & Lopes da Silva, 1999; see also footnote 20). This effect results in the improper adjustment of the alpha- and theta subbands.[68]

Khader & Rösler (2004) investigated whether the processing of nouns vs. verbs engenders processing differences in spectral power and coherence. Whereas they found no significant differences between verb and noun processing in the high-frequency gamma range, they observed a significant theta power *decrease* for both word types. This theta *desynchronisation*

---

[67] To this end, the averaged band pass filtered activity (frequency-specific ERP) is subtracted from each band pass filtered single trial. Then, the obtained differences (the residual activity) are squared and averaged over the sequence of trials for each lead, experimental condition and for each subject. This squared difference is also called inter trial variance (ITV) (Kaufman, Schwartz, Salustri, & Williamson, 1989; Kalcher & Pfurtscheller, 1995).

[68] It is well known that theta and lower alpha show opposite reactivity to increased cognitive demands. Whereas theta power increases (synchronisation), lower-alpha power decreases (desynchronisation) (cf. Klimesch, 1999). Therefore, inappropriate lowering of the IAF by solely 0.5 Hz would distort both the lower-1 alpha band (cancellation of lower-1 alpha decrease through a portion of theta increase) and the theta band (due to an overlap with the delta band which shows the largest power values of the spectrum).

was more pronounced for verbs than for nouns at left frontal sites. However, this finding is at variance with other studies consistently showing theta *enhancement* in a variety of cognitive tasks (e.g. Doppelmayr, Klimesch, Schwaiger, Stadler, & Röhm, 2000). It is well known that with respect to a resting period, theta power synchronises with increasing task demands. As discussed above, the presentation of a warning signal elicits a strong event-related theta synchronisation, particularly at frontal recording sites (see Fig. 1. in Klimesch, Doppelmayr, Schwaiger, Auinger, & Winkler, 1999). However, in the Khader & Rösler (2004) study, power spectra were calculated relative to the presentation of a fixation frame. Hence, the observed theta desynchronisation in response to nouns and verbs should likely be reinterpreted as synchronisation.[69]

Whereas the afore mentioned studies investigated language-related processing correlates in the frequency domain more or less independently of present ERP findings (they handled both oscillatory activity and ERPs as separate but complementary phenomena), only one study has hitherto attempted to directly link *language-specific* ERP effects (or components) with concurrent changes in oscillatory activity. Roehm, Winkler, Swaab, & Klimesch (2002) investigated the relationship between linguistic processes, ERPs and ongoing rhythmic activity by examining an N400 cloze probability effect.[70] The starting point for their investigation was the general hypothesis that ERPs can be explained by the superposition of evoked oscillations (Basar, 1980, 1998, 1999; Basar, Basar-Eroglu, Karakas, & Schürmann, 2001), as well as the recent proposals that many ERP features are produced by partial EEG phase resetting of ongoing activity (e.g. Makeig, Westerfield, Jung, Enghoff, Townsend, Courchesne, & Sejnowski, 2002; Rizzuto, Madsen, Bromfield, Schulze-Bonhage, Seelig, Aschenbrenner-Scheibe, & Kahana, 2003; Klimesch, Schack, Schabus, Doppelmayr, Gruber, & Sauseng, 2004). Indeed, they not only found that the N400 cloze probability effect was highly correlated with an increase in evoked delta oscillations, but that this increase in evoked power was mainly due to an enhanced phase locking of delta oscillations.

---

[69] This assumption is supported through the findings that nouns elicited stronger absolut theta power, but a less pronounced decrease in relative theta power as opposed to verbs (Khader & Rösler, 2004:112). The same objection pertains to their coherence analysis. In relation to a precedent baseline, critical stimuli showed a relative decrease of theta coherence, although in absolute values they showed an coherence increase.

[70] Sentence final words with a low cloze probability (mean 3.8%) like in *The worker was critized by his family* vs. sentence final words with a high cloze probability (mean 83.98%) like in *They were startled by the sudden noise* elicited a pronounced N400 effect.

Coherence studies

The measure of coherence involves the computation of coherences between pairs of electrodes.[71] It is thereby a measure of correlation between two signals as a function of frequency. A coherence value of 1 indicates that the two channels maintain the same phase difference on every epoch, while a coherence value close to 0 indicates that the phase differences are random from epoch to epoch. Inter-electrode coherence is believed to indicate the degree of functional coupling of brain regions. However, the physiological significance of varying coherence still remains unclear since both increases or decreases of coherence may occur over brain areas involved in specific information processing (Altenmüller & Gerloff, 1999). Furthermore, ordinary coherence is susceptible to amplitude changes due to stimulus evoked responses. Hence, increases in coherence can either be due to a functional coupling between two areas (*internal synchronisation*) or can be the result of a stimulus-evoked response of each cortical area (*external synchronisation*).[72] Coherence between two channels will also appear to increase as a consequence of a decreased phase variability of the response of each channel. Furthermore, amplitude decreases due to activity decrease or revocation of previous increase can also lead to enhanced coherence values. Therefore, because ordinary coherence might reflect both genuine phase correlation and volume conduction effects, the oversimplified interpretation of high correlation coefficients between two regions in the sense of *common information processing* (strong coupling) is not warranted. This interpretation would only be valid in the case of a genuine consistency in the variation of phase across trials at two channels independently of stimulus-evoked phase locking (i.e. independently of the timing of the stimulus). Because current studies focussing on investigations of language processing by means of coherence measures mostly used ordinary coherence, and because

---

[71] The coherence of two channels m and k is a squared correlation coefficient that measures the fraction of variance in either channel at a given frequency that has amplitude and phase consistently (linearly) predicted by the other channel across epochs (Bendat & Piersol, 1986).

[72] It has been proposed that both contributions can be isolated by means of *partial coherence* (Srinivasan, 2004), a coherence measure which removes the contributions of phase locking to the stimulus to observed coherence. The partial coherence equals 1 when the residual signal at two channels, after removing the stimulus-locked components from each epoch, maintains constant relative phase between channels. It is claimed that only partial coherences between distant electrodes can be meaningfully interpreted as a reflection of synchronisation between distant brain areas. However, under the condition that there is trial-to-trial variabilty in evoked responses (Truccolo et al., 2002), partial coherence has exactly the same shortcomings as the measure of IBP, i.e. partial coherence just measures the inter-trial variance with respect to coherence.

coherence is primarily a measure of (long-range) *interelectrode* interactions,[73] we will not discuss results from coherence studies in the present context (but for a comprehensive review see Weiss & Mueller, 2003).

2.5 Methodological basics

In the following paragraph, we give a comprehensive overview of the frequency-analytical methods to be used in the experimental part of the present thesis. Because all of the applied frequency-based measures are determined by Gabor wavelet analyses (in order to achieve adequate time-frequency resolution as well as direct amplitude and phase estimates), we first introduce the basic advantages of wavelet analysis. Then, we will present three different frequency-based measures to be employed in supplementation to the calculation of event-related potentials.

Gabor Wavelet analysis

Temporal localisation of specific frequencies of a signal is constrained by the *uncertainty principle*: the more precise the temporal localisation, the more inaccurate the frequency information, and vice versa.[74] Therefore, the two extremes are, on the one hand, the signal itself (e.g. an EEG-epoch or average ERP), and its Fourier transformation on the other hand. Whereas in the case of an ERP (signal), the temporal resolution is maximal but without explicit information about the different frequencies contained therein, the Fourier transformation yields exact information about the frequencies of the ERP, but the temporal information of the ERP is lost or in fact assumed to be constant (Sinkkonen, Tiitinen, & Näätänen, 1995). Fourier analysis is well suited to projecting a signal on infinite sinusoids. The prerequisite is that the signal is stationary, i.e. the assumption that spectral characteristics do *not* change over time and therefore a signal x can be decomposed into a sum of sinusoidal

---

[73] Raw scalp coherence between electrode sites closer than about 8–10 cm is typically large or moderate only as a result of passive current spread and reference electrode effects, even when the underlying cortical sources are uncorrelated (Nunez, 1995, 2000).

[74] The *Heisenberg Uncertainty Principle* (originally introduced in the framework of quantum physics) states that one cannot determine the exact position of a signal at a specific moment in time. That is, one must sacrifice time precision for signal precision (if we need exact time values, we have to sacrifice frequency information, or vice versa).

waves with constant amplitude and phase. However, when a signal is not stationary, as is the case for EEG and ERP data sets, Fourier analysis is less adequate. In this case, time-frequency analysis must be used, where the spectrum is estimated as a function of time. Wavelet analysis was devised to analyse signals with rapidly changing spectra (for a relatively non-mathematical tutorial review of basic wavelet concepts see Samar, Bopardikar, Rao, & Swartz, 1999). It performs a time-frequency analysis of a signal, i.e. the estimation of the spectral characteristics of a signal as a function of time. In this sense, wavelet analysis is close to the windowed short-term Fourier transform. The major difference is that the window size is fixed for the short-term Fourier, whereas it is adapted to the frequency of the signal in wavelet analysis (Sinkkonen, Tiitinen, & Näätänen, 1995). Because of this difference, wavelet analysis has a more accurate time-frequency resolution (e.g. the duration of the window is shorter for higher-frequency bands). If a wavelet transform is applied to single trials, it allows for the identification of non-phase locked activities, as long as their signal-to-noise ratio is high enough. When it is applied to the average evoked potential, it mainly provides information on phase-locked oscillatory bursts. However, the quantification of phase-locking on the basis of average ERPs is not independent of signal amplitude, but inseparably intermingled with it. Therefore, a measure is needed which quantifies phase locking of oscillatory bursts irrespective of their amplitude.

In this way, Gabor wavelet analysis provides an optimal compromise between the time and frequency accuracies. Each convolution of a complex wavelet (wavelet family) with a signal $x(t)$ leads to a time-frequency (TF) representation of the energy of the signal (TF energy). In addition, it is possible to completely separate amplitude and phase information from each other. More specifically, the application of Gabor expansion to a signal $x(t)$ yields a transformation into a complex time-frequency signal $y(f_n,t)$ for all frequencies f_n of interest. Therefore, the amplitude $A(f_n,t)$ and phase $\Phi(f_n,t)$ of a signal can be obtained as functions of frequency and time (Re[.] and Im[.] denote the *real* and *imaginary* parts of the complex signal):[75]

$$A(f_n,t) = |y(f_n,t)|$$

$$\Phi(f_n,t) = \arg\{\mathrm{Re}[y(f_n,t)], \mathrm{Im}[y(f_n,t)]\}$$

---

[75] For a more detailed technical explanation of the method, we refer to *Appendix A* of Schack, Witte, Helbig, Schelenz, & Specht (2001).

In the experimental part of the present thesis, the following three different frequency-based measures will be applied: evoked power (EPow), whole power (WPow), and phase locking index (PLI).

Evoked Power (= EPow)

Evoked power is calculated on the basis of individual ERPs (i.e. averaged per participant, condition and electrode site) and then averaged over all participants (cf. Figure 1A, B, and C). More precisely, the Gabor expansion is applied to individual ERPs, thereby yielding a complex time-frequency signal $y(f_n,t)$. From this, the amplitude $A(f_n,t) = |y(f_n,t)|$ of the individual ERP is obtained as a function of frequency and time. Subsequently, the evoked power is calculated according to

$$S(f_n,t) = A^2 (f_n,t) = |y(f_n,t)|^2$$

and then averaged over all participants. Hence, EPow measures the proportion of evoked EEG activity in a specific frequency band (evoked TF energy) relative to the onset of a critical stimulus.

Whole Power (= WPow)

Whole power is calculated on the basis of *single trial power estimates* (i.e. individual trials for each condition and participant) with subsequent averaging (cf. Figure 1D and E). Thus, whole power is calculated analogously to evoked power, but, importantly, Gabor expansion is already applied to single trials and then subsequently averaged. In this way, *whole power* measures the total power in a respective frequency band (i.e. phase-locked *and* non-phase-locked activities are summed).[76] WPow is therefore similar but not identical to traditional band power.

---

[76] Strictly speaking, noise energy is also added up, so that only high signal-to-noise ratio activities will emerge. Therefore, it has been proposed to subtract the mean TF energy of a prestimulus interval (considered as baseline level) from pre- and poststimulus TF energy (e.g. Tallon-Baudry et al., 1996). This strategy would be similar to the calculation of event-related de/synchronization (ERD/ERS; Pfurtscheller & Aranibar, 1977; Pfurtscheller, 1999) which measures the proportional in- or decrease of stimulus-related bandpass-specific energy (power) in relation to a reference interval. An alternative approach (based on subtraction of a baseline condition) will be described in chapter 3.1.4.

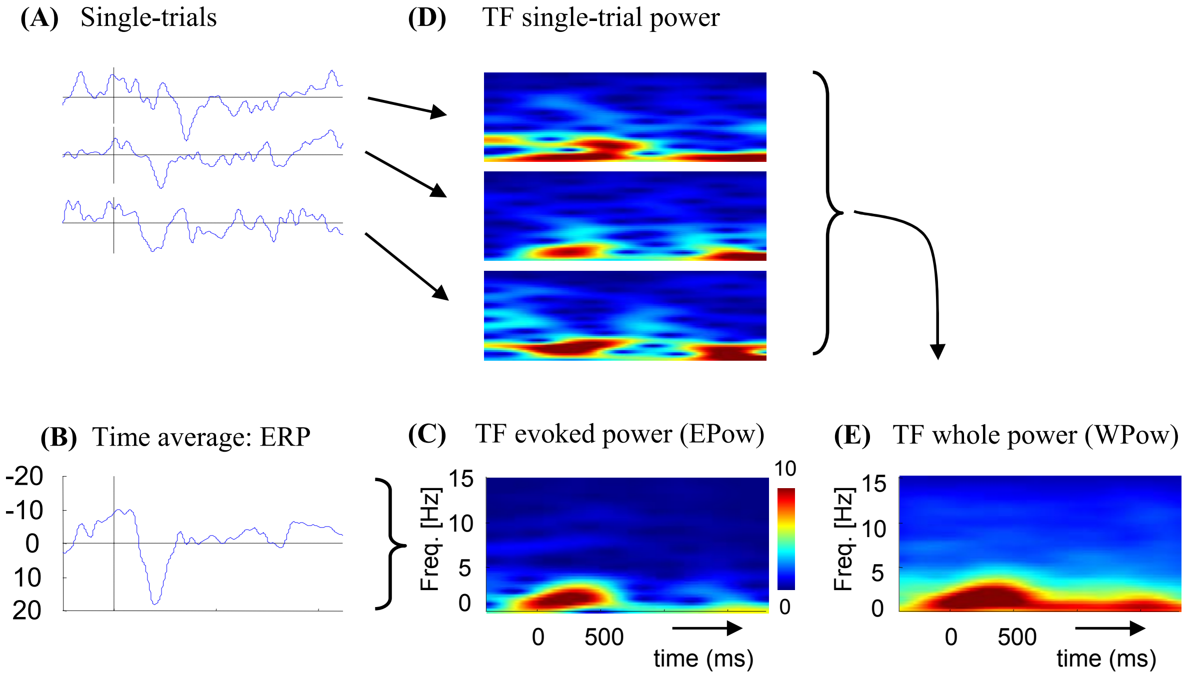

Figure 1. Schematic illustration of EPow and WPow calculation. (A) Successive EEG trials. (B) Averaging across single trials leads to the conventional event-related potential. (C) Time-frequency (TF) power representation of the evoked frequency responses. The x-axis represents time and the y-axis frequency. The colour scale codes the degree of power. The non-phase-locked activity is cancelled out. When the time-frequency power is computed for each single trial (D), and then averaged across trials (E), the phase-locked and non-phase-locked activity is revealed.

Phase Locking Index (= PLI)

The PLI measures the degree of inter-trial variation in phase between the responses to critical stimuli (Schack & Klimesch, 2002). It thereby quantifies phase-locking of oscillatory activity irrespective of its amplitude. To rate the phase variation across trials (with respect to stimulus onset), Gabor expansion is applied to single trials in order to calculate the phases $\Phi^k(f_n,t)$, k = 1, …, K for each single trial *k* and subsequently averaged over trials and participants (cf. Figure 2). The PLI is defined by

$$\mathrm{PLI}(f_n,t) = \left|\left\langle e^{j\Phi^k(f_n,t)} \right\rangle\right|, \mathrm{j} = \sqrt{-1}$$

The PLI is a normalised measure which ranges between 0 and 1, i.e. if PLI = 1 (or close to 1) there is no (or little) variance in phase across trials whereas a PLI = 0 (or close to 0) reflects maximal (or close to maximal) variance across trials. It is determined per condition, time-point, frequency and electrode site for each participant and then averaged over participants. A very similar measure had already been proposed by Tallon-Baudry, Bertrand, Delpuech, & Pernier (1996). They calculated a *phase-locking factor* on the basis of the 'phase-averaging' methods previously proposed in the frequency domain by Jervis, Nichols, Johnson, Allen, & Hudson (1983).[77] In addition, Lachaux, Rodriguez, Martinerie, & Varela (1999) introduced the *phase-locking value* (PLV) to detect synchrony in a precise frequency range between two recording sites. The PLV measures the intertrial variability of a phase difference between two signals *x* and *y* at time *t*.

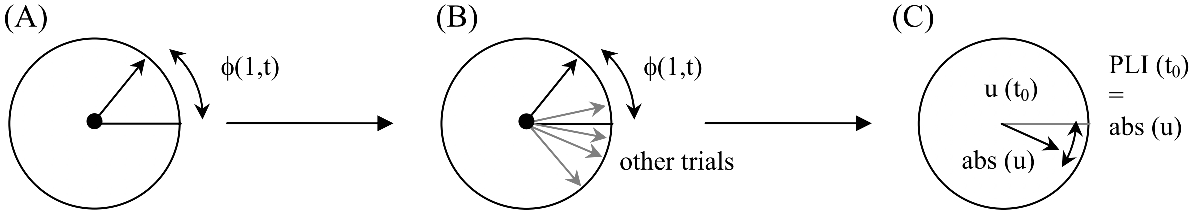

Figure 2. Estimation of phase locking index. (A) The convolution of f(t) with a Gabor wavelet centered at frequency *F* provides the instantaneous phase ϕ(t) for each time point. (B) By averaging these phase differences across the trials, (C) we obtain a complex value *u* (for each latency t), the amplitude of which (abs (u)) is the phase-locking index (Figure adapted from Lauchaux et al., 1999).

Some general predictions with regard to the measures EPow, WPow, and PLI

In the following paragraph, we will briefly highlight some conceivable scenarios with regard to the previously introduced measures EPow, WPow, and PLI, which would allow us to draw several conclusions about the underlying frequency dynamics of specific ERP component differences (or, more precisely, about specific ERP effects).

Under the hypothesis that event-related potentials are due to the superposition of induced or evoked oscillatons, and in the light of the assumption that there are basically two mechanisms

---

[77] Makeig et al. (2002) call their measure *event-related intertrial coherence* (ITC). However, ITC is analogous to the *phase locking factor* from Tallon-Baudry et al. (1996).

which can occur independently of each other (amplitude and phase modulations), the following three fundamental and simplified scenarios are conceivable with respect to a comparison of two idealised ERPs: (1) two ERP components are absolutely identical (that is, no differential ERP effect), (2) there is a differential effect due to activity differences in the same frequency band, and (3) there is an effect due to at least some activity in one or more different frequency bands (cf. Figure 3).

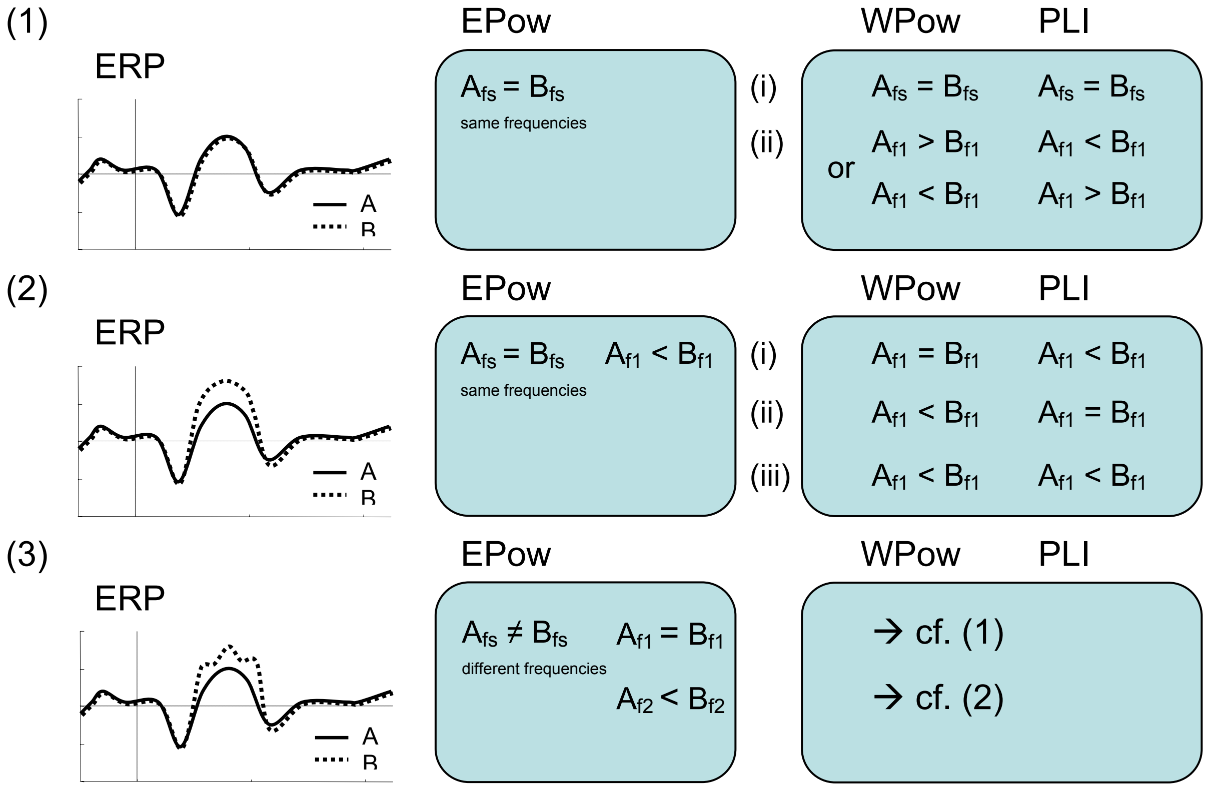

Figure 3. Three possible scenarios with regard to the comparison of ERPs and the frequency-based measures evoked power (EPow), whole power (WPow), and phase locking index (PLI). (1) For both conditions, A and B, identical ERPs show up. Therefore, EPow for A and B must also show the same modulation for all frequencies (fs). However, with regard to WPow and PLI, phase or amplitude modulation can differ with regard to a frequency band (f1). (2) A differs from B due to an amplitude enhancement of B. (3) B not only shows an increased amplitude in comparison to A, but also superimposed high frequency activity. Abbreviations used: fs = frequency spectrum; f1, f2 = specific frequency bands.

(1) If the two ERPs for condition A and B are identical, then their respective EPow must be identical (both measures just reflect the opposite side of the very same coin). With regard to the underlying dynamics in terms of amplitude or phase modulation, there are two

possibilities as to how this surface identity could be obtained: (i) There are no differences in WPow and PLI between A and B at all. This would simply confirm that both signals are also identical with respect to their underlying dynamics.[78] (ii) Frequency band F_i in condition B ($=F_iB$) shows more WPow than F_iA. This presupposes that F_iA accordingly displays a higher PLI than F_iB. Of course, the relation can be also exactly the other way round.

(2) If the ERP component for B in a given time range is enhanced in comparison to A, but both components display the same power spectrum (i.e. their frequencies are equal), this difference must be observable in a specific frequency band in EPow. Then, three underlying conditions could be responsible for this EPow increase: (i) WPow for F_iA and F_iB are equal, then the PLI for F_iB must be stronger than for F_iA. (ii) If the PLI for F_iA and F_iB are equal, then the WPow for F_iB must be more pronounced than for F_iA. (iii) WPow as well as PLI for F_iB could be enhanced in comparison to WPow and PLI from F_iA. In this case, the ERP effect cannot be ascribed to a single mechanism.[79]

(3) Furthermore, there could be a differential ERP component for B in comparison to A due to a different activation of specific frequency bands. In this case, the power spectrum shows a new spectral peak and this is also reflected in EPow. However, the appearance of a new frequency can be regarded as a special case of scenario (2; that is, there are differences in a specific frequency band). For all other frequencies which show no difference in EPow, scenario (1) would apply. Therefore (3) can be accounted for in terms of (1) and (2).

Note, finally, that the case where two ERPs *appear* to be slightly different, but this difference is not statistically significant (e.g. only small ripples due to high frequency activity), can be subsumed under (2) and (3).

---

[78] Note that, in principle, there still could be some *induced* activity in any frequency band in either condition. This, however, implies that the frequency band activity in a given time range must have a completely random or a perfectly bimodal distribution, so that at each time the averaged values would be zero (That is, there is an increase in WPow, but PLI must be zero). Hence, in real data this scenario is highly improbable. Therefore, we do not consider this option in the present simplified version of our model.

[79] Of course, these three possibilities would also hold if two or more frequency bands are reactive and show differential activation. Important is only that both ERP components show the same frequency profile.

Chapter 3

Evidence for a Differentiation of Superficially Indistinguishable N400 Components on the Basis of their Underlying Frequency Characteristics

As already discussed in the first chapter, the crucial starting position of the present thesis is the fundamental hypothesis that frequency-analytical methods can deliver valuable information and enhanced insights about processes and mechanisms involved in higher level cognitive processing (cf. Basar, 1980, 1998; Klimesch, 1999). There already exists ample evidence that this approach has successfully enhanced our understanding of primary sensory and motor-related processes (e.g. Pfurtscheller, 1994, 1999; Pfurtscheller & Klimesch, 1991; Klimesch et al., 2004; Brandt, 1997) and of higher cognitive processes as for example in the area of attention or memory research (for a review see Klimesch, 1996, 1997, 1999; Bastiaansen, 2000; cf. Chapter 2). As discussed in Chapter 2, to date there have only been very few attempts to investigate language processing with frequency-analytical methods (e.g. Roehm et al., 2001; Roehm et al., 2002; Pulvermüller, 1999; Pulvermüller et al., 1994; Bastiaansen et al., 2002a,b; Khader & Rösler, 2004). More importantly, to the best of our knowledge, there has been not a single attempt to combine event-related potentials (ERPs) and frequency-analytical methods in the framework of electrophysiological investigations of *language processing*, although the overwhelming majority of electrophysiologically-based psycholinguistic research is conducted with ERPs (cf. Chapter 1).

Considering the conclusions drawn in Chapter 1 that the specific functional interpretation of (almost all) traditional language-related ERP components is becoming more and more vague, and relying on the frequency-analytical methods introduced in Chapter 2, the perspective to supplement ERP measures with corresponding frequency-based analyses not only appears to constitute a promising approach to resolving the uncertainty of interpretation regarding language-related ERP components. It furthermore opens up the possibility to gain deeper insights with regard to the functional organisation of the language comprehension system and its inherent complexity via the analysis and consideration of corresponding dynamics in the frequency domain. For this reason, the present chapter will address the first of the three pivotal questions posed in the introduction, i.e., the question of whether it is possible to dissociate two language-related ERP-components that are indistinguishable on the surface on the basis of their respective underlying frequency characteristics. To this end, we will reanalyse ERP data from a previous language processing experiment in the light of previous findings and conclusions (Chapter 1 and 2), and, more importantly, with the help of the methodological tools introduced in Chapter 2.

3.1 Experiment 1: One component, but two linguistic processes

The hypothesis that the application of frequency-analytical measures not only provides valuable information complementary to event-related potentials (ERPs), but also enhances our understanding of (language-related) ERPs themselves presupposes that it should, in principle, be possible to describe ERP components by means of their inherent frequency dynamics. If such a characterisation in the frequency domain is not just a mere mirror image of an ERP component, which most likely would not provide additional information (cf. Chapter 2), it should unravel a unique profile and specification of the involved underlying processes (in terms of discriminative frequency dynamics). Moreover, this should allow us to draw further conclusions with regard to the functional differentiation and significance of the components under examination.

The crucial touchstone for the investigation of the question of whether it is possible to dissociate functionally different but superficially indistinguishable language-related ERP components on the basis of their respective underlying frequency characteristics would be an experimental situation in which (at least) two unequivocally different linguistic manipulations elicit two superficially indistinguishable ERP components. If frequency-analytical measures could then be applied successfully to distinguish these indistinguishable ERP components by means of their respective underlying frequency characteristics, this would be strong evidence for the relevance of the proposed research strategy with respect to the framework of higher cognitive processing in general and language processing in particular.

Therefore, in Experiment 1 we reanalysed the data of an ERP study reported by Frisch and Schlesewsky (2001), in which two superficially indistinguishable N400 effects were observed. The first was elicited as part of a biphasic N400-P600 pattern in (ill-formed) German sentences with two subjects (such as C in Table 3.1 below), whereas the second obtained in grammatical sentences with an inanimate subject (such as B in Table 3.1).

Condition	**Example**
A. GRAM-AN	| Peter | fragt sich, | welchen Arzt | der Jäger | gelobt | hat. | *Peter asks himself, [which doctor]*$_{OBJ}$ *[the hunter]*$_{SUBJ}$ *praised has*
B. GRAM-IN	| Peter | fragt sich, | welchen Arzt | der Zweig | gestreift | hat. | *Peter asks himself, [which doctor]*$_{OBJ}$ *[the twig]*$_{SUBJ}$ *brushed has*
C. UNGRAM-AN	| Peter | fragt sich, | welcher Arzt | der Jäger | gelobt | hat. | *Peter asks himself, [which doctor]*$_{SUBJ}$ *[the hunter]*$_{SUBJ}$ *praised has*
D. UNGRAM-IN	| Peter | fragt sich, | welcher Arzt | der Zweig | gestreift | hat. | *Peter asks himself, [which doctor]*$_{SUBJ}$ *[the twig]*$_{SUBJ}$ *brushed has*

Table 3.1. Example stimuli in each of the four experimental conditions (from Frisch & Schlesewsky, 2001). Abbreviations used: GRAM (‘grammatical’), UNGRAM (‘ungrammatical’), AN (‘second argument is animate’), and IN (‘second argument is inanimate’). All measures reported are relative to the second argument (underlined). The segmentation of the sentences for stimulus presentation is indicated with vertical bars.

With regard to the primary goal of language comprehension – determining “who is doing what to whom” in a given sentence – only condition A in Table 3.1 does not elicit any difficulties. In condition B, by contrast, the comprehension system is confronted with an inanimate, and therefore atypical subject. The difference between A and B is analogous to that between English sentences such as “*The girl hit the boy*” and “*The stone hit the boy*”. Whereas both are well-formed utterances of English, the latter violates the expectation that the subject (the Causer of the hitting event) is also a wilfully controlling Agent, thereby giving rise to enhanced processing cost (Weckerly & Kutas, 1999). In contrast to condition B, conditions C and D are ill-formed. The source of their ungrammaticality is similar to that of “*She hit he*” in English, in which the pronoun in object position (*he*) is a form only applicable to subjects (as in *He hit him*). In contrast to English, which unambiguously signals the interpretive relationship between participants (“who is doing what to whom”) by means of linear order, German also allows objects to precede subjects (as in condition A). Therefore, morphological case marking (e.g. welcher/der, “which/the$_{\text{SUBJECT}}$” vs. welchen/den, “which/the$_{\text{OBJECT}}$”) is the only reliable means of establishing interpretive relationships in German and this process fails when both arguments are identically marked.

3.1.1 Method

ERP and frequency-band analyses were applied to the original data from the Frisch and Schlesewsky (2001) study. For a comprehensive overview of the ERP results and the conclusions drawn, see the original study from Frisch & Schlesewsky (2001).[1]

Materials

The stimulus material for Experiment 1 comprised four critical conditions (cf. Table 3.1 above). For each critical condition, a set of 40 sentences was created, resulting in 160 critical sentences. Half of the critical sentences had two animate arguments (cf. Table 3.1, conditions A and C), in the other half, the first argument was animate and the second inanimate (cf. Table 3.1, conditions B and D). Furthermore, 50% of the critical sentences had an object and a subject argument and were therefore grammatically correct (conditions A and B, cf. Table 3.1), the other 50% were incorrect by having two arguments both marked as subject (conditions C and D, cf. Table 3.1). Additionally, a set of 160 similar filler sentences was constructed. These 160 filler sentences were randomly interspersed with the 160 critical sentences, resulting in 320 sentences. Grammaticality was counterbalanced over all sentences, i.e. 50% of the sentences were ungrammatical in order to avoid strategic processing.

Participants

Sixteen undergraduate students from the University of Potsdam participated in the experiment (9 female; mean age 22 years). All participants were right-handed monolingual native speakers of German and had normal or corrected-to-normal vision.

Procedure

Sentences were presented visually in the centre of a computer screen (segmentation shown in Table 3.1), with presentation times of 450 ms (plus 100 ms interstimulus interval, ISI) for the first argument in the subordinate clause, 400 ms (plus 100 ms ISI) for the second argument and 300 ms (plus 200 ms ISI) for all other segments (proper name, verbs, auxiliary).

---

[1] Frisch, S. & Schlesewsky, M. (2001). The N400 indicates problems of thematic hierarchizing. *NeuroReport*, 12, 3391-3394.

Following an 800 ms pause at the end of a sentence, participants were asked to judge its well-formedness within 2500 ms by pressing one out of two buttons. In 25% of all trials (randomly distributed), participants performed a second task, in which they were asked to judge whether a probe word had occurred in the preceding sentence or not. Half of the probes were incorrect, and false probes were semantically and/or phonologically related to actual words in the sentence. The experimental session began with a short training session of 24 training sentences (six in each of the four critical conditions, cf. Table 3.1), followed by 8 experimental blocks comprising 40 sentences each.

The EEG was recorded from 15 Ag/AgCl electrodes with a sampling rate of 250 Hz (impedances < 5 kOhm) and referenced to the left mastoid (re-referenced to linked mastoids offline). The horizontal and vertical electrooculograms (EOGs) were monitored. Only artefact-free trials for which the (first) judgement task was performed correctly entered the data analysis. Average ERPs were calculated per condition per participant from 200 ms prior to the onset of the critical stimulus item (i.e. the second argument) to 1000 ms post onset, before grand-averages were computed over all participants. Averaging took place relative to a baseline interval from -200 to 0 ms before the onset of the second argument.

Data Analysis

For the statistical analysis of the ERP data, repeated measures ANOVAs involving the critical two condition factors GRAMMATICALITY (= GRAM; grammatical vs. ungrammatical) and ANIMACY (= ANIM; animate vs. inanimate) were calculated for mean amplitude values per time window per condition in four lateral regions of interest (ROIs) as well as for the midline electrodes. Time windows were chosen as in Frisch & Schlesewsky (2001). Lateral regions were defined as follows: *left-anterior* (F3, FC5, C3); *left-posterior* (P3, CP5, PO3); *right-anterior* (F4, FC6, C4); *right-posterior* (P4, CP6, PO4). The midline electrodes were analysed in terms of the factor electrode (ELEC) with three midline electrodes (Fz, Cz, Pz) as levels.

The statistical analysis was carried out in a hierachical manner, i.e. only significant interactions ($p \leq .05$) were resolved. Interactions between the two conditions factors were resolved by the factor animacy in order to examine the differences between the ERP effects engendered by the violation depending on the animacy of the second argument.[2] In order to avoid excessive type 1 errors due to violations of sphericity, we applied the correction of Huyn & Feldt (1970) when the analysis involved factors with more than one degree of freedom in the numerator. For post hoc single comparisons between conditions, the probability level was adjusted according to the modified Bonferroni procedure from Keppel (1991).

3.1.2 ERP results

Figure 3.1 shows grand-average ERPs for the four critical conditions (cf. Appendix B1 for a more extensive selection of electrodes). Visual inspection indicates that approximately between 200 and 500 ms post onset of the critical second argument, the two ungrammatical conditions (C/D) and the grammatical inanimate condition (B) elicit an N400 in comparison to the control condition (A) (cf. Figure 3.1 below). Additionally, the two ungrammatical conditions (C/D) show a late positivity (P600) between approximately 600 and 1000 ms in comparison to the control condition (A).

The ERPs were analyzed statistically for midline and lateral electrodes separately in two time windows, namely 300-480 ms for the N400 and 600-850 ms for the P600.

Time window 1: 300-480 ms

The analysis of the lateral electrodes in the first time window showed main effects of ANIMACY (F (1,15) = 7.34, $p < .02$) and GRAMMATICALITY (F (1,15) = 8.79, $p < .01$). Additionally, there were significant interactions ANIMACY x GRAMMATICALITY (F (1,15) = 6.59, $p < .03$) and ROI x ANIMACY (F (3,45) = 4.38, $p < .01$) as well as a marginal interaction ROI x GRAMMATICALITY (F (3,45) = 2.37, $p < .09$). In view of the interactions with ROI and the global interaction ANIMACY x GRAMMATICALITY, we conducted pairwise comparisons for each of the four regions of interest.

---

[2] Note that the resulting two single comparisons are based on identical lexical material and are therefore free of potentially confounding lexical infuences such as frequency or semantic distinctions, which are known to strongly affect the N400 amplitude.

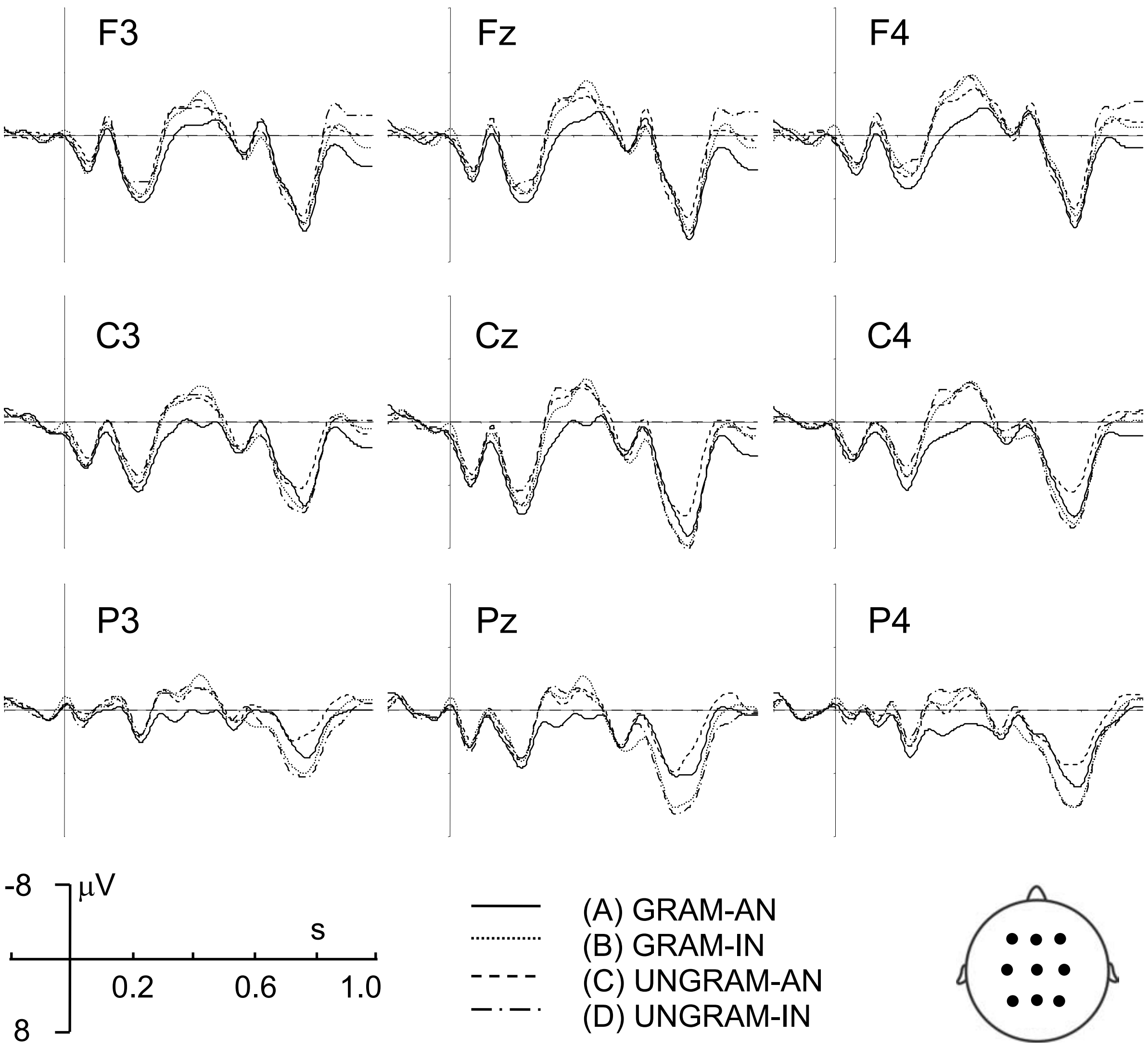

Figure 3.1. Grand average ERPs (N=16) for the four critical conditions (grammatical-animate = GRAM-AN; grammatical-inanimate = GRAM-IN; ungrammatical-animate = UNGRAM-AN; ungrammatical-inanimate = UNGRAM-IN; cf. Table 3.1) at the position of the second NP (onset at the vertical bar) in Experiment 1. Negativity is plotted upwards.

The *significant* results are shown in Table 3.2.[3]

---

[3] Note that all pairwise comparisons between the conditions *B*, *C*, and *D* were non-significant (*left-anterior*: $F < 1$; *right-anterior*: B vs. C ($F < 1$); B vs. D ($F < 1$); C vs. D (F (1,15) = 1.15, $p < .31$); *left-posterior*: B vs. C (F (1,15) = 1.00, $p < .34$); B vs. D ($F < 1$); C vs. D ($F < 1$); *right-posterior*: B vs. C ($F < 1$); B vs. D ($F < 1$); C vs. D (F (1, 15) = 1.00, $p < .34$).

ROI	Effect(s) of ANIM x GRAM	Pairwise comparisons
left-anterior	*F* (1,15) = 5.24, *p* < .04	A vs. B: *F* (1,15) = 8.13, *p* < .02 A vs. C: *F* (1,15) = 9.85, *p* < .01 A vs. D: *F* (1,15) = 8.58, *p* < .02
right-anterior	*F* (1,15) = 6.35, *p* < .03	A vs. B: *F* (1,15) = 11.16, *p* < .005 A vs. C: *F* (1,15) = 14.86, *p* < .005 A vs. D: *F* (1,15) = 22.07, *p* < .001
left-posterior	*F* (1,15) = 6.25, *p* < .03	A vs. B: *F* (1,15) = 17.26, *p* < .005 A vs. C: *F* (1,15) = 9.72, *p* < .01 A vs. D: *F* (1,15) = 8.43, *p* < .02
right-posterior	*F* (1,15) = 5.18, *p* < .04	A vs. B: *F* (1,15) = 15.04, *p* < .005 A vs. C: *F* (1,15) = 10.37, *p* < .01 A vs. D: *F* (1,15) = 20.21, *p* < .001

Table 3.2. Effects of ANIM x GRAM in each of the four ROIs and significant pairwise comparisons for the time window 300-480 ms in Experiment 1.

All of the significant single comparisons shown in Table 3.2 resulted from a more negative waveform for the three critical conditions in opposite to the grammatical animate condition.

With regard to the midline electrodes, there were main effects of ANIMACY (*F* (1,15) = 7.55, *p* < .02) and GRAMMATICALITY (*F* (1,15) = 5.62, *p* < .04) as well as a significant interaction ANIMACY x GRAMMATICALITY (*F* (1,15) = 5.77, *p* < .04). Global pairwise comparisons revealed significant differences between the three critical conditions and the grammatical animate condition (A vs. B: *F* (1,15) = 4.47, *p* < .03; A vs. C: *F* (1,15) = 5.71, *p* < .02; A vs. D: *F* (1,15) = 4.32, *p* < .03) which all resulted from more negative waveforms in comparison to the control condition (A).[4]

Time window 2: 600-850 ms

In the second time window, the statistical analysis for the lateral electrodes showed a main effect of GRAMMATICALITY (*F* (1,15) = 4.45, *p* < .05) as well as a significant interaction

---

[4] Non-significant pairwise comparisons for the midline electrodes: B vs. C (*F* (1, 15) = 1.00, *p* < .43); B vs. D (*F* (1, 15) = 1.04, *p* < .41); C vs. D (*F* (1, 15) = 1.80, *p* < .20)

ROI x GRAM (*F* (3,45) = 3.07, *p* < .04). Resolution of the interaction by ROI revealed significant effects of GRAM for both posterior regions (*left-posterior*: *F* (1,15) = 13.75, *p* < .005; *right-posterior*: *F* (1,15) = 7.26, *p* < .02) due to a more positive waveform for the two ungrammatical conditions.

In the analysis of the midline electrodes, the main effect GRAMMATICALITY (*F* (1,15) = 5.10, *p* < .04) reached significance. Additionally, there was a significant interaction ELEC x GRAM (*F* (3,45) = 12.05, *p* < .001). The interaction was resolved by ELEC, thus revealing a significant effect of GRAM at electrode PZ (*F* (1,15) = 19.30, *p* < .002). This effect resulted from a more positive waveform for the ungrammatical conditions.

3.1.3 Interim discussion

Between approximately 300 and 500 ms post onset of the critical second argument, the two ungrammatical conditions (C/D) and the grammatical inanimate condition (B) elicited an N400 in comparison to the control condition (A) (cf. Figure 3.1 and 3.2). Most importantly, the statistical analysis revealed no difference between the three critical conditions with regard to the N400. Additionally, the two ungrammatical conditions (C/D) showed a late positivity (P600) between approx. 600 and 1000 ms in comparison to the two grammatical conditions (A/B).

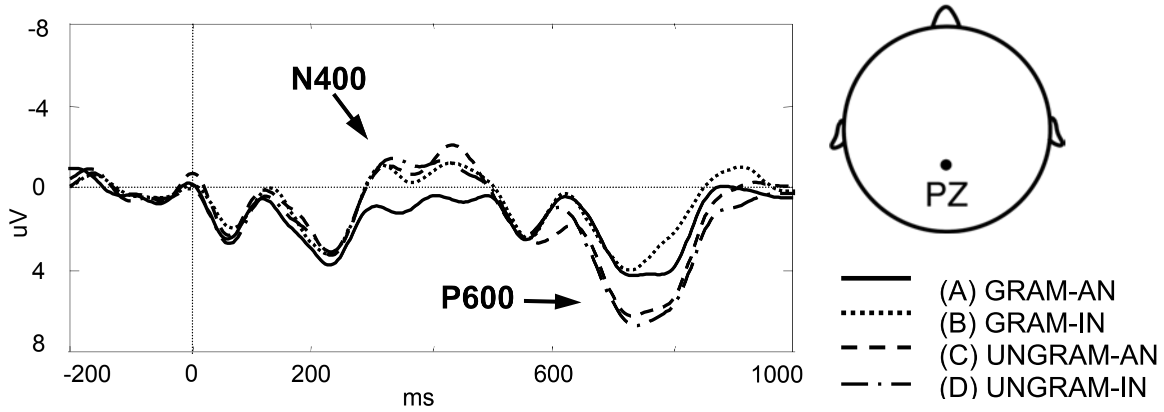

Figure 3.2. Grand average ERPs (N=16) at electrode PZ for the four conditions described in Table 1. The vertical bar corresponds to the onset of the critical second argument (cf. Table 3.1) and negativity is plotted upwards.

Because the P600 effect only showed up for the ungrammatical conditions, it may be viewed as a reflex of ungrammaticality detection (Hahne & Friederici, 2002). With regard to the N400 effects, matters are somewhat more complex. As described above, the N400 effect in condition B reflects additional processing cost associated with the integration of a subject with atypical animacy characteristics (cf. also Weckerly & Kutas, 1999), while the N400 in condition C is engendered by the presence of two subjects. It cannot be stressed enough that, despite clearly differing functional interpretations, these two N400 effects are indistinguishable on the surface (as supported by the statistical analysis, cf. footnote 3 and 4). Due to this surface similarity of the two effects, the nature of the N400 effect in condition D, in which the second argument is both inanimate (as in B) and induces an ungrammaticality (as in C) cannot be determined.

3.1.4 EEG frequency analysis

Methods

With regard to EEG frequency analysis, the three different measures *evoked power* (EPow), *whole power* (WPow), and *phase locking index* (PLI) were applied to the EEG data of the present experiment. Although the applied measurements were already introduced in detail in Chapter 2, we will nevertheless briefly repeat the essential methodological basics. EPow measures the proportion of evoked EEG activity in a specific frequency band relative to the onset of a critical stimulus. It is calculated on the basis of ERPs per participant, condition and electrode site and then averaged over all participants (Schack & Klimesch, 2002). WPow, by contrast, measures the total power in a frequency band on the basis of single trial analyses and is calculated on the basis of individual trials for each condition and participant with subsequent averaging (e.g. Basar, 1998). The PLI measures the degree of inter-trial variation in phase between the responses to critical stimuli and thereby quantifies phase-locking of oscillatory activity irrespective of its amplitude (Schack & Klimesch, 2002; Basar, 1998; Tallon-Baudry et al., 1996; Lachaux et al., 1999; Makeig et al., 2002). The PLI ranges between 0 and 1, i.e. it is close to 1 when there is little variance in phase across trials and close to 0 otherwise. The PLI is determined per condition, time-point, frequency and electrode site for each participant and then averaged over participants (for a more detailed description, see Chapter 2.5).

All frequency measures were determined by Gabor wavelet analysis in frequency bins of 0.33 Hz. Note that the frequency bin width is determined by the length of the EEG single trial time window plus a 25% tapering window on both sides of the interval (to reduce onset/offset effects). In this case, 2000 ms (-600 to 1400 ms relative to the onset of the critical item) plus 2 x 500 ms resulting in a 3000 ms time window. The calculation of the frequency resolution is according to the formula: 1/time(s) = frequency(Hz).

For the graphical representation of the Gabor wavelet-based time-frequency plots, the coefficient matrices (EPow, WPow) or PLI values of the animate grammatical control condition were subtracted from those of the critical conditions, thereby resulting in time-frequency difference plots (cf. Figure 3.3). Note that, on the basis of this strategy, positive difference values indicate higher coefficients or PLI values for the critical conditions, whereas negative difference values indicate lower values.[5]

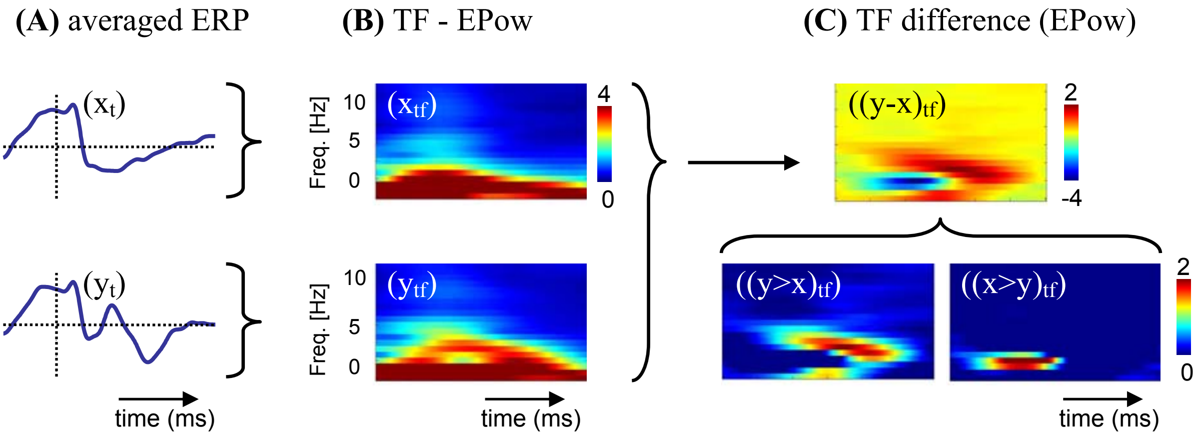

Figure 3.3. Calculation and graphical illustration of time-frequency *difference* plots. (A) Averaged ERPs for control condition *x* and critical condition *y* as a function of time (x_t, y_t). (B) Calculation of evoked power (EPow) and representation of the coefficients as time-frequency plot (TF) for each condition. The x-axis represents time, and the y-axis, frequency. (C) *Upper part*: TF evoked power difference representation. The control condition is subtracted from the critical condition. Hot colours denote positive and cold colours negative difference values. Note that the colour scale is not symmetrical. *Lower part*: To enhance the clarity of the graphical illustration, *positive* and *negative* difference values are depicted in separate TF power difference plots. The colour scale codes the degree of power or power difference.

---

[5] As a matter of course, all statistical analyses were conducted on the basis of absolute Gabor wavelet coefficients or PLI values. Difference values were only calculated for an improved graphical illustration of the relative effects.

The time-frequency analyses presented here are restricted to electrode Pz for the sake of brevity.[6] To achieve an improved frequency resolution, Gabor wavelet transformations were applied to EEG epochs from -600 prior to onset to 1400 ms post onset of the critical second argument. Note also that, although the wavelet transformation provides an optimal compromise between time and frequency resolution (cf. Chapter 2.4), it is nevertheless subject to the uncertainty principle and therefore still leads to a smearing of effects in both the time and the frequency domain (Samar et al. 2002). Thus, the edges of the effects shown in the time-frequency figures should be interpreted with caution.

Data Analysis

For the statistical analysis of the frequency band characteristics, multi-factorial analyses of variance (MANOVAs) were computed per value of interest for each participant, condition, time window and averaged frequency bin using the factors GRAMMATICALITY (grammatical vs. ungrammatical) and ANIMACY (animate vs. inanimate). For EPow, analyses were computed using the Gabor coefficients of the averaged conditions. In the case of WPow, Gabor coefficients were determined per trial for each participant, condition, time window and frequency bin and then averaged before entering the statistical analysis. The PLI was determined by comparing single trials per condition, participant, time window and frequency bin, with the average values for each participant entering the statistical analysis. Note that, on the basis of this analysis, only *relative effects between* the conditions can be interpreted, with the animate grammatical condition (A in Table 3.1) serving as the control condition.

We present analyses restricted to the delta and theta frequency bands (1-7.5 Hz). Visual inspection of the time-frequency difference plots showed no systematic variations across conditions in higher frequency bands with regard to the measures applied here. Furthermore, there was no evidence for negative values (i.e. activity decreases) in any of the time-frequency difference plots.

---

[6] Note also that first positive evidence on the basis of a preliminary single electrode analysis would be entirely sufficient in order to show (with regard to the current issue) that the proposed frequency-analytical measures are *in principle* able to distinguish superficially indistinguishable ERP components by means of underlying frequency characteristics.

3.1.5 Results

As is evident from Figure 3.4, in the upper theta band (6-7.5 Hz), the two inanimate conditions (B/D) show higher EPow in comparison to their animate counterparts (A/C) independently of grammaticality. This observation is confirmed by the statistical analysis, which revealed a main effect of ANIMACY (F (1,15) = 5.29, p < .04) between 200 and 400 ms (averaged frequency bins: 6.33-7.33 Hz). Thus, the inanimate conditions lead to a higher degree of stimulus-evoked activity in the upper theta band. In the lower theta band (3.5-5 Hz), by contrast, the two ungrammatical conditions (C/D) show significantly higher EPow than the grammatical conditions (A/B) in the same time window (F (1,15) = 5.06, p < .04) (averaged frequency bins: 3.66-4.66 Hz). In this frequency band, it is therefore the grammatical violation that leads to a higher degree of stimulus-evoked activity. These findings show that the N400 elicited by ungrammaticality and that elicited by inanimate subjects, which were indistinguishable on the surface, correspond to evoked activity in two clearly separable frequency ranges.

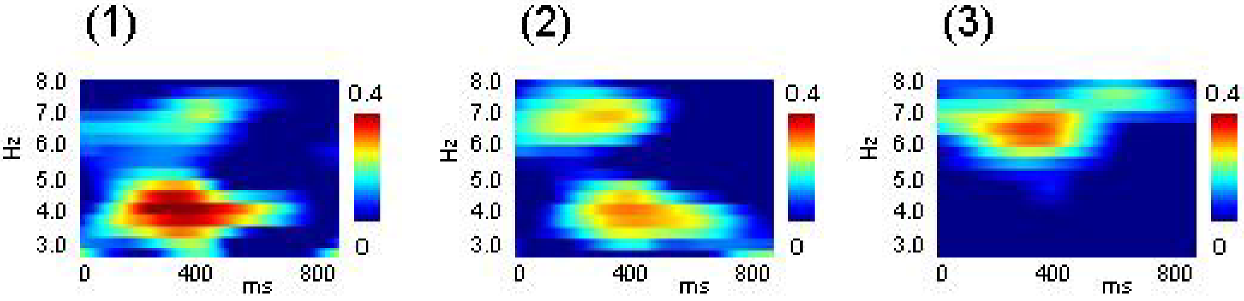

Figure 3.4. Gabor wavelet-based time-frequency plots showing evoked power (EPow) differences between the ungrammatical animate (condition C) (Fig. 3.4.1), ungrammatical inanimate (condition D) (Fig. 3.4.2), and grammatical inanimate conditions (condition B) (Fig. 3.4.3) in comparison to the grammatical animate control condition (condition A) at electrode PZ (N=16). The colour scale depicts the magnitude of the wavelet coefficient differences (cf. Figure 3.3). In the upper theta band (6-7.5 Hz), the two inanimate conditions (B and D) show higher EPow in comparison to the control condition (A) (Fig. 3.4.2 and 3.4.3), whereas the ungrammatical animate condition (C) does not (Fig. 3.4.1). In the lower theta band (3.5-5 Hz), the two ungrammatical conditions (C and D) (Fig. 3.4.1 and 3.4.2) but not the grammatical inanimate condition (B) (Fig. 3.4.3) show higher EPow in comparison to the control condition (A).

The two distinct frequency-based correlates for the violation N400 and the animacy N400 (cf. Figure 3.4 above) receive converging support from the delta band analysis (averaged frequency bins: 1-2.33 Hz). Here, the two ungrammatical conditions (C/D) show higher EPow between 600 and 1000 ms, whereas the inanimate grammatical condition (B) does not (Figure 3.5; main effect of grammaticality: F (1,15) = 46.74, p < .001). Thus, the two ungrammatical conditions do not differ with regard to EPow in this frequency band. However, an analysis of WPow and PLI measures revealed converse behaviour for the two conditions: whereas the animate ungrammatical condition (C) is associated with a higher PLI (F (1,15) = 5.59, $p < .04$), the inanimate ungrammatical condition (D) elicits higher WPow (F (1,15) = 4.76, $p < .05$). In this way, the generally higher degree of evoked activity for the ungrammatical conditions can be attributed to underlyingly different processes, namely to a larger extent of phase-locking (i.e. more consistent timing across trials) in the animate and a greater synchronisation (i.e. higher activity of the underlying neuronal population) in the inanimate condition.

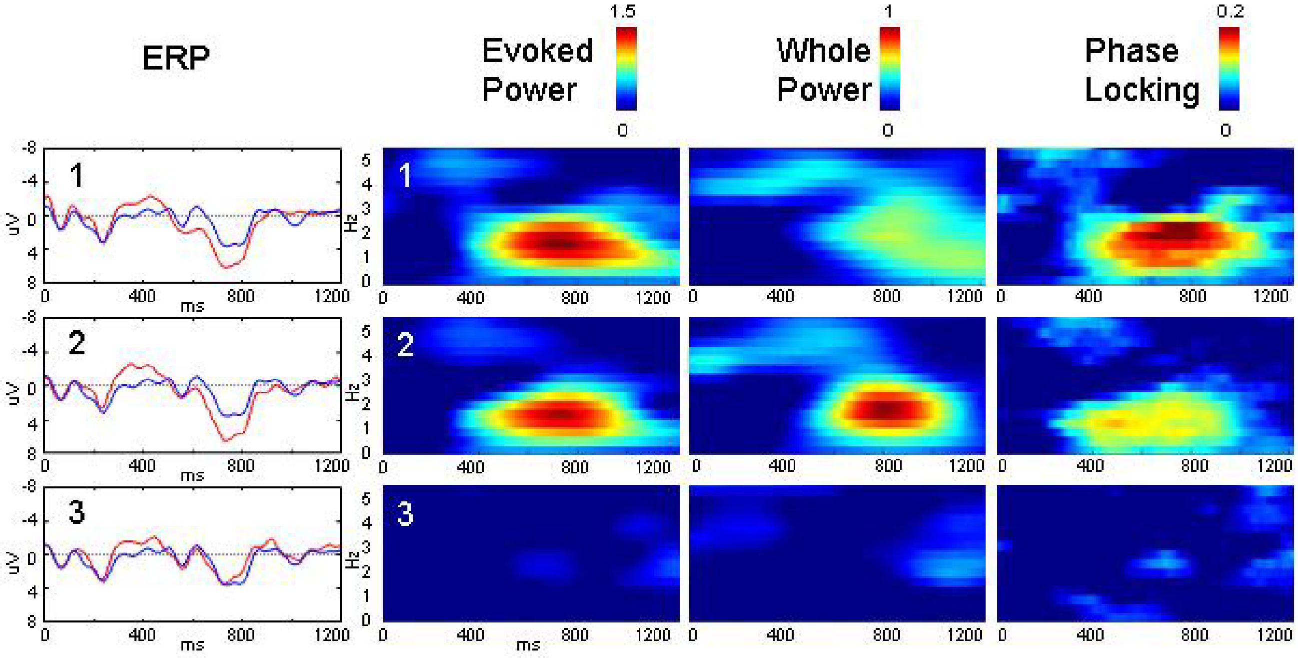

Figure 3.5. Grand average ERPs and Gabor wavelet-based time-frequency plots in the delta band (1-3 Hz) for the ungrammatical animate (C) (Fig. 3.5.1), ungrammatical inanimate (D) (Fig. 3.5.2), and grammatical inanimate conditions (B) (Fig. 3.5.3) in comparison to the grammatical animate control condition (A) at electrode PZ (N=16). ERPs are shown in the far left panel, whereas the remaining three panels depict wavelet coefficient differences in evoked power (EPow; second panel from left) and whole power (WPow; second panel from right) and phase-locking index differences (PLI; far right panel). The colour scale depicts the magnitude of the wavelet coefficient differences for EPow and WPow and the PLI value difference for PLI. The ERPs show N400 differences (200-500 ms) in all three comparisons and P600 effects (600-1000 ms) for the two ungrammatical conditions (C and D) (Fig. 3.5.1, 3.5.2). In terms of EPow, the two ungrammatical conditions (C and D) (Fig. 3.5.1, 3.5.2) but not the grammatical inanimate condition (B) (Fig. 3.5.3) show power increases in comparison to the control condition (A). With regard to WPow and the PLI, an increase is observable for both ungrammatical conditions (C and D) (Fig. 3.5.1, 3.5.2) in comparison to the control condition (A), although for WPow this increase is significantly more pronounced for the inanimate ungrammatical condition (D) whereas for PLI it is significantly more pronounced for the animate ungrammatical condition (C).

3.1.6 Discussion

The primary aim of Experiment 1 was to show that language-related ERP components, which are indistinguishable from a surface perspective, but which are clearly of distinct linguistic origin, can be dissociated on the basis of their corresponding frequency characteristics. Thereby, the present methodological approach also tried to make a contribution to the problem originating from the vagueness of interpretation associated with traditional language-related ERP components, specifically the N400 component.

It is important to stress that the inability to achieve this aim would have had inevitable consequences for the frequency-analytical measures introduced here. That is, one would have had to conclude that the proposed analysis as a promising complementary methodological approach to ERPs simply lacks the ability to salvage the currently lost indicator function of language-related ERP components (although indistinguishability at the single case level could also imply that a postulated functional difference is simply not existent).

However, our analyses showed that the two instances of the ERP component generally referred to as the 'N400' examined in the present experiment are associated with evoked activity in clearly distinct frequency ranges. That is, we were able to dissociate an 'upper theta N400' (correlated with (in)animacy) from a 'lower theta N400' (correlated with (un)grammaticality). This ability to dissociate an 'upper theta N400' from a 'lower theta N400' thus appears to constitute a promising first step in approaching the uncertainty of interpretation regarding language-related ERP components, specifically the N400. Even further insights with regard to the functional organisation of the language comprehension system and its inherent complexity can be obtained from the results of the delta band. Both ungrammatical conditions showed an equal evoked power increase in the delta band in comparison to the animate grammatical condition.[7] These findings can easily be reconciled with the functional interpretation of the P600, which appeared in an overlapping time range.[8] In Friederici's neurocognitive model of sentence processing (1999, 2002) the P600 is linked to the third processing phase, which takes place from approx. 500-600 ms post critical word

---

[7] Note that no EPow increase in delta was evident for the inanimate grammatical condition.

[8] Additional support for the assumption that P600 is correlated with the evoked delta power increase (apart from the temporal overlap) stems not only from the conjoint presence of the power increase for the ungrammatical conditions, but also from its conjoint absence for the inanimate grammatical condition (cf. Figure 3.4.3).

onset onwards. In this phase, reanalysis and repair mechanisms are assumed to set in when necessary (especially when there is a mapping problem, cf. Bornkessel, 2002). Similar interpretations of the delta band (i.e. delta as a reflection of matching processes or ‘conflict resolution’) have been proposed on the basis of findings from non-linguistic cognitive processes (Basar, 1998; Schürmann et al., 2001). However, with regard to the *additional* delta band measures, we found a PLI increase for the animate ungrammatical condition (C) in comparison to its inanimate counterpart (D). This PLI increase indicates a more consistent timing across events (Basar, 1998; Makeig et al., 2002) for the former, which might be taken to suggest a more effective and efficient interaction of various subprocesses. Secondly, there was an increase in WPow for the inanimate ungrammatical (D) condition in comparison to the animate ungrammatical condition (C). Whole power increases are indicative of higher neuronal synchronisation and thereby a higher degree of neuronal activity either within or across neuronal populations (Nunez, 1995). These differences suggest that the conflict resolution strategies applied differ between the two ungrammatical conditions. In both cases, a processing conflict arises because the presence of two subjects renders the sentence uninterpretable. However, the inanimate ungrammatical condition (D) provides a possible solution to the question of ‘who is doing what to whom’, because an inanimate argument is less likely to realise the subject function (Weckerly & Kutas, 1999). No such solution is available in the animate ungrammatical case (C). Thus, in the animate ungrammatical condition (C), the irresolvable conflict leads to an abortion of processing and, thereby, to an immediate reorganisation of the language processing system (possibly in the sense of phase resetting; cf. Makeig et al., 2002). This results in the more consistent timing across trials reflected in the higher PLI. In the inanimate ungrammatical condition (D), the repair mechanism prompted by the animacy cue elicits a higher degree of processing effort in working towards rendering the sentence interpretable. These higher reanalysis costs require an increased effort of the neuronal system and thereby result in the higher WP.

To conclude, the findings of Experiment 1 clearly showed that two N400 components, which are indistinguishable from a surface perspective, but which are undoubtedly of distinct linguistic origin, could be unequivocally dissociated on the basis of their corresponding frequency characteristics. Thus, with regard to the crucial question posed at the beginning of this chapter, that is, whether it is possible to successfully dissociate language-related ERP components by means of analyses in the frequency domain, the answer must, for the time being, be affirmative. Furthermore, the present findings also provide a first step to resolving the vagueness of interpretation associated with traditional language-related ERP components, specifically the N400.

However, with regard to the relation between ERPs and corresponding frequency bands, caution remains warranted. In Chapter 2, we repeatedly stressed that the individual adjustment of frequency bands (according to IAF) is crucial for an adequate calculation and interpretation of the obtained results. Yet, obviously, in the present analyses we didn't follow this approach (i.e. we didn't adjust the analysed frequency bands). However, firstly, we have to point out that this objection primarily concerns interpretations with regard to the different alpha subbands. In Chapter 2.2, we already refered to the hitherto unsolved issue of frequency band adjustments outside the traditional alpha range (for example in the delta band). Furthermore, on a single subject level, an individual adjustment appears to be necessary only for frequency measures which are calculated on the basis of frequency bands which represent averaged values over a certain frequency range (for example ERD/ERS).[9] For measures which estimate the whole frequency spectrum (like the Gabor wavelet-based time-frequency estimates applied here), it is not evident how and why frequencies should be individually adjusted.[10] Secondly, and even more importantly our primary aim was to establish a *direct* estimate of the underlying frequency characteristics of the observed group-averaged ERP effects. However, one rationale behind the proposal to individually adjust frequency bands was the aim to unravel task-related frequency band-specific activity changes which otherwise would be *invisible* due to inter-individual differences.[11] Hence, from our perspective, an adjustment of frequency bands would even be 'counterproductive', in the sense that it would blur the direct relation between ERP effects and their frequency dynamics.

Furthermore, although it is very tempting to attribute the encountered correlates from the frequency domain directly to ERP effects which occur roughly in the same time range (i.e. upper and lower theta EPow increase with N400 and delta EPow increase with P600), we have to consider the possible impact of the applied method with respect to time-frequency

---

[9] As an averaging over different frequencies can lead to the cancellation of opposite effects (such as power increases vs.decreases).

[10] However, this is different with regard to group averages (at least with respect to the *why*-question).

[11] That is, whereas our starting point is the evaluation of differences in group-averaged ERPs by means of EPow, task-related differences which are based on inter-individual IAF differences could only be revealed through an individual adjustment of frequency bands. Hence, per definition, they are neither observable in group-averaged ERPs nor in the respective EPows.

resolution. Because even Gabor wavelet transformation leads to a smearing of effects in both the time and the frequency domains (Samar et al. 2002), the *edges* of the effects shown in the time frequency figures must be interpreted with caution. This holds especially with respect to bi- or multiphasic ERP patterns (cf. the present N400/P600 pattern)[12], thus making it difficult to undoubtedly correlate possibly overlapping frequency-specific activity with single ERP components (or effects).[13] Unfortunately, this circumstance also blurs the further investigations based on questions (B) and (C) of the present thesis, namely, first, the attempt to characterize the processing nature of the 'classical' semantic N400 (cf. Chapter 4) and second, to distinguish the 'semantic' N400 from N400s outside the lexical-semantic domain, such as the 'reanalysis' N400 (cf. Bornkessel, 2002) (cf. Chapter 5). In order to achieve this, the following experiment will initially have to 'elicit' and analyse a clear monophasic N400 to obtain a first clear characterisation of the N400 by means of its underlying frequency dynamics.

---

[12] Additionally, it cannot be excluded that, in bi- or multiphasic ERP patterns, a high degree of interaction exists between successive components, thereby giving rise to potential component overlap (cf. Rugg & Coles, 1995; Kutas & Van Petten, 1994; Garnsey, 1993).

[13] However, this only holds for effects which are close together in time and/or space (frequency). 'Focal activity points' are less likely to be subject to smearing effects.

Chapter 4

Tackling the semantic N400 effect

In Experiment 1 of the previous chapter, we successfully showed that two N400 components, which were indistinguishable from a surface perspective, but which were of distinct linguistic origin, could be unequivocally dissociated on the basis of their corresponding frequency characteristics (thereby allowing us to answer the first of our main research questions in the affirmative; cf. Introduction). However, in the final paragraph of Chapter 3, we also discussed the caveats associated with the correlation of frequency band specific activity with *bi-* or *multiphasic* ERP components or effects. Due to potential component overlap as well as smearing effects due to the Gabor wavelet transformation, it turned out to be difficult to describe and interpret the precise dynamics of the individual frequency band characteristics with regard to their actual impact on the respective components. We thus concluded that a more exact characterisation of the frequency-analytical correlates of ERP components or effects would require the examination of monophasic components or effects.[1] Furthermore, it is far from obvious to what degree (if at all) the N400s in Experiment 1 are related or comparable to the well known 'classical' semantic N400 effects (e.g. Kutas & Federmeier, 2000). For these reasons and in view of addressing our second question (B), that is to achieve a frequency-based characterisation of the processing nature of the 'classical' lexical-semantic N400 effect, the present chapter will present an experiment designed to elicit a (graded) standard N400 effect. On the basis of this standard effect, we expect to obtain a precise characterisation of the N400 in terms of its inherent frequency dynamics. This is most important as a first step on the way to a more exact classification and specification of the distinctive frequency characteristics of the 'classical' N400.

4.1 Experiment 2: Antonyms in sentence context

Experiment 2 was designed to elicit a graded standard semantic N400 effect by means of what we propose to call an '*antonym mismatch paradigm*'.

---

[1] This holds especially for later ERP components, which are primarily reflected in lower frequency bands. These components are less focused in the time domain and hence less easily captured with regard to a precise temporal localisation of on- and offsets.

The *antonym mismatch paradigm* involves the explicit or implicit processing of antonym relations such as in (1), in comparison to non-matching but semantically related words from the same word category such as in (2) and non-matching non-related words from the same word category such as in (3). Moreover, the antonym relations can be presented either as word pairs or in sentence context.

(1) *white* vs. *black*
(2) *white* vs. *yellow*
(3) *white* vs. *nice*

Therefore, the *antonym mismatch paradigm* can be regarded as a highly constrained variant of so-called semantic-priming paradigms (e.g. lexical decision tasks, word and picture naming tasks, semantic categorisation tasks; cf. Balota, 1994).[2] All these paradigms have in common that 'context' can have a facilitating effect on task performance. For instance, the accuracy, the speed, or both, of a task decision are generally improved when a 'target' word is preceded by a semantically or associatively related 'prime' word or a congruent sentence fragment as opposed to an unrelated word or an incongruent sentence fragment (for a comprehensive review see Neely, 1991).

Kutas & Hillyard (1984) were the first to observe that the amplitude of the N400 is a inverse function of the subjects' expectancy for the terminal word in a sentence (as measured by its cloze probability; cf. Chapter 1). In their pioneering study, they not only manipulated the degree of expectancy (high vs. medium vs. low; (4/6) vs. (5/7)) but additionally the degree of contextual constraint (high vs. medium vs. low; (4/5) vs. (6/7)), thereby revealing that the N400 amplitude was more sensitive to expectancy than to the degree of contextual constraint.

(4) He mailed the letter without a stamp. *high constraint/high expectancy*
(5) The bill was due at the end of the hour. *high constraint /low expectancy*
(6) There was nothing wrong with the car. *low constraint /high expectancy*
(7) He was soothed by the gentle wind. *low constraint /low expectancy*

---

[2] For example, in a lexical decision task, the subject has to decide whether a given string of characters is a word or not. If a semantically related word precedes the target word, the target word will be recognised faster, that is, semantic priming will occur (Neely, 1977; Meyer & Schvaneveldt, 1971).

Although both low expectancy sentence final words in (5) and (7) elicited a pronounced posterior negativity (N400), there was no difference in N400 amplitude between them. On the other hand, they both showed a more pronounced negativity in comparison to low constraint/high expectancy words (6). However, most impressively, the "…highly probable words at the ends of highly constrained sentences were followed by broad, late positivity" (Kutas & Hillyard, 1984:161). Furthermore they showed that unexpected words that were semantically related to highly expected words elicited lower N400 amplitudes than non-related words. Hence, they concluded that sentence fragments can prime semantically related words, possibly resulting in the anticipatory activation and retrieval of appropriate schemata (although the critical word is not yet physically present but only expected on the basis of the preceding context).

A number of investigators recorded ERPs during judgments about category membership using the so-called *sentence verification task*. Fischler, Bloom, Childers, Roucos, & Perry (1983) were the first to combine ERPs with a sentence verification task. In their initial report, they showed that the N400 is larger in response to sentence-ending words (predicates) when the subject and predicate of a sentence are semantically non-related (e.g. "*A canary is a rock*", "*A dog is not a bird*") as opposed to when they are related (e.g. "*A canary is a bird*"). This effect showed up regardless of the truth value of the sentence. Kounios & Holcomb (1992) extended these findings by showing that the *category-exemplar* order variable contributes to the N400 amplitude independent of the semantic relatedness. In (8) and (9), the same N400 was elicited regardless of the plausibility of the item in the local context (Kounios & Holcomb, 1992). Moreover, although there also was no difference in N400 between (10) and (11), both sentences with the linear order *category-exemplar* (10, 11) elicited a stronger N400 than those with the order *exemplar-category* as in (8) and (9).

(8) All/Some apples are <u>fruits</u>.
(9) No apples are <u>fruits</u>.
(10) All/Some fruits are <u>apple</u>.
(11) No fruits are <u>apples</u>.

These results are taken as further evidence for the impact of contextual constraint. It has been argued that this effect was due to a lesser predictability of the terminal word when categorical statements begin with superordinate (category) words in contrast to subordinate (exemplar) words (cf. Kutas & Van Petten, 1994). However, this conclusion is not mandatory, because Kounios & Holcomb not only found this N400 effect for *exemplars* in comparison to *categories* for the predicate segments, but also for the initial subject segments. Therefore, the observed N400 effect was more likely due to differences in the semantic representation underlying the words. Kutas and colleagues (in: Kutas & Van Petten, 1994) investigated the impact of predictability on different types of categorical statements with regard to priming. These authors used categorical instances such as '*a type of animal*' and antonym statements like '*the opposite of black*' as primes and either matching or non-matching targets. They found that non-matching targets in comparison to matching targets elicited a substantially more pronounced N400 effect in the antonym condition as opposed to the category condition. Again, as for the superordinate/subordinate categorical statements, this difference has been interpreted in terms of predictability, i.e. antonyms are highly predictable (high typicality) whereas exemplars (or category members) are less predictable. Unfortunately, Kutas & Van Petten (1994) as well as Kutas & Federmeier (2000) delivered no further details about the experimental procedure or stimulus material.[3] However, in a further study, Kutas & Iragui (1998) investigated the effects of aging on the N400 congruity effect by means of a semantic categorisation task with (presumably) the same stimulus manipulation as reported in Kutas & Van Petten (1994). Approximately half of the stimuli were antonym statements such as (12), whereas the other half consisted of less constrained category statements like in (13). All trials began with the auditory presentation of a phrase (prime) followed by the visual presentation of either a congruent or incongruent word (target) as in (12) and (13).

			Congruent		Incongruent
(12)	The opposite of black	→	"*white*"	/	"*peach*"
(13)	A piece of furniture	→	"*table*"	/	"*noose*"

As in Kutas & Van Petten (1994), congruent antonyms elicited a pronounced positive shift, whereas incongruent antonyms gave rise to a large negative component, thus resulting in a very pronounced N400 effect. On the other hand, incongruent category statements showed the same sized negative peak as incongruent antonyms and a reduced negativity for congruent category statements, thus giving rise to a moderate N400 effect. In another study, Kutas &

---

[3] Kutas & Van Petten state that the large N400 effect in the antonym condition is due to "…an earlier and larger positivity to congruent words…" (1994:121); in addition, their Fig. 7 clearly reveals that congruent words indeed elicited a large positive shift.

Hillyard (1989) showed that the degree of semantic relatedness elicits graded N400 amplitudes. In a letter search task, they presented words in close succession. They instructed subjects to decide whether a target letter was present in either the first or the second member of a word pair. Target words produced the largest N400 when the word pairs were non-related, intermediate when the semantic relationship was relatively weak, and smallest when words were strongly related.

Only a few studies examined the N400 elicited by indirectly related target words (Kiefer, Weisbrod, Kern, Maier, & Spitzer, 1998; Weisbrod, Kiefer, Winkler, Maier, Hill, Roesch-Ely, & Spitzer, 1999; Chwilla, Kolk, & Mulder, 2000; Hill, Strube, Roesch-Ely, & Weisbrod, 2002). For indirectly related words, the association between prime and target is established solely by an intermediate link, i.e. the prime is associated to a strong associate of the target (e.g. lion – [tiger] - stripes). Hence, there is no way to generate an immediate expectation which includes the target from the prime word. Weisbrod et al. (1999) used a lexical decision task to investigate the processing of primes and targets that were either directly semantically related (e.g. hen - egg), indirectly semantically related (e.g. lion – [tiger] - stripes) or not related (e.g. sofa - wing). The main finding of this study was a significant semantic priming effect, a corresponding N400 amplitude reduction and a decrease in N400 latency for the indirectly related target words although prime and target word were only associated via an intermediate link. These findings were supported by a subsequent study from Chwilla, Kolk, & Mulder (2000). However, whereas Weisbrod et al. (1999) interpreted their N400 mediated priming effect as evidence for an *intralexical* automatic spread of activation, Chwilla et al. (2000) took their findings as support for a postlexical integration mechanism (semantic matching). In addition, Chwilla et al. (2000) investigated the influence of task instruction on the N400 mediated priming effect by means of an explicit integration instruction. Participants were informed about the presence of indirectly related word pairs and it was explained to them how the two words were related via the mediating word. Indeed, they observed an enhanced N400 mediated priming effect due to the integration instruction.

Federmeier & Kutas (1999a) addressed the question of whether the organisation of long-term memory affects the processing of equally probable words in sentence context (on the basis of local, context-based plausibility). They compared the response to congruent sentence completions such as (11a; expected on basis of context information from prior sentence) with the response to two types of equally incongruent completions: those that came from the same semantic category as the expected completion as in (11b; within category violations) and those that did not (11c; between category violations).

(11) They wanted to make the hotel more look like a tropical resort. So along the driveway they planted rows of … (a) … palms
(b) … pines
(c) … tulips

The authors argued that, although equally plausible, the within-category violations share more features with the expected exemplar than the between-category violations. Because neither unexpected ending is implausible within the local (i.e. intra-sentential) context, they should both be expected to elicit a same-sized N400 from the perspective of the view that the N400 only reflects integration with recently activated information in working memory. The results of this study showed that, although both unexpected endings engendered larger N400s than the expected endings, those elicited by within-category violations were significantly smaller than those elicited by between-category violations. It therefore appeared that physical, functional, and perhaps situational similarity between two members of a semantic category affect language processing, even when these relationships do not alter the items' subjective plausibility in the sentence (Kutas & Federmeier, 2000). Kutas & Federmeier concluded that both the immediate language context held in working memory and the context-independent relationships between items in long-term semantic memory affect the neural processes reflected in the N400. Furthermore, they assumed that featural overlap between a sentence-final within-category violation (e.g. *pines*) and the item expected in the context (e.g. *palms*) can affect processing only if the features of the expected item are already activated in the mind of the comprehender, as this expected item was never actually presented. Indeed, this conclusion is strongly supported by the studies of indirect semantic priming discussed above. Moreover, Kutas & Federmeier showed an interaction of contextual constraint and sentence ending type, that is the impact of semantic memory organisation was more pronounced when contextual constraint was strong whereas it was less pronounced when contextual constraint was weak. Hence, they finally concluded that the brain uses sentence context information to predict (i.e. to anticipate and prepare for) the perceptual and semantic features of items likely to appear, in order to comprehend the intended meaning of a sentence at a fast speed.

To summarise, taking into consideration the findings from the diverse semantic and contextual priming studies discussed above, it is quite obvious that there is a set of parameters which can lead to the elicitation of a strong and reliable N400 effect. Based on the findings that N400 amplitude is reduced with increasing strength of semantic association (e.g. Kutas, Lindamood, & Hillyard, 1984; Kutas & Van Petten, 1994; Kounios & Holcomb, 1992) as well as with the degree of expectancy and contextual constraint (e.g. Kutas & Hillyard, 1984; Federmeier & Kutas, 1999a, b), we constructed a stimulus set based on antonym relations, with the aim to elicit a strong and *graded* semantic N400 effect (cf. Table 4.1). Because we presented the antonym relations in sentence contexts (e.g. "The opposite of black is…"), they were highly constrained to the effect that there was only one reasonable outcome (e.g. "…white"). This outcome was determined by the specific expectation built up on the basis of the preceding stereotype sentence frame ("The opposite of *X* is *Y*"). In addition, there was a strong semantic-associative relationship between the prime and target of an antonym word pair.[4] Furthermore, participants were instructed that they would have to decide if a given sentence proposition, which denoted a antonym relation, was true or not (*antonymy sentence verification task*).[5] However, in contrast to Kutas & Iragui (1998) we not only compared antonyms to non-matching words, but introduced a further *related category violation* condition, which was strongly semantically related to the expected antonym and hence should show a substantial priming effect. Because we presented the critical word pairs as part of a complete sentence (proposition), our condition manipulation resembled that of the Federmeier & Kutas (1999a) study, in the sense that antonyms can be regarded as 'highly expected sentence completions' in contrast to related and non-related category violations, which can be regarded as '*within*' and '*across category violations*'. However, in our study we deployed a much higher contextual constraint and expectancy by focusing solely on the processing of antonym relations (cf. Table 4.1).

---

[4] In the strongest case, one could assume that antonyms might differ solely by a single binary feature such as "+/-dead" in: "the opposite of dead is alive."

[5] Note that the *antonymy sentence verification task* can be regarded as a variant of the *sentence verification task,* in which simple sentences (e.g. "All sharks are fish") are presented to subjects, whose task is to judge whether each sentence is true or false (Collins & Quillian, 1969; Meyer, 1970).

Condition	**Example**
A. Antonyms	Das Gegenteil von *schwarz* ist weiss. The opposite of *black* is *white*.
B. Related	Das Gegenteil von *schwarz* ist gelb. The opposite of *black* is *yellow*.
C. Non-related	Das Gegenteil von *schwarz* ist nett. The opposite of *black* is *nice*.

Table 4.1. Example sentences for each of the experimental conditions. The critical word is underlined.

It was expected (cf. Federmeier & Kutas, 1999a; Kutas & Van Petten, 1994; Kutas & Iragui, 1998) that both category violation conditions should elicit a pronounced N400 effect due to the high contextual constraints imposed by the antonym context (i.e. sentence frame plus specific instruction, thereby giving rise to a global contextual effect). Both category violations render the proposition wrong since, in both cases, the sentence-final word does not match the predicted and solely compatible target item. In this sense, both category violation types cannot be distinguished from each other and should behave alike: the opposite of *black* is neither *yellow* nor *nice*, but solely *white*. Moreover, it was expected that the related (or within) category violations should elicit a less pronounced N400 amplitude than the non-related category violations, due to the former's strong semantic relation to the prime (possibly due to a high degree of semantic feature overlap). Note, however, that the induced category violation was purely semantic in nature. There was no syntactic violation (e.g. word category violation) or structural complexity or ambiguity. Therefore, we didn't expect a late positivity due to reanalysis or repair processes (Friederici, 1999; Hagoort, Brown, & Osterhout, 1999).

4.1.1 Method

Materials

The three critical conditions for the experiment are shown in Table 4.1 below. Eighty sets (triplets) of these three conditions were created, resulting in 240 experimental sentences. These were assigned to 4 lists of 160 critical sentences (80 for the antonyms, 40 for the two mismatch conditions each) in a counterbalanced manner such that each participant saw 40 complete triplets of a given set plus the remaining 40 sentences from the antonym condition. A complete set of materials for this experiment is listed in Appendix A1.

Participants

Seventeen undergraduate students from the Philipps-University of Marburg participated in the Experiment (13 female; mean age 23.7 years; age range 20 – 28 years). In this and all of the following experiments, all participants were right-handed (as assessed by an adapted and modified German version of the Edinburgh Handedness Inventory; Oldfield, 1971), monolingual native speakers of German and had normal or corrected-to-normal vision. Again, for all experiments to be reported here, participants received 7 EUR per hour (DM 13 per hour for Experiment 6).

Procedure

Sentences were presented visually in the centre of a computer screen in a word-by-word manner. Each trial began with the presentation of an asterisk (2000 ms) in order to fixate participants' eyes at the centre of the screen and to alert them to the upcoming presentation of the sentence. Single words were presented for 350 ms with an inter-stimulus interval (ISI) of 200 ms. After the presentation of a sentence, there was a 650 ms pause before participants were required to complete the antonymy sentence verification task (signalled through the presentation of a question-mark), which involved judging whether the proposition was right or wrong. Subjects had to respond by pressing the left or right mouse button for 'yes' or 'no'. The time window for the button press was restricted to 3000 ms. After the button press there was an inter-trial interval (ITI) of 2250 ms before the next trial started. For each participant, the antonymy sentence verification task required the answer 'yes' equally as often as the answer 'no' (80 sentences with correct antonym pairs, 80 sentences with incorrect second word).

Participants were asked to avoid movements and to blink their eyes between their response to the antonymy sentence verification task and the presentation of the next sentence. The experimental session began with a short training session followed by 4 experimental blocks comprising 40 sentences each, between which the participants took short breaks. The entire experiment (including electrode preparation) lasted approximately 2 hours (due to a second experiment which will not be reported here).

The EEG was recorded by means of 27 sintered AgAgCl-electrodes fixed at the scalp by means of an elastic cap (Easy Cap International). The ground electrode was positioned at C2. Recordings were referenced to the left mastoid, but re-referenced to linked mastoids offline. The electrooculogram (EOG) was monitored by means of electrodes placed at the outer canthus of each eye for the horizontal EOG and above and below the participant's left eye for the vertical EOG. Electrode impedances were kept below 5 kOhm. All EEG and EOG channels were amplified using a BrainVision BrainAmp amplifier (time constant 0.9 s, high cutoff 70 Hz) and recorded continuously with a digitisation rate of 250 Hz. The plots of grand average ERPs were smoothed off-line with a 10 Hz low pass filter, but all statistical analyses were computed on unfiltered data.

Average ERPs were calculated per condition per participant from 200 ms prior to the onset of the critical stimulus item (i.e. the second 'antonym') to 1000 ms post onset, before grand-averages were computed over all participants. Trials for which the antonymy sentence verification task was not performed correctly were excluded from the averaging procedure as well as the single trial analysis, as were trials containing ocular or other artefacts. The semiautomatic artefact inspection was performed using the criteria 'bad gradient' (maximal allowed voltage step per sampling point: 50.00 μV), 'bad max-min' (maximal allowed absolute difference: 200.00 μV in a 200 ms interval), and 'bad amplitude' (allowed amplitude ± 80.00 μV), followed by a manual inspection of the data.

Data Analysis

For the behavioural data, error rates and reaction times were calculated for each condition. Incorrectly answered trials were excluded from the reaction time analysis. We computed a repeated measures analysis of variance (ANOVA) involving the critical factor TYPE (antonyms vs. related vs. non-related) and the random factors subjects (F_1) and items (F_2).

For the statistical analysis of the ERP data, repeated measures ANOVAs involving the critical factor TYPE (antonyms vs. related vs. non-related) were calculated for mean amplitude values per time window per condition in four lateral regions of interest (ROIs) as well as for the midline electrodes. Lateral regions were defined as follows: *left-frontotemporal* (F7, F3, FC5); *left-posterior* (P7, P3, CP5); *right-frontotemporal* (F8, F4, FC6); *right-posterior* (P8, P4, CP6). The midline electrodes were analysed in terms of the factor electrode (ELEC) with three midline electrodes (Fz, Cz, Pz) as levels.

The statistical analysis was carried out in a hierachical manner, i.e. only significant interactions ($p \leq .05$) were resolved. In order to avoid excessive type 1 errors due to violations of sphericity, we applied the correction of Huyn & Feldt (1970) when the analysis involved factors with more than one degree of freedom in the numerator. For post hoc single comparisons between conditions, the probability level was adjusted according to the modified Bonferroni procedure from Keppel (1991).

4.1.2 Results

Behavioural Data

An overview of the behavioural results with regard to error rate and reaction time is given in Table 4.2 below.

TASK	Error rates (%)		Reaction times (ms)	
	average	sd	average	sd
antonyms	1.54	1.84	478,38	143,75
related	5.88	3.30	533,44	166,62
non-related	0.29	0.80	440,45	119,05

Table 4.2. Percentages of error rates and mean reaction times for the antonymy sentence verification task.

The statistical analysis of the error rates for the antonymy sentence verification task revealed a significant main effect of TYPE (F_1 (2,32) = 28.75, $p < .001$; F_2 (2,158) = 22.05, $p < .001$) This effect was due to the higher error rates for the related category violations (5.88%) in comparison to antonyms (1.54%) as well as to the lower error rates for the non-related category violations (0.29%) in comparison to antonyms. Resolving the main effect revealed a significant difference for antonyms compared with both non-related category violations (F_1 (1,16) = 6.48, $p < 0.03$; F_2 (1,79) = 6.38, $p < 0.02$) and related category violations (F_1 (1,16) = 20.19, $p < .001$; F_2 (1,79) = 17.78, $p < .001$) as well as between non-related and related category violations (F_1 (1,16) = 50.23, $p < .001$; F_2 (1,79) = 37.06, $p < .001$).

With regard to the reaction times, there was again a main effect of TYPE (F_1 (2,32) = 10.60, $p < .001$; F_2 (2,158) = 9.40, $p = 0.002$). A resolution of the main effect revealed a significant difference between non-related category violations and both related category violations (F_1 (1,16) = 16.85, $p < 0.002$; F_2 (1,79) = 11.32, $p < 0.002$) and antonyms (F_1 (1,16) = 11.86, $p < 0.004$; F_2 (1,79) = 8.55, $p < 0.006$). The difference between antonyms and related category violations was only marginally significant in the analysis by subjects (F_1 (1,16) = 5.03, $p < 0.04$) but highly significant factoring the analysis by items (F_2 (1,79) = 7.39, $p < 0.009$).

The low error rates showed that participants had no problem in reading the sentences and performing the antonymy sentence verification task. Note that the reaction times are measured from the onset of the question mark, which served as a cue for the performance of the antonymy sentence verification task.

ERPs

A complete overview of the statistical results is listed in Appendix C1. Figure 4.1 shows grand-average ERPs for the three critical conditions (a more extensive selection of electrodes is presented in Appendix B2). Visual inspection indicated that, for the two category violation conditions (related and non-related category violations), the critical items elicited a broad, centro-parietal negativity between approximately 200 and 500 ms. This effect was less pronounced for the related category violations (=REL) than for the non-related category violations (=NON). Moreover, in the same time range, there seemed to be a pronounced posterior positive shift for the antonym conditions. Additionally, between approximately 450 and 800 ms post onset of the critical item, there was a broad and long lasting positivity for the two category violation conditions. Whereas frontally, the effect seemed to be more pronounced for REL than for NON, the reverse was observable at centro-parietal locations, that is NON elicited a more positive waveform than REL.

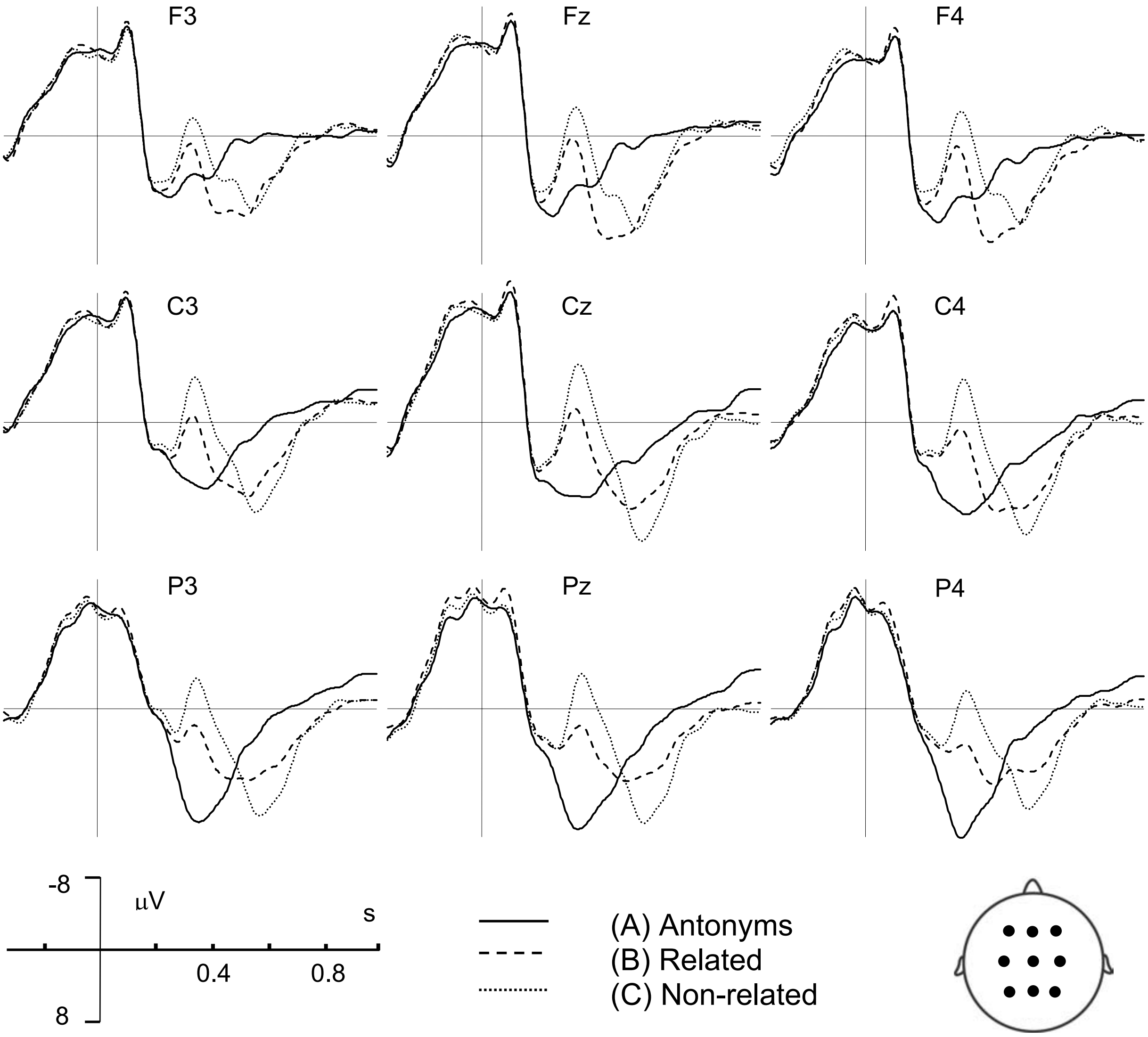

Figure 4.1. Grand average ERPs for antonyms, related and non-related category violations (onset at the vertical bar) in Experiment 2. Negativity is plotted upwards.

Repeated measure ANOVAs, carried-out for fourteen successive 50 ms time windows beginning at 200 ms till 900 ms poststimulus onset (T1 – T14), confirmed these observations. Between 250 and 800 ms, the global analyses revealed significant main effects of TYPE for ROIs (*250-300 ms*: F (2,32) = 9.07, $p < .002$; *300-350 ms*: F (2,32) = 43.78, $p < .001$; *350-400 ms*: F (2,32) = 46.20, $p < .001$; *400-450 ms*: F (2,32) = 13.67, $p < .001$; *450-500 ms*: F (2,32) = 11.84, $p < .001$; *500-550 ms*: F (2,32) = 24.59, $p < .001$; *550-600 ms*: F (2,32) = 49.07, $p < .001$; *600-650 ms*: F (2,32) = 31.23, $p < .001$; *650-700 ms*: F (2,32) = 20.89, $p < .001$; *700-750 ms*: F (2,32) = 6.00, $p < .01$; *750-800 ms*: F (2,32) = 3.50, $p < .05$) as well as for midline electrodes (*250-300 ms*: F (2,32) = 13.63, $p < .002$; *300-350 ms*: F (2,32) = 56.09, *p* < .001; *350-400 ms*: *F* (2,32) = 44.84, *p* < .001; *400-450 ms*: *F* (2,32) = 10.00, *p* < .002; *450-500 ms*: *F* (2,32) = 7.74, *p* < .005; *500-550 ms*: *F* (2,32) = 16.43, *p* < .001; *550-600 ms*: *F* (2,32) = 41.41, *p* < .001; *600-650 ms*: *F* (2,32) = 30.76, *p* < .001; *650-700 ms*: *F* (2,32) = 21.09, *p* < .001; *700-750 ms*: *F* (2,32) = 6.17, *p* < .01; *750-800 ms*: *F* (2,32) = 6.00, *p* < .01).

The significant main effects between 250 and 400 ms were due to a more negative waveform for non-related and related category conditions in comparison to the antonym condition. Single comparisons revealed that, for all regions, the negativity between 300 and 400 ms was significantly stronger for NON in comparison to REL. (cf. Table 4.3). Furthermore, post hoc analyses of the significant interactions of TYPE x ROI between 250 and 400 ms (*250-300 ms*: *F* (6,96) = 3.74, *p* < .01; *300-350 ms*: *F* (6,96) = 11.05, *p* < .001; *350-400 ms*: *F* (6,96) = 26.46, *p* < .001) and TYPE x ELEC between 300 and 400 ms (*300-350 ms*: *F* (4,64) = 10.55, *p* < .001; *350-400 ms*: *F* (4,64) = 31.56, *p* < .001) revealed that the differences between the antonym condition and the two category violation conditions, respectively, were more pronounced at posterior regions. This effect seemed to be due to a very strong positive shift for antonyms. In addition, between 350 and 400 ms there was no significant effect for REL at frontal regions, due to an already beginning positivity.

For the time window between 400 and 500 ms, the situation was more complex. The resolution of the significant interactions for the respective time windows for ROIs (*400-450 ms*: *F* (6,96) = 16.70, *p* < .001; *450-500 ms*: *F* (6,96) = 7.54, *p* < .005) and midline electrodes (*400-450 ms*: *F* (4,64) = 25.68, *p* < .001; *450-500 ms*: *F* (4,64) = 17.78, *p* < .001) revealed two competing effects: On the one hand, there was still a significant negativity for NON and REL in comparison to antonyms at posterior regions between 400 and 450 ms. On the other hand, in the same time window, there was a significant difference for REL against ANT due to a frontal positivity (FZ, left- and right-frontotemporal). This significant positivity for REL lasted until 700 ms. Although, likewise, there was a significant frontal positivity for NON vs. ANT between 450 and 700 ms, this effect was significantly stronger for REL in comparison to NON in the time window 400 to 550 ms (cf. Table 4.3). Furthermore, resolution of the significant interactions between 500 and 800 ms of TYPE x ROI (*500-550 ms*: *F* (6,96) = 3.66, *p* < .03; *550-600 ms*: *F* (6,96) = 5.57, *p* < .005; *600-650 ms*: *F* (6,96) = 10.00, *p* < .001; *650-700 ms*: *F* (6,96) = 10.03, *p* < .001; *700-750 ms*: *F* (6,96) = 7.76, *p* < .001; *750-800 ms*: *F* (6,96) = 5.18, *p* < .04) and TYPE x ELEC (*500-550 ms*: *F* (4,64) = 10.03, *p* < .001; *550-600 ms*: *F* (4,64) = 5.81, *p* < .01; *600-650 ms*: *F* (4,64) = 7.21, *p* < .005; *650-700 ms*: *F* (4,64) =

8.64, *p* < .001; *700-750 ms*: *F* (4,64) = 3.87, *p* < .03; *750-800 ms*: *F* (4,64) = 3.36, *p* < .04), revealed a sustained positivity for both category violation conditions in comparison to antonyms at posterior regions. Notably, between 550 and 700 ms, this posterior positivity was significantly stronger for NON in comparison to REL (cf. Table 4.3).

To conclude, both category violation conditions elicited a significant biphasic N400/P600 pattern relative to the antonym condition, which served as a control condition. The N400 effect was observable centro-parietally between 250 and 450 ms and was significantly more pronounced in the non-related violation condition than the related violation condition. Moreover, the N400 effect seemed largely due to a pronounced posterior positive shift for antonyms in comparison to both category violation conditions. In the later time window, two positivities could be distinguished for both category violation conditions. A frontal positivity between 400 and 550 ms, which was more pronounced for related compared to non-related category violations, and a slightly later posterior positivity between 500 and 800 ms, which was significantly stronger for non-related in comparison to related category violations.

A schematic overview of the significant single comparisons for each of the four ROIs and the three midline electrodes is shown in Table 4.3 (for a more detailed overview of all the significance values see Appendix C1).

ROIs		time windows in ms													
		t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14
		200-250	250-300	300-350	350-400	400-450	450-500	500-550	550-600	600-650	650-700	700-750	750-800	800-850	850-900
FroL	Type			**	**	**	**	**	**	**	#				
	rel			#		**	**	**	**	**	#				
	non			*	#		*	**	**	**	#				
	with			#	**	**	*	#							
Fz	Type		**	**	**	**	**	**	**	**	**	#			
	rel		**	**		**	**	**	**	**	**				
	non		**	**	*		**	**	**	**	*				
	with			**	**	**	**								
FroR	Type		**	**	**	**	**	**	**	**	**	#			
	rel		**	**		**	**	**	**	**	**				
	non		**	**	**		**	**	**	**	#				
	with			**	**	**	**	#				#			
Cz	Type		**	**	**	**	*	**	**	**	**	*	*		
	rel		**	**	**		*	**	**	**	**	*	*		
	non		**	**	**	**		**	**	**	**	*	*		
	with			**	**	**	**		**	*	#				
PosL	Type		*	**	**	**		**	**	**	**	**	**	*	*
	rel			**	**	#		*	**	**	**	**	**	*	#
	non		*	**	**	**		**	**	**	**	**	*	*	#
	with		#	**	**	**			**	**	**				
Pz	Type		**	**	**	**		*	**	**	**	**	**		**
	rel		**	**	**	#		*	**	**	**	**	**		**
	non		**	**	**	**		#	**	**	**	*	*		**
	with			**	**	**			**	**	*				
PosR	Type		**	**	**	**		**	**	**	**	**	**	*	*
	rel		**	**	**			**	**	**	**	**	**	*	#
	non		**	**	**	**		*	**	**	**	*	#		*
	with			**	**	**			**	*	#				

Table 4.3. Graphical overview of the significant effects in each of the 4 ROIs (frontal-left = FroL; frontal-right = FroR; posterior-left = PosL; posterior-right = PosR) and 3 midline electrodes (Fz, Cz, Pz) in 14 successive 50ms time windows (t1 – t14) from 200 ms to 900 ms post-onset of the critical items. For post hoc single comparisons, all significance values are adjusted according to the modified Bonferroni procedure (Keppel, 1991) (# = marginally significant (< 0.9); * = < .05; ** = < .01). The main effect for the 3 conditions (ANT = antonyms, REL = related category violations, NON = non-related category violations) is coded as Type = ANT x REL x NON. The 3 Single comparisons are: rel = ANT x REL; non = ANT x NON, with = REL x NON.

4.1.3 Interim discussion

The two basic findings of Experiment 2 may be summarised as follows: Firstly, both category violation conditions elicited a broad centro-parietal N400 effect between 250 and 450 ms post onset of the critical item in comparison to the antonym condition (=N400 congruity effect). This effect was less pronounced for related category violations: the stronger neuronal activation for non-related category violations resulted in a higher N400 amplitude as well as a longer duration of the negative component. Moreover, antonyms elicited a pronounced positive shift at posterior electrode sites in the N400 time range. Secondly, both category violation conditions elicited a broadly distributed P600-like positivity between 500 and 800 ms post onset of the critical item in comparison to the antonym condition. At frontal electrode sites, this effect was more pronounced and had an earlier onset for related category violations. In contrast, at centro-parietal electrodes, the P600 had a later onset and was significantly stronger for non-related category violations. However, on the basis of visual inspection of Figure 4.1 and the results of the statistical analyses (see Table 4.3), we assume that we are, in fact, dealing with two independent late positivities:[6] a *frontal positivity* between 400 and 550 ms, which was more pronounced for related than for non-related category violations, and a slightly later *posterior positivity* between 500 and 800 ms, which was significantly stronger for non-related in comparison to related category violations (for a further discussion see below).

The statistical analyses of the error rates (ER) revealed significant differences between the antonyms and the two category violation conditions as well as between both category violation conditions. In addition, although participants had no time pressure and were not instructed to react as soon as possible, there were significant differences between all three

---

[6] It could be argued that the earlier onset and more pronounced amplitude of this effect (i.e. the P600) for related category violations in comparison to non-related category violations was due to a fronto-centrally located interaction of the N400 and P600 components. In terms of such a view, the enhanced N400 for non-related category violations cancels out the P600, which leads to the impression of a delayed P600 onset and damped P600 amplitude. However, we assume that this effect is due to a frontal positivity. Supporting evidence for this assumption of a dual distinction of the late positivity stems from the results from the Gabor-wavelet analyses of the present experiment (cf. below) as well as from the ERP and Gabor-wavelet results of Experiment 3. These findings suggest that the positivity should be viewed as the combination of a frontal and a posterior positivity with presumably different functional significance. However, a detailed discussion of the observed positivities as well as a more elaborative investigation of their functional interpretation is beyond the scope of the present thesis.

conditions with regard to the reaction times (RT). More importantly, both measures revealed the same pattern, that is the fewest errors and shortest mean reaction time for non-related category violations in contrast to the most errors and longest mean reaction time for related category violations (NON < ANT < REL). These patterns clearly indicate that there is no reason to assume a speed-accuracy trade-off effect (Pachella, 1974; Dosher, 1976; Woodworth, 1899; Fitts, 1954).

However, the graduation of the ERP effects evidently did not mirror the pattern of the behavioural results: both N400 and P600 were more pronounced for non-related than related category violations (ANT < REL < NON). Therefore, neither the N400 nor the P600 can simply be interpreted as a reflection of processing effort. This differentiation between the behavioural and ERP findings stands in contrast to much of the (lexical decision) word-pair priming literature, in which these measures have been showed to respond to the same variables (e.g. Bentin, McCarthy, & Wood, 1985; Holcomb, 1988). Whereas the N400 proved to be sensitive exclusively to the semantic relatedness of word pairs, the RT seemed to be more sensitive to the task demands.[7] In fact, relatedness obviously slowed the speed of the antonym sentence verification task (see Table 4.2), in contrast to typical lexical-decision priming results.

On the basis of on previous findings (cf. Kutas et al., 1984; Kutas & Van Petten, 1994; Federmeier & Kutas, 1999a,b), it was expected that the processing of the critical category violation conditions in comparison to the control condition should elicit a clear graded N400 effect that is more pronounced for non-related vs. related category violations. However, the appearance of a late positivity in both violation conditions was somewhat unexpected and surprising.[8] Whereas the N400 has generally been interpreted as a marker of lexical-semantic processes (see Chapter 1), the P600 is linked to syntactic processes (e.g. Friederici, 2002). Indeed, it can be found in response to different aspects of syntactic processing, such as reprocessing (reanalysis) and repair processes. The former aspect (reprocessing) for example shows up in garden-path sentences (Osterhout & Holcomb, 1992, 1993). When the

---

[7] It would be part of further examinations to discuss the present results in the light of current semantic-memory theories, i.e. in terms of processing stages of, for example, semantic information retrieval and computational verification (e.g. Chang, 1986).

[8] However, visual evaluation of the ERP figures in Kounios & Holcomb (1992) revealed that, in comparison to their related counterparts, non-related predicates showed - besides the N400 - the tendency towards a slight centro-posterior positivity (although this effect is not reported).

disambiguating word is encountered, the initially pursued syntactic structure must be revised and, hence, reanalysis sets in. On the other hand, repair processes are triggered when the processing system is confronted with syntactically incorrect input (Neville, Nicol, Barrs, Forster, & Garrett, 1991; Friederici, Pfeifer, & Hahne, 1993). The repair-related P600 has been observed in response to phrase structure violations, morphosyntactic violations and violations of verb-argument structure (cf. Hagoort et al., 1999).[9] Hagoort et al. (1999) hypothesised that these two positivities are indeed functionally different; this assumption is supported by the observation that both positivities showed a different topographical distribution (possibly due to the contribution of different generators). These authors proposed that the processing costs associated with 'overwriting the preferred or most activated structure' results in a more frontally distributed P600,[10] whereas a 'structural collapse' results in a more posterior P600. Further support for this presumed distinction stems from recent experimental findings of Friederici, Hahne & Saddy (2002).[11]

Unfortunately, it is not immediately obvious how the present late positivities, which were undoubtedly elicited by lexical-semantic manipulations, could be related to the above-

---

[9] Note, that there is also evidence for the existence of a third subcomponent embedded in the late positive component complex, namely so-called the P345 (Mecklinger, Schriefers, Steinhauer, & Friederici, 1995; Friederici, Steinhauer, Mecklinger, & Meyer, 1998). The P345 is assumed to reflect diagnosis and immediate recovery from diespreferred structures. However, it has been shown that the P345 appears with a shorter latency and is uninfluenced by semantic aspects (Mecklinger et al., 1995) or probability variation (Steinhauer, Mecklinger, Friederici, & Meyer, 1997).

[10] This frontal P600 possibly also functions as a marker of syntactic complexity, i.e. it has been observed that the frontal P600 reflects processes of syntactic integration (Kaan, Harris, Gibson, & Holcomb, 2000; cf. also Friederici, Hahne, & Saddy, 2002).

[11] These authors differentiated a complexity-related frontal P600 as in (i) from a repair-related posterior P600 as in (ii) in comparison to a neutral grammatical sentence as in (iii) (Friederici et al., 2002).

(i) *Dem Vater getragen hat er den Mantel.*
The$_{DAT}$ *father carried*$_{PARTICIPLE}$ *has he the coat.*
(He has carried the coat for the father.)

(ii) **Dem Vater trugen er den Mantel.*
The$_{DAT}$ *father carried*$_{PAST\ TENSE,\ PLURAL}$ *he*$_{SINGULAR}$ *the coat.*
(He carried$_{PLURAL}$ *the coat for the father.)*

(iii) *Dem Vater trug er den Mantel.*
The$_{DAT}$ *father carried*$_{PAST\ TENSE,\ SINGULAR}$ *he*$_{SINGULAR}$ *the coat.*
(He has carried the coat for the father.)

sketched interpretations of the P600. However, although the distinction between frontal and posterior P600 components, reflecting integration and repair mechanisms, respectively, was proposed for structural processing, it is tempting to utilise this distinction and the accompanying interpretative framework for an explanation of the present P600 pattern. Nevertheless, in view of the actual aim of the current experiment – viz. to elicit a monophasic N400 – such a starting point would clearly burn down the house in order to roast the pig.

Returning to the N400, the present results fully complied with our predictions based on prior findings from Kutas & Hillyard (1984), Kutas et al. (1984), Federmeier & Kutas (1999a,b) and Kutas & Iragui (1998). The degree of semantic relatedness between the expected (i.e. the opposites of the antonym primes) and non-expected sentence final words was mirrored in the graded N400 effect (Kutas & Hillyard, 1984; Kutas et al., 1984; Federmeier & Kutas, 1999a,b).[12] Furthermore, visual inspection of Figure 4.1 clearly revealed that the very strong N400 effect for both category violation conditions was mainly due to a large posterior *positive* shift for antonyms in comparison to both category violation conditions (cf. Kutas & Hillyard, 1984; Kutas & Van Petten, 1994; Kutas & Iragui, 1998), whereas the difference between both category violations appeared to be due to a less pronounced negativity for related category items in comparison to non-related category words. Therefore, one could speculate whether the pronounced positive 'N400' shift for antonyms (and hence the N400 effect) was truly exclusively due to a *decrease* of negativity in comparison to related and non-related category violations (thereby probably reflecting a decreased activation level or a stronger prime-induced preactivation), or, instead, whether this effect should be regarded as the result of an interaction with an *increased* positivity (i.e. as a reflection of a 'nested' positive component or due to a component overlap). We will return to this issue in the discussion in Chapter 4.1.6.

---

[12] Note, however, that the present experimental findings do not allow us to determine the degrees to which the N400 reflects expectancy-based priming or semantic priming, respectively. Nonetheless, it is clear that there must be a strong interaction between the two because neither of the two priming mechanisms can unequivocally explain the observed N400 pattern on its own.

4.1.4 EEG frequency analysis

Methods

To analyse the EEG of Experiment 2 in the frequency domain, the three measures evoked power (EPow), whole power (WPow), and phase locking index (PLI) were applied. All measures were determined by Gabor wavelet analysis in frequency bins of 0.55 Hz. Recall that the frequency resolution is determined by the size of the time window under consideration plus a 25% tapering window on both sides of the interval (to reduce onset/offset effects), in this case 1200 ms (-200 to 1000 ms, relative to the onset of the critical item) plus 2 x 300 ms resulting in a 1800 ms window.

For the statistical analysis of the frequency band characteristics, multi factorial analyses of variance (MANOVAs) were computed per value of interest for each participant, condition, time window and averaged frequency bin using the factor TYPE (antonyms vs. related vs. non-related) (cf. Chapters 2.5 and 3.1.4).

Recall that the figures below (Figure 4.2 and 4.3) represent *difference* maps based on subtractions of Gabor wavelet coefficients and PLI values. Thus, the control condition (antonyms) was subtracted from both critical conditions (category violations) to reveal task or condition specific activation patterns (cf. Chapter 3.1.4). To improve the clarity of the graphical illustrations, *positive* and *negative* values are represented in two different figures, i.e. one only revealing task specific increases (i.e. positive values = *Task* minus *Base*; e.g. Figure 4.3) and the other only task specific decreases (i.e. negative values = *Base* minus *Task*; e.g. Figure 4.2). It should be apparent that the notions *increase* and *decrease* should therefore be understood relationally in the present context, i.e. aphoristically in the sense of higher (more positive) and lower (more negative) values with regard to the control condition. Strictly speaking, positive values, for example could either be due to an activation *increase* of the critical condition in relation to the control condition or to an activation *decrease* of the control condition in comparison to the critical condition. Of course, exactly the opposite is the case for negative values.[13] However, a recursion to absolute values can help in resolving this ambiguous matter.

---

[13] In this way, negative values are either a reflection of an activation *decrease* of the critical condition in relation to the control condition or an activation *increase* of the control condition in comparison to the critical condition.

4.1.5 Results

Statistical analyses are restricted to lower frequency bands (< 6 Hz) for the midline electrodes FZ, CZ, PZ and the parietal electrodes P3 and P4 (Note that the graphical representation is limited to electrode PZ; illustrations of the results of electrodes FZ and CZ are given in Appendix D1). Visual inspection of the time-frequency plots showed no systematic variations across conditions in higher frequency bands with regard to the applied measures. We will begin with the most conspicuous effects revealed by visual inspection of the Gabor wavelet-based time-frequency plots. To this effect, we first report the eye-catching activity decreases of the critical conditions in comparison to the antonym control condition (i.e. '*Base* minus *Task'*, see Figure 4.2).

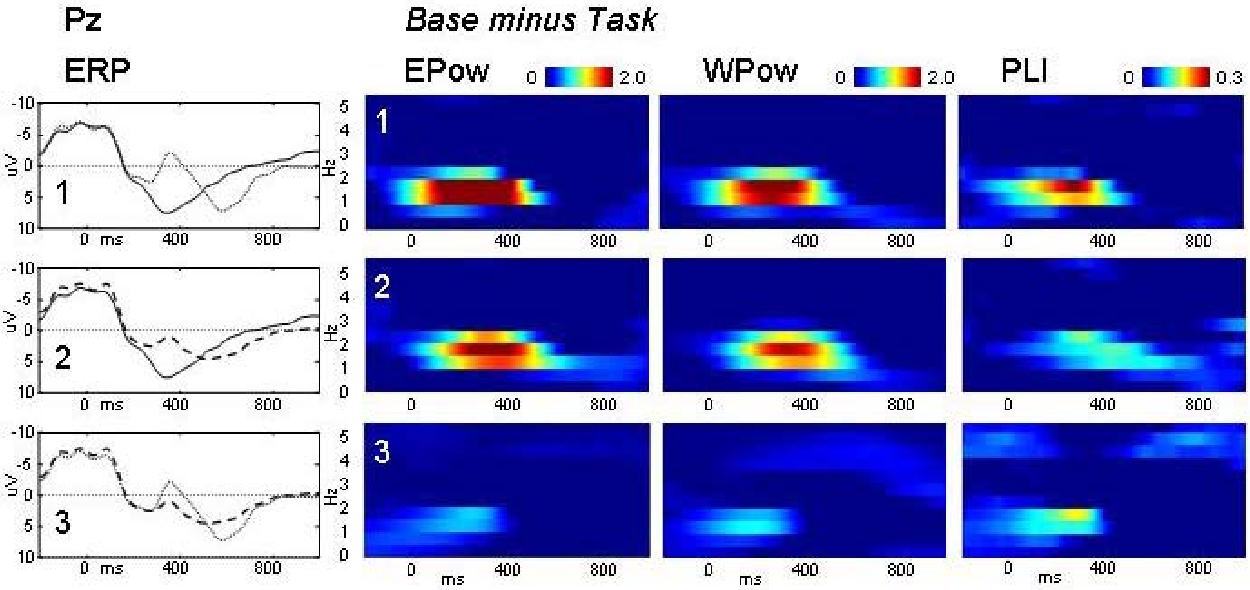

Figure 4.2. Grand average ERPs and Gabor wavelet-based time-frequency plots in the delta band (1-3 Hz) for the non-related category (Fig. 4.2.1; upper panel) and related category conditions (Fig. 4.2.2; lower panel) in comparison to the antonym control condition at electrode PZ (N=17). ERPs are shown in the far left panel, whereas the remaining three panels depict wavelet coefficient differences in evoked power (EPow; second panel from left) and whole power (WPow; second panel from right) and phase-locking index differences (PLI; far right panel). The colour scale depicts the magnitude of the wavelet coefficient differences for EPow and WPow and the PLI value difference for PLI. The ERPs show N400 differences (200-500 ms) in both comparisons and a P600 effect (500-800 ms) for the non-related condition. Note that the critical conditions are subtracted from the antonym control condition. Therefore, in terms of EPow, WPow and PLI, the non-related category condition (Fig. 4.2.1) and related category condition (Fig. 4.2.2) show power and phase locking *decreases* in comparison to the control condition (approximately in the N400 time window).

As is evident from Figure 4.2, in the delta band (1-3 Hz), the two category violation conditions show a decreased EPow in comparison to the antonym condition. This observation is confirmed by the statistical analysis, which revealed a main effect of TYPE (*F* (2,32) = 27.64, *p* < .001) between 100 and 400 ms (averaged frequency bins: 1.10-2.75 Hz). Single comparisons for each category violation condition in comparison to the antonym condition revealed a significant difference for non-related category violations (*F* (1,16) = 29.14, *p* < .001) as well as for related category violations (*F* (1,16) = 51.53, *p* < .001), but no significant difference between both. This pattern was observable at all electrodes under investigation (for all details see Appendix E1).

Pz ***Delta***	**EPow**	**Wpow**	**PLI**
TYPE	**	*	**
NON x ANT	**	*	**
REL x ANT	**	*	**
NON x REL			

P4 ***Delta***	**EPow**	**WPow**	**PLI**
TYPE	**	**	**
NON x ANT	**	*	**
REL x ANT	**	**	**
NON x REL			

Table 4.4. Main effect of TYPE and pairwise comparisons for electrodes Pz and P4 with regard to the three measures applied for the delta frequency band (time window: 100-400 ms; averaged frequency bins: 1.10-2.75 Hz). For post hoc single comparisons, all significance values are adjusted according to the modified Bonferroni procedure (Keppel, 1991) (# = marginally significant (< 0.9); * = < .05; ** = < .01).

A consideration of the measures WPow and PLI revealed that the decrease in evoked power was due to a decay of whole power (main effect of TYPE: *F* (2,32) = 3.96, *p* < .03) for both violation conditions (NON: *F* (1,16) = 5.27, *p* < .04; REL: *F* (1,16) = 5.71, p < .04) as well as a decrease of phase locking (main effect of TYPE: *F* (2,32) = 38.70, *p* < .001), which again applied for both conditions (NON: *F* (1,16) = 41.29, *p* < .001; REL: *F* (1,16) = 55.07, *p* < .001). As for EPow, there was no significant difference between the critical conditions with respect to WPow and PLI (cf. Table 4.4). Thus, both category violation conditions led to a decrease of stimulus-evoked activity in the delta band in relation to the antonym condition. Most importantly, it must be stressed that, although the decrease of delta activity was clearly restricted to the N400 time range, there was no difference between the two violation conditions in the delta band (cf. Table 4.4).

In addition to the already described decrease in delta activity, inspection of Figure 4.3 reveals that, almost concurrently, there was a stimulus-evoked increase in lower theta band activity (~3.5-5 Hz; main effect of TYPE; *F* (2,32) = 14.02, *p* < .001) between 200 and 600 ms (averaged frequency bins: 3.30-4.95 Hz).

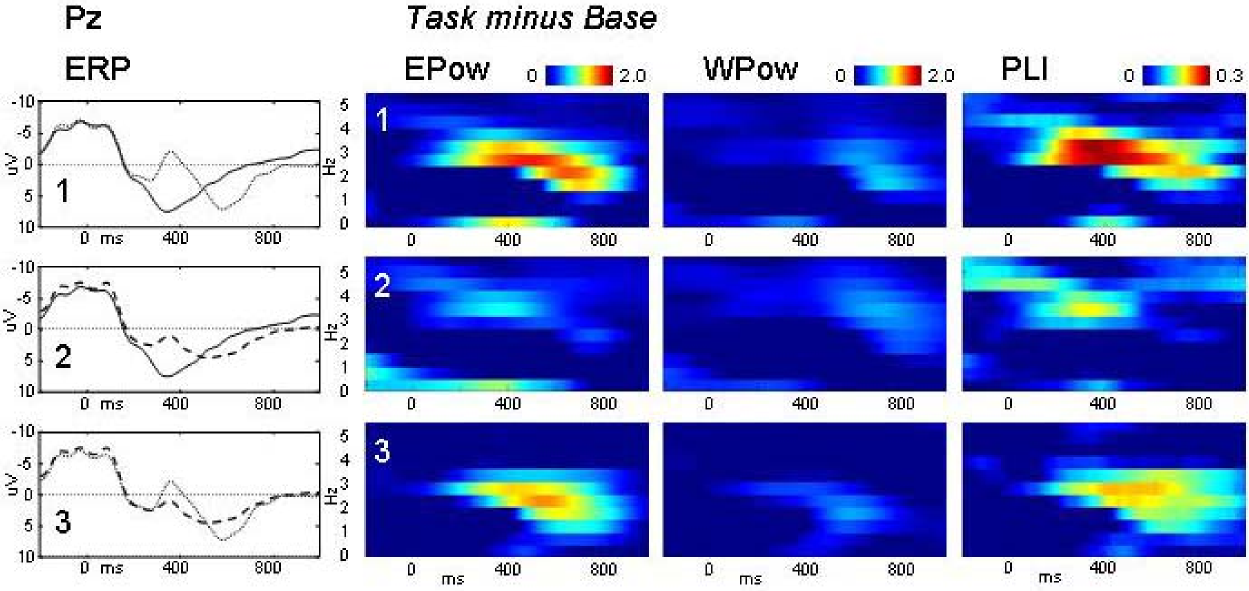

Figure 4.3. Grand average ERPs and Gabor wavelet-based time-frequency plots in the lower theta band (3.5-5 Hz) for the non-related category (Fig. 4.3.1) and related category conditions (Fig. 4.3.2) in comparison to the antonym control condition at electrode PZ (N=17). Note that the antonym control condition is subtracted from the two critical conditions. Hence, in terms of EPow and PLI, the non-related category condition (Fig. 4.3.1) but not the related category condition (Fig. 4.3.2) shows a power and phase locking increase in comparison to the control condition. With regard to WPow, no power increase is observable for both category violations.

Single comparisons revealed that there was only a marginal effect (and solely confined to electrode PZ) in EPow for the related category conditions, whereas, for the non-related category condition, there was a highly significant evoked power increase (*F* (1,16) = 22.68, *p* < .001) at all electrode sites (cf. Tabel 4.5 and Appendix E1)[14]. Moreover, there was a significant main effect of TYPE for PLI (*F* (2,32) = 21.77, *p* < .001), which was due to an increase in PLI for non-related conditions (*F* (1,16) = 35.89, *p* < .001). This finding suggests

---

[14] Note also that, for all electrode sites, there was a significant difference between NON and REL, not only for EPow but also for PLI (cf. Table 4.5 and Appendix E1).

that the EPow increase for non-related conditions was primarily a result of an enhanced phase-locking in the N400-time range.

Pz ***Lower Theta***	**Epow**	**Wpow**	**PLI**
TYPE	**		**
NON x ANT	**		**
REL x ANT	#		*
NON x REL	**		**

P4 ***Lower Theta***	**Epow**	**WPow**	**PLI**
TYPE	**		**
NON x ANT	**		**
REL x ANT			
NON x REL	**		**

Table 4.5. Main effect of TYPE and pairwise comparisons for electrodes Pz and P4 for the lower theta frequency band between 200 and 600 ms (averaged frequency bins: 3.30-4.95 Hz); (# = marginally significant (< 0.9); * = < .05; ** = < .01).

In this frequency band, it was therefore the non-related category violation that led to a higher degree of stimulus-evoked activity due to a higher degree of phase-coupling. These findings show that the graded N400 elicited by non-related category violations and that elicited by related category violations can be correlated with two different processes interacting with each other and mirrored in clearly separable frequency bands with different inherent processing characteristics. Furthermore, there was a decrease in stimulus-evoked delta activity in both category violations, which was due to a decrease of whole power and phase-locking. Moreover, there was a stimulus-evoked increase in lower theta activity due to enhanced phase-locking, which was solely observable for non-related category violations.

A more complex picture appeared with regard to the time range of the late positivity. Further statistical analyses of the time-frequency matrices in the P600 time range between 600 and 800 ms revealed significant main effects in the upper delta band (averaged frequency bins: 1.65-3.30 Hz) for the factor TYPE for all three measures, i.e. EPow (F (2,32) = 11.70, $p < .001$), WPow (F (2,32) = 7.58, $p < .005$), and PLI (F (2,32) = 12.82, $p < .001$). The resolution of the main effects showed that these effects were due to a significant enhancement of EPow, WPow and PLI for the non-related category violations (in comparison to antonyms), but not for related category violations. This pattern was not only observable at electrode PZ, but also at P3 and P4 (cf. Table 4.6 and Appendix E1).

Pz ***Delta (late)***	**EPow**	**WPow**	**PLI**
TYPE	**	**	**
NON x ANT	**	**	**
REL x ANT		**	
NON x REL	**		**

P4 ***Delta (late)***	**EPow**	**WPow**	**PLI**
TYPE	**	**	**
NON x ANT	**	**	**
REL x ANT		*	
NON x REL	**		**

Table 4.6. Main effect of TYPE and pairwise comparisons for electrodes Pz and P4 for the delta frequency band between 600 and 800 ms (averaged frequency bins: 1.65-3.30 Hz); (* = < .05; ** = < .01).

However, at the fronto-central electrode sites FZ and CZ, the picture was somewhat different (cf. Table 4.7). At FZ, there was only a significant main effect of TYPE for EPow (*F* (2,32) = 13.92, *p* < .001) and PLI (*F* (2,32) = 24.54, *p* < .001), but not for WPow (*F* < 1). Additionally, in contrast to posterior electrode sites, both violation conditions differed significantly from the antonym condition with respect to EPow (NON: *F* (1,16) = 28.67, *p* < .001; REL: *F* (1,16) = 5.97, *p* < .03), although there was an additional significant difference between the two category violation conditions (*F* (1,16) = 8.18, *p* < .02). Furthermore, both EPow effects were due to enhanced phase-locking (NON: *F* (1,16) = 56.96, *p* < .001; REL: *F* (1,16) = 9.06, *p* < .01).

Fz ***Delta (late)***	**EPow**	**WPow**	**PLI**
TYPE	**		**
NON x ANT	**		**
REL x ANT	*		*
NON x REL	*		**

Cz ***Delta (late)***	**EPow**	**WPow**	**PLI**
TYPE	**	#	**
NON x ANT	**	*	**
REL x ANT	#		
NON x REL	*		*

Table 4.7. Main effect of TYPE and pairwise comparisons for electrodes Fz and Cz for the lower theta frequency band between 600 and 800 ms (averaged frequency bins: 1.65-3.30 Hz); (# = marginally significant (< 0.9); * = < .05; ** = < .01).

The same pattern was observable at electrode CZ. Nevertheless, there was already a marginally significant main effect of TYPE for WPow (*F* (2,32) = 3.15, *p* < .06), due to enhanced WPow for NON (*F* (1,16) = 7.27, *p* < .02), and only a marginally significant EPow difference for REL in comparison to antonyms (*F* (1,16) = 4.46, *p* < .06).

Hence, in the P600-time range, there was a stimulus-evoked activity enhancement at fronto-central electrode sites in the upper delta frequency range for both category violation conditions, which was due to a higher degree of phase-locking. Moreover, this upper delta EPow and PLI enhancement was more pronounced for non-related as compared to related category violations. For posterior electrode sites, however, only the non-related category condition led to a higher degree of stimulus-evoked upper delta activity. In addition this upper delta EPow effect was due to stronger phase-locking along with an increased whole power. However, we already have stressed in Chapter 3.1.6 that the edges of the observed effects, despite the optimal time-frequency resolution of Gabor wavelets, might be subject to smearing effects, thereby rendering a precise demarcation of onsets and offsets in time and frequency difficult. Therefore, the distinction of an upper delta effect (in comparison to the lower theta frequency) is entirely tentative. It is based, firstly, on the visual evaluation of the time-frequency plots (i.e. the observation that there is a ‘bending’ of the theta frequency towards a lower frequency range in the time range of the late positivity effect). Secondly, it is based on the premise that a reflection of the observed P600-differences must also be present in EPow (and hence in WPow or PLI). Furthermore, the above objection clearly does not refer to the ‘centre of activation’ (activation peak) of an observed effect. That is, two clearly distinguishable activation centres are indicative of distinct effects in time and/or frequency. However, the visual inspection of the time-frequency plots (cf. Appendix D1) for the electrodes Fz and, less pronounced, Cz clearly reveals distinct ‘activation peaks’ in time *and* frequency thereby supporting the tentative distinction between a lower theta and an upper delta effect.

4.1.6 Discussion

The primary aim of the present experiment was to investigate and characterise the underlying frequency dynamics of a standard N400 effect. To this end, we introduced an antonym sentence verification task under the assumption that the processing of antonym relations in comparison to category violations would lead to a clear graded semantic N400 effect. Indeed, the present experimental manipulation elicited a strong and graded N400 effect in the predicted direction, that is, the N400 was more pronounced for non-related category violations than for related category violations in comparison to antonyms. However, a further aim deemed to be crucial was to elicit a monophasic N400 effect. Because both category violation conditions showed a pronounced biphasic N400-P600 pattern, it is obvious that, in this respect, the experimental manipulation was unsuccessful. As discussed in the final paragraph of Chapter 3, bi- or multiphasic ERP effects render the unambiguous attribution of frequency dynamics difficult, due to potential component overlap, concurrent superposition of frequency bands and smearing effects in the time-frequency domain due to the wavelet analysis. This is particularly problematic with respect to the analysis of low frequency dynamics, because of their inherently relatively poor temporal resolution.

Nevertheless, in comparison to the observed biphasic N400-P600 pattern, we could distinguish three different EPow effects in the frequency domain: (i) a pronounced increase in the delta band for antonyms in comparison to both category violation conditions in the N400 time range; (ii) an increase in the lower theta band for non-related category violations in comparison to antonyms and the related category violation condition in the N400 time range; (iii) an increase in the upper delta band for both category violation conditions in comparison to antonyms in the P600 time range; this increase was more pronounced for the non-related than for the related category condition.

With regard to the pronounced N400 effect, we hypothesised that a large portion of this effect might be due to an enhanced *positive* ERP deflection for antonyms. That is, the N400 effect might not simply have been due to a reduced negativity for antonyms in comparison to both category violation conditions, but rather might have been the reflection of a nested positive component for antonyms. This hypothesis was strongly supported by the findings from the applied frequency measures. Under the assumption that the N400 effect is the result of a reduced negativity for antonyms in comparison to both category violations, the subtraction of the evoked power wavelet coefficients of the antonym condition (which served as a control condition) from the two category violation conditions should reveal a visibly enhanced activity for the latter. Furthermore, this enhanced activity should be graded, that is, more pronounced for non-related category violations than for related category violations (simply because the N400 effect showed this graduation). However, as was evident from Figures 4.2 and 4.3, there was no single correlate of the graded N400 effect observable in the frequency domain (in the time range of the N400 effect), which conformed to the above assumptions.[15] The most important and eye-catching observation was that the EPow time-frequency

---

[15] Of course, the assumption that the N400 effect is partly due to a reduced N400 component does not necessarily imply a single correlate in the frequency domain.

difference maps indicated a large *positive* difference in evoked delta power for antonyms in comparison to both category violation conditions (cf. Figure 4.2). In addition, this positive difference showed *no graduation* between related and non-related category violations. It was also evident that this difference was confined to the time range of the N400 effect. Even considering Gabor wavelet based smearing effects, which most likely blurred the precise temporal localisation of the on- and offset of the effects, this difference effect faded at approx. 500 ms post-onset of the critical item. Because the late positive portion of the biphasic N400-P600 effect didn't start before 500 ms, it seems very unlikely that the difference effect in evoked delta activity was confounded with the latter effect. Therefore, this increase in evoked delta band power for antonyms can be unambiguously attributed to the N400 effect. Note that, in principle, the observed difference in evoked delta power must not necessarily reflect a delta power increase for antonyms in contrast to category violations. It also could be due to a more pronounced power decrease for category violations in comparison to antonyms. However, a comparison of the time course of delta power activation by means of time-frequency plots based on absolute EPow coefficient values revealed a clear event-related *increase* in delta power for antonyms. Hence, it is tempting to interpret this increase as a correlate of the positive shift in the N400 time range for antonyms and therefore as support for the hypothesis that the N400 effect is not a monolithic effect.

A second correlate of antonym processing was visible in the lower theta band. Here, the non-related category violation condition showed an increased evoked power in comparison to the antonym and the related category condition.[16] Analogously to the graded N400 effect, this pattern allowed one to distinguish the two category violations from each other (i.e. to relate them with respect to their 'gradedness'). However, in contrast to the delta band activity, the increase in the lower theta band can only be tentatively linked with the N400 effect. As the theta increase appeared between approximately 200 and 800 ms, it fully overllaped with the biphasic N400-P600 effect. Nevertheless, in the previous section, we already pointed to some arguments which suggest to us that an early and a late effect can be distinguished. First, between 500 and 800 ms post-onset of the critical stimulus, the frequency of the lower theta activity seemed to "slow down". Additionally, visual inspection of the EPow time-frequency difference plots of electrode FZ revealed that there were clearly two distinct *activation peaks* for both category violation conditions in comparison to antonyms: an earlier increase in lower

---

[16] There was only a marginal EPow increase in the lower theta band for related category violations (confined to electrode PZ and due to an increased PLI).

theta and a later increase in ‘upper delta’ (cf. Appendix D1).[17] Hence, there was some evidence for the proposed distinction of an N400-related early lower theta increase and a P600-related late (upper) delta activity, despite the obvious smearing effects. Moreover, whereas the early EPow increase in lower theta was clearly due to an enhanced phase locking (without a concurrent increase in WPow), the picture for the late effect was more complex (but see above). We also proposed the distinction of a late frontal and a late posterior positivity. Although this distinction is tentatively supported by the topographical distribution of the observed upper delta effects, we do not discuss this issue in more detail in the present thesis. However, these findings will be subject to further investigations.

With regard to the primary aim of the present experiment, that is, to provide an exact and unequivocal characterisation of a semantic N400 effect, the lower theta EPow increase cannot unrestrictedly be attributed or related to the present N400 effect. This is the case although the evoked lower theta activity seems to be necessary to explain the graded effect between both category violation conditions.

In summary, the above observations constitute first evidence against the hypothesis that the present N400 effect is a monolithic effect (i.e. entirely due to a reduced N400 component for antonyms in comparison to both violation conditions). Instead, we hypothesised that the major proportion of the present N400 effect was due to an increased activity in the delta band for antonyms in comparison to the category violation conditions, thus reflecting an embedded positive component for antonyms. Moreover, the evoked delta power increase was due to an increase in whole power as well as in phase locking.[18] Whereas an increased phase locking indicates a more consistent timing across trials, an increase in whole power can be taken as a reflection of an enhanced synchronisation of underlying neural populations. That is, increases in whole power might be a reflection of enhanced processing ‘effort’. However, further implication of the present results as well as a proposed functional interpretation will be

---

[17] Note that this late frontal upper delta increase in EPow and PLI for category violations might be a reflection of the proposed distinction between a frontal and posterior late positivity (cf. Chapter 4.1.3; Hagoort et al., 1999; Friederici, Hahne, & Saddy, 2002). However, because the focus of the investigation is on the N400, we will not further discuss the above findings with respect to late positivities in the context of the present thesis.

[18] Unfortunately, if both WPow and PLI concurrently show activity changes, it is not possible (at least with the frequency measures applied here), to quantify the *relative* contributions of power or phase locking to EPow. However, if we compare two or more conditions, the respective measures can show different degrees of activity relative to each other (cf. Experiment 1, Chapter 3).

discussed in the final section of the present chapter (together with and in the light of the findings from the subsequent experiments).

As already discussed above, the major problem of the present experimental manipulation was the somewhat unexpected appearance of a biphasic N400-P600 pattern (cf. Chapter 4.1.3), which rendered the desired frequency-analytical characterisation of the N400 effect, as well as its subsequent functional interpretation, difficult (at least with regard to the lower theta band). Therefore, we have to consider the possible reasons for the elicitation of this late positivity. In general, the P600 is regarded as a correlate of syntactic processes (cf. Chapter 2; Friederici, 2002). However, the present antonymy sentence verification task undisputably involved semantic processing conflicts due to a semantic violation (i.e a wrong antonym relation), without any structural manipulations. Yet, late positivities have also been interpreted as a reflection of final evaluation processes with respect to the well-formedness of a sentence. Hence, one could speculate that the embedding of antonym word pairs in a sentence context might have been responsible for the elicitation of a late positivity. Whereas a semantic violation like *The honey was murdered* is simply not plausible, i.e. is semantically odd (but conceivable in another possible world), the sentence *The opposite of black is green* is not only implausible but simply wrong (in all possible worlds). It not only contradicts our general world knowledge, but furthermore violates the whole sentence proposition (with regard to its inherent ‘logic’). In addition to the demands of the explicit antonymy verification task, it is very likely that the stereotype sentence context enhanced the tendency to build up a specific *expectation* with regard to the sentence-final words (the second antonym). This additional restricting factor might have enhanced the anticipatory aspect of the present task, thereby giving rise to an increased emphasis on evaluative or integrative processes. This in turn might have led to the elicitation of a late positivity. However, a further possibility might have been that the explicit *task instruction* to judge or verify the sentences with regard to their ‘underlying’ antonym relations led to the appearance of a late positivity. Nevertheless, we first conducted a further experiment in order to test whether the late positivity is still observable when antonym relations are presented out of sentence context. Therefore, in the subsequent experiment, we employed the same stimulus material as in the present experiment, but presented the antonym relations as word pairs.

4.2 Experiment 3: Antonyms in word lists (word pairs)

As already outlined at the end of Chapter 4.1, the present experiment addresses the question whether sentence context effects might have influenced the processing of antonym relations and, as a consequence, might have led to the elicitation of a late positivity complex (frontal and posterior) in the preceding experiment. This is particularly important in the light of the superordinated aim to elicit a monophasic semantic N400 effect in order to unequivocally characterise its underlying frequency dynamics. To this end, in the present experiment, we used exactly the same stimulus material as in the previous experiment, but presented the stimuli as word pairs instead of complete propositions.

4.2.1 Method

Materials

Stimulus material was the same as in Experiment 2. However, for stimulus presentation we used only word pairs instead of sentences. The three critical conditions for the experiment are shown in Table 4.8 below. Eighty triplets of these three conditions were created, resulting in 240 experimental word pairs. These were assigned to 4 lists of 160 critical word pairs (80 for the antonyms, 40 for the two mismatch conditions each) in a counterbalanced manner such that each participant saw 40 complete triplets of a given set plus the remaining 40 word pairs from the antonym condition. For a complete set of materials see the critical items from Experiment 2, listed in Appendix A1.

Condition	**Example**
A. *Antonyms*	schwarz - <u>weiss</u> black - *white*
B. *Related*	schwarz - <u>gelb</u> black - *yellow*
C. *Non-related*	schwarz - <u>nett</u> black - *nice*

Table 4.8. Example word pairs for each of the experimental conditions. The critical word is underlined.

Participants

Seventeen right-handed undergraduate students from the Philipps-University of Marburg participated in the Experiment (11 female; mean age 23.2 years; age range 20-29 years). None of the participants had taken part in either of Experiments 1 or 2.

Procedure

Word pairs were presented visually in the centre of a computer screen in a word-by-word manner. Each trial began with the presentation of an asterisk (2000 ms) in order to fixate participants' eyes at the centre of the screen and to alert them to the upcoming presentation of the word pair. The first word (prime) was presented for 400 ms with an inter-stimulus interval (ISI) of 400 ms, whereas the second word (target) was presented for 350 ms. After the presentation of both words, there was a 650 ms pause before participants were required to complete an *antonym verification task* (signalled through the presentation of a question-mark), which involved judging whether the preceding word pair was an antonym pair or not. Subjects had to respond by pressing the left or right mouse button for 'yes' or 'no'. The time window for the button press was restricted to 3000 ms, whereas the subsequent trial started immediately after the button press. For each participant, the antonym verification task required the answer 'yes' equally as often as 'no' (80 word pairs with correct antonym pairs, 80 with an incorrect second 'antonym'). Between the trials, there was an inter-trial interval (ITI) of 1400 ms.

Participants were asked to avoid movements and to blink their eyes between their response to the antonym verification task and the presentation of the next word pair. The experimental session began with a short training session followed by 4 experimental blocks comprising 40 word pairs each, between the participants took short breaks. The entire experiment (including electrode preparation) lasted approximately 2 hours (due to a second experiment which will not be reported here).

The EEG was recorded as for Experiment 2, except that the high cutoff frequency was 100 Hz. Average ERPs were calculated per condition per participant from 334 ms prior to the onset of the critical stimulus item (i.e. the second word of the word pair) to 1000 ms post onset, before grand-averages were computed over all participants. Trials for which the antonym verification task was not performed correctly were excluded from the averaging procedure as well as from the single trial analysis, as were trials containing ocular or other artefacts (cf. Experiment 2).

Data Analysis

The statistical analysis was carried out like in Experiment 2.

4.2.2 ERP results

Behavioural Data

The statistical analysis of the error rates for the antonym verification task revealed significant main effects of TYPE (F_1 (2,32) = 10.34, $p < 0.001$; F_2 (2,158) = 14.76, $p < 0.001$). These effects were due to the higher error rates for the related category violations (4.56%) in comparison to the antonyms (1.69%) as well as to the lower error rates for the non-related category violations (0.29%) in comparison to the antonyms. Resolving the main effect revealed a significant difference for antonyms compared with both related category violations (F_1 (1,16) = 6.03, $p < 0.03$; F_2 (1,79) = 12.63, $p < 0.002$) and non-related category violations (F_1 (1,16) = 8.14, $p < 0.02$; F_2 (1,79) = 4.16, $p < 0.05$) as well as between related and non-related category violations (F_1 (1,16) = 15.98, $p < 0.002$; F_2 (1,79) = 17.92, $p < 0.001$).

With regard to the reaction times, there was again a significant main effect of TYPE (F_1 (2,32) = 15.77, $p < 0.001$; F_2 (2,158) = 11.29, $p < 0.001$). A resolution of the main effect revealed a significant difference between antonyms and related category violations (F_1 (1,16) = 13.93, $p < 0.003$; F_2 (1,79) = 10.96, $p < 0.002$) as well as between related and non-related category violations (F_1 (1,16) = 29.00, $p < 0.001$; F_2 (1,79) = 20.49, $p < 0.001$). However, in contrast to Experiment 2, there was no significant difference between antonyms and non-related category violations, neither for the factor subjects (F_1 (1,16) = 1.70, $p < 0.3$) nor for the factor items (F_2 (1,79) = 1.00, $p < 0.4$). Hence, the following pattern emerged with regard to the reaction times:

NON / ANT < REL

An overview of the behavioural results with regard to error rates and reaction times is given in Table 4.9. The low error rates showed that participants had no problem in reading the word pairs and performing the antonym verification task. Note that the reaction times are measured from the onset of the question mark, which served as a cue for the performance of the antonym verification task (see Experiment 2).

task	error rates (%)		reaction times (ms)	
	average	sd	average	sd
antonyms	1.69	1.87	457,25	153,04
related	4.56	4.78	505,85	146,72
non-related	0.29	0.83	444,14	135,23

Table 4.9. Percentages of error rates and mean reaction times for the antonym verification task.

ERPs

Figure 4.4 shows grand-average ERPs for the three critical conditions (a complete overview of the measured electrodes is shown in Appendix B3). Visual inspection indicated that, for the two category violation conditions (related and non-related category), the critical items elicited a broad, centro-parietal negativity between approximately 250 and 500 ms. This effect was less pronounced for the related category violations (REL) than for the non-related category violations (NON). In addition, antonyms elicited a pronounced positive shift at centro-parietal electrode sites in comparison to both category violation conditions. It is apparent that this N400 pattern is essentially identical to the N400 pattern in Experiment 2. Furthermore, between approximately 400 and 800 ms post onset of the critical item, there was an enhanced positivity for related and non-related category conditions in comparison to the antonym condition. As in Experiment 2, this positivity seemed to be more pronounced frontally for REL than for NON, whereas at centro-parietal regions NON elicited a more positive waveform than REL. Notably, the positivity effect appeared to be much less pronounced for both category violations than in Experiment 2.

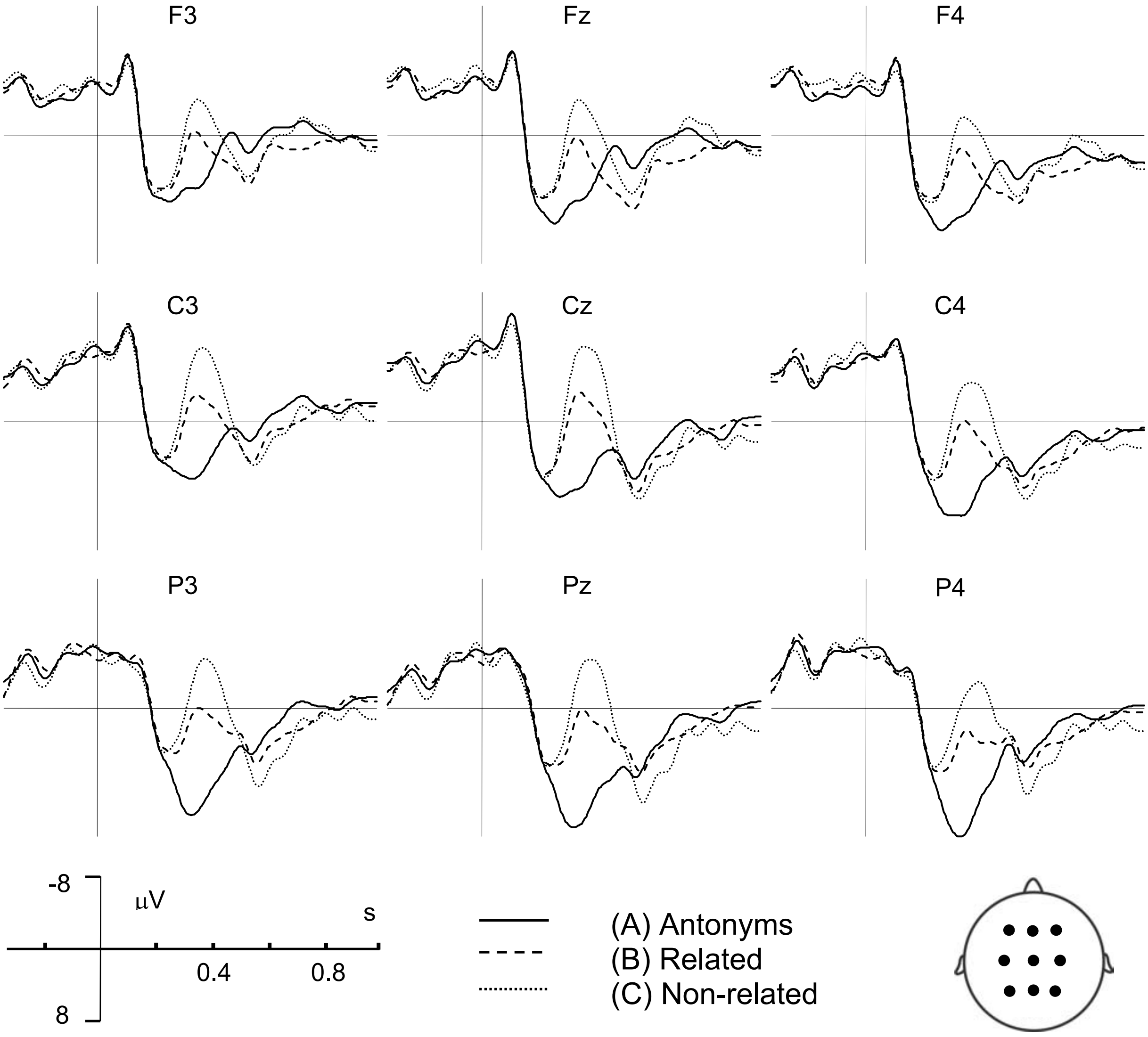

Figure 4.4. Grand average ERPs for antonyms, related and non-related category violations in Experiment 3 (onset at the vertical bar). Negativity is plotted upwards.

The statistical analysis was carried out as in Experiment 2, i.e. repeated measure ANOVAs were calculated in twenty-four successive 50 ms time windows, from -200 ms until 1000 ms (t1 – t24). The global analysis revealed significant main effects between 250 and 500 ms of TYPE for ROIs (*250-300 ms*: *F* (2,32) = 9.47, *p* < .01; *300-350 ms*: *F* (2,32) = 23.12, *p* < .01; *350-400 ms*: *F* (2,32) = 48.04, *p* < .01; *400-450 ms*: *F* (2,32) = 25.12, *p* < .01; *450-500 ms*: *F* (2,32) = 3.09, *p* < .06) and for midline electrodes (*250-300 ms*: *F* (2,32) = 13.90, *p* < .05; *300-350 ms*: *F* (2,32) = 26.57, *p* < .01; *350-400 ms*: *F* (2,32) = 44.39, *p* < .01; *400-450 ms*: *F* (2,32) = 24.13, *p* < .01; *450-500 ms*: *F* (2,32) = 3.16, *p* < .06). All significant main effects between 250 and 400 ms were due to more negative waveforms for non-related and related category conditions in comparison to the antonym condition. Single comparisons revealed that, for all regions, the negativity was significantly stronger for NON in comparison to REL. (cf. Table 4.10).

Furthermore, post hoc analyses of the significant interactions of TYPE x ROI between 250 and 450 ms (*250-300 ms*: *F* (6,96) = 5.88, *p* < .01; *300-350 ms*: *F* (6,96) = 9.02, *p* < .01; *350-400 ms*: *F* (6,96) = 13.69, *p* < .01; *400-450 ms*: *F* (6,96) = 16.52, *p* < .01) and TYPE x ELEC between 300 and 450 ms (*300-350 ms*: *F* (4,64) = 8.82, *p* < .01; *350-400 ms*: *F* (4,64) = 27.24, *p* < .01; *400-450 ms*: *F* (4,64) = 25.96, *p* < .01) revealed that the negativity for the two category violation conditions was more pronounced at posterior regions.

For the time window between 450 and 600 ms, the picture was more complex. The resolution of the significant interactions for the respective time windows for ROIs (*450-500 ms*: *F* (6,96) = 8.14, *p* < .01; *500-550 ms*: *F* (6,96) = 4.02, *p* < .01; *550-600 ms*: *F* (6,96) = 6.89, *p* < .01) and midline electrodes (*450-500 ms*: *F* (4,64) = 19.47, *p* < .01; *500-550 ms*: *F* (4,64) = 11.30, *p* < .01; *550-600 ms*: *F* (4,64) = 8.13, *p* < .01) showed that there was still a significant negativity for NON in comparison to antonyms at FZ and right-frontal regions between 450 and 500 ms. By contrast, in the same time window, there was the beginning of a significant difference for REL against ANT due to a frontal positivity (FZ, left- and right-frontotemporal). This significant positivity for REL lasted until 600 ms (left-frontal, FZ). Between 500 and 600 ms, there was also a significant positivity for NON vs. ANT, which was restricted to left-frontotemporal regions and FZ (cf. Table 4.10).

ROIs		time windows in ms													
		t9	t10	t11	t12	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22
		200-250	250-300	300-350	350-400	400-450	450-500	500-550	550-600	600-650	650-700	700-750	750-800	800-850	850-900
FroL	Type			**	**	*	**	**	*			*			
	rel			*	**		**	*	*			#			
	non			**	**	#		*	#						
	with			*	**	*						*			
Fz	Type		**	**	**	**	**	**	*		*	**	*		
	rel		**	**	**		**	*	*		#	*	*		
	non		**	**	**	*	*	*							
	with			**	**	**	*				#	**	#		
FroR	Type		**	**	**	**	**	#				*	*		
	rel		**	**	**		*	#							
	non		**	**	**	**									
	with			**	*	**	**					*	*		
Cz	Type		**	**	**	**					*				
	rel		**	**	**										
	non		**	**	**	*					**				
	with			**	**	**									
PosL	Type		**	**	**	**			**	**	**	**	*		
	rel			**	**	**			*	*	*	**	*		
	non		**	**	**	**			**	**	**	*	*		
	with		#	*	**	**			*	*	*				
Pz	Type		**	**	**	**	**		**	*	**				
	rel		**	**	**	**	**								
	non		**	**	**	**	**		**	**	**				
	with			*	**	**			*	#	*				
PosR	Type		**	**	**	**	**		**	*	**	*	*		
	rel		**	**	**	**						*	*		
	non		**	**	**	**	*		**	**	**	#	*		
	with			**	**	**	#		*						

Table 4.10. Overview of the significant effects in each of the 4 ROIs (frontal-left = FroL; frontal-right = FroR; posterior-left = PosL; posterior-right = PosR) and 3 midline electrodes (Fz, Cz, Pz) in 14 successive 50ms time windows (t9 - t22) starting at 200 ms till 900 ms post-onset of the critical items. For post hoc single comparisons ,all significance values are adjusted according to the modified Bonferroni procedure (Keppel, 1991) (# = marginally significant (< 0.9); * = < .05; ** = < .01). The main effect for the 3 conditions (ANT = antonyms, REL = related category violations, NON = non-related category violations) is coded as Type = ANT x REL x NON. The three Single comparisons are: rel = ANT x REL; non = ANT x NON, with = REL x NON. There is no significant effect for any comparison in the time windows t1 - t8 (< 200 ms) and t23/24. The light shaded areas show the significant *frontal* positivity, whereas the dark shaded areas show the *posterior* positivity.

Additionally, the global analysis for the later time windows revealed significant main effects of TYPE (for ROIs) between 550 and 750 ms (*550-600 ms*: *F* (2,32) = 7.73, $p < .01$; *600-650 ms*: *F* (2,32) = 4.12, $p < .05$; *650-700 ms*: *F* (2,32) = 4.94, $p < .05$; *700-750 ms*: *F* (2,32) = 5.39, $p < .01$) and significant interactions of TYPE x ROI between 550 and 800 ms (*550-600 ms*: *F* (6,96) = 6.89, $p < .01$; *600-650 ms*: *F* (6,96) = 5.99, $p < .01$; *650-700 ms*: *F* (6,96) = 7.85, $p < .01$; *700-750 ms*: *F* (6,96) = 4.33, $p < .01$; *750-800 ms*: *F* (6,96) = 3.77, $p < .01$) as well as of TYPE x ELEC between 550 and 900 ms (*550-600 ms*: *F* (4,64) = 8.13, $p < .01$; *600-650 ms*: *F* (4,64) = 5.23, $p < .01$; *650-700 ms*: *F* (4,64) = 11.87, $p < .01$; *700-750 ms*: *F* (4,64) = 5.78, $p < .01$; *750-800 ms*: *F* (4,64) = 8.33, $p < .01$; *800-850 ms*: *F* (4,64) = 3.56, $p < .05$; *850-900 ms*: *F* (4,64) = 3.06, $p < .05$). A resolution of these interactions revealed that the significant interactions between 550 and 700 ms were due to a pronounced positivity for NON in comparison to ANT at posterior regions. Furthermore, there was a significant difference for REL against ANT between 550 and 850 ms that was restricted to left-posterior regions.

A schematic overview of the significant single comparisons for each of the four ROIs and the three midline electrodes is shown in Table 4.10 above.

4.2.3 Interim discussion

The statistical analyses of the error rates for the antonym verification task mirrored the results from Experiment 2, i.e. there were significant differences between antonyms and the two violation conditions as well as between both violation conditions. Error rates were lowest for non-related category violations and highest for related category violations. Also, the reaction time pattern observed in Experiment 2 was basically replicated, i.e. reaction times were slowest for related and fastest for non-related category violations (although the statistical analyses revealed no significant difference between antonyms and non-related category violations). This indicates that the sequence pattern of both reaction times and error rates is not dependent on the stimulus presentation type (i.e. sentence vs. word pairs) but rather on the specific task demands posed by the processing of antonym relations.

The basic ERP-findings of Experiment 3 may be summarised as follows: (1) As in Experiment 2, both category violations elicited a broad centro-parietal N400 between approximately 250 and 400 ms post onset of the critical item. The N400 was less pronounced for related category violations in comparison to non-related category violations. The stronger activation for non-related category violations resulted not only in a higher N400 amplitude, but also in a longer duration of the negative component. Moreover, as in Experiment 2, antonyms elicited a pronounced positive shift at posterior electrode sites in the N400 time range in comparison to both category violations. (2) In both category violation conditions there was an ‘early’, frontally distributed positivity between 450 and 600 ms post onset of the critical item. This positivity seemed to be more pronounced and with an earlier onset for related than for non-related category violations. In comparison to Experiment 2, this frontal positivity was strongly attenuated. However, like in Experiment 2, the difference between the related and the non-related violation conditions might have been due to an interaction of the positivity with the preceding and stronger N400 for non-related category violations. (3) Furthermore, only non-related category violations elicited a late positivity at posterior regions between 550 and 700 ms in comparison to the antonym condition. As for the frontal positivity, this posterior positivity was strongly attenuated in comparison to Experiment 2.

In sum, Experiment 3 showed almost the same ERP pattern as Experiment 2. Visual inspection revealed no distinguishable differences between the two stimulus presentation modes with regard to the observed N400 effects (i.e. either presented in sentence context or as word-pairs). Likewise, both the frontal and the posterior positivity showed the same graduation pattern in both experimental manipulations. However, there was an impressing difference between the two manipulations with respect to the prominence of the late positivity effects: processing the critical items within a sentence frame led to a significantly more pronounced positivity than in the present word-pair manipulation. Yet, although the present positivities were highly attenuated, they were both still significant. Indeed, in the present experiment, the two different late positivities could be distinguished much more clearly than in the previous experiment with respect to their time course and topographical distribution.[19]

---

[19] This was probably the case because the reduced amplitudes of the positivities led to a lesser degree of component overlap with the preceding N400 and between the frontal and the posterior positivity.

4.2.4 EEG frequency analysis

Methods

As in Experiments 1 and 2, we applied the three frequency-based measures evoked power (EPow), whole power (WPow) and phase locking index (PLI) for the EEG analysis (cf. Experiment 1). All measures were determined by Gabor wavelet analyses in frequency bins of 0.5 Hz (time window –334 to 1000 ms plus 50% tapering window). As for Experiment 2, analyses were confined to lower frequency bands (< 6 Hz) for the midline electrodes FZ, CZ, PZ and the parietal electrodes P3 and P4.[20] The statistical analysis was carried out as in Experiment 2.

Results

Figure 4.5 shows that, for both category violation conditions, there was a pronounced decrease of delta band activity (1-3 Hz) in comparison to the antonym condition for all three applied measures (EPow, WPow and PLI). This decrease was confined approximately to the time range of the N400 effect of the corresponding ERP analysis.

The statistical analyses confirmed these observations. For EPow, there was a significant main effect of TYPE for the electrodes PZ (F (2,32) = 20.10, $p < .01$) and P4 (F (2,32) = 22.18, $p < .01$) between 100 and 500 ms (averaged frequency bins: 1.0-3.0 Hz). Single comparisons for each category violation condition in comparison to the antonym condition revealed significant differences for non-related category violations (*PZ*: F (1,16) = 24.29, $p < .01$; *P4*: F (1,16) = 23.28, $p < .01$) as well as for related category violations (*PZ*: F (1,16) = 21.92, $p < .01$; *P4*: F (1,16) = 25.77, $p < .01$), but no significant difference between them (*PZ*: F (1,16) = 1.46, $p = .244$; *PZ*: $F < 1$). This pattern emerged at all electrode sites under investigation (for more details see Appendix E2).

---

[20] Just as for Experiment 2, the visual inspection of the time-frequency plots showed no systematic variations across conditions in higher frequency bands with regard to the applied measures.

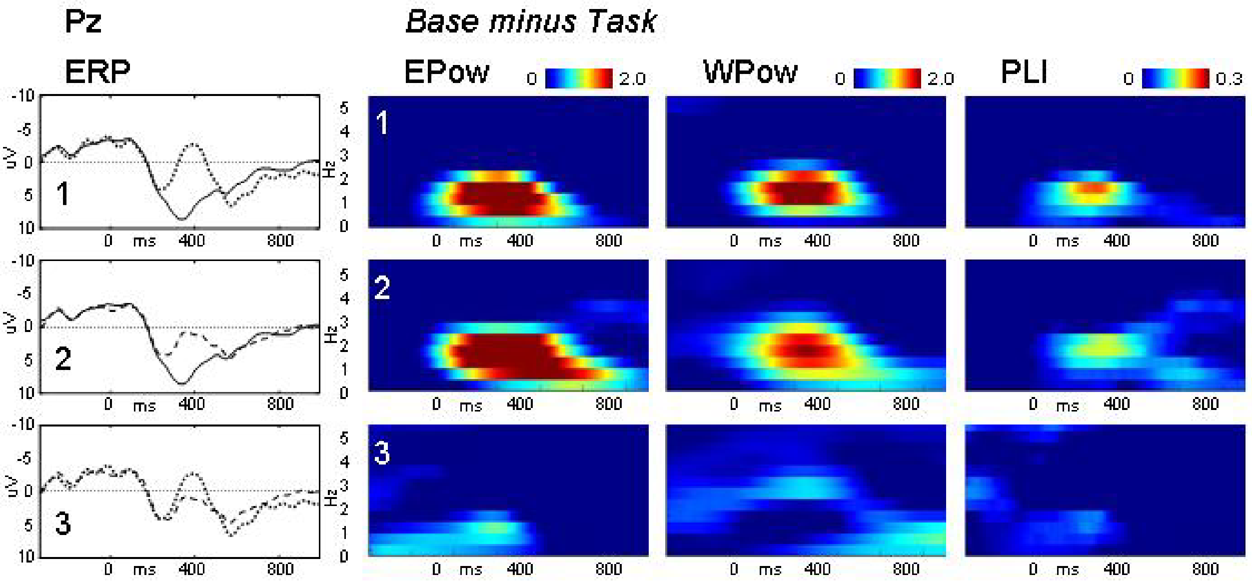

Figure 4.5. Grand average ERPs and Gabor wavelet-based time-frequency difference plots in the delta band (1-3 Hz) for the non-related (Fig. 4.5.1) and related category conditions (Fig. 4.5.2) in comparison to the antonym control condition at electrode PZ (N=17). Figure 4.5.3 shows the difference between non-related and related category violations. The colour scale depicts the magnitude of the wavelet coefficient differences for EPow and WPow and the PLI value difference for PLI. Note that the violation conditions were subtracted from the antonym condition, thereby indicating *relative decreases* in activity for the former (cf. Exp. 1).

The global analyses for WPow and PLI again revealed significant main effects of TYPE at electrode PZ (*WPow*: F (2,32) = 20.01, $p < .01$; *PLI*: F (2,32) = 10.56, $p < .01$) and P4 (*WPow*: F (2,32) = 24.67, $p < .01$; *PLI*: F (2,32) = 10.34, $p < .01$). Post hoc pairwise comparisons showed that there were significant differences for related and non-related category violations in comparison to the antonym condition for WPow at PZ (*NON*: F (1,16) = 23.77, $p < .01$; *REL*: F (1,16) = 24.70, $p < .01$) and P4 (*NON*: F (1,16) = 29.98, $p < .01$; *REL*: F (1,16) = 31.40, $p < .01$), as well as for PLI at PZ (*NON*: F (1,16) = 14.74, $p < .01$; *REL*: F (1,16) = 13.02, $p < .01$) and P4 (*NON*: F (1,16) = 10.57, $p < .01$; *REL*: F (1,16) = 16.28, $p < .01$). As for EPow (cf. Table 4.11), it is important to stress that there was no difference between both category violation conditions, neither with respect to WPow ($F < 1$) nor PLI ($F < 1$).[21]

---

[21] All the results also hold for the remaining electrode sites (cf. Appendix E2).

Pz *Delta*	**EPow**	**Wpow**	**PLI**
TYPE	**	**	**
NON x ANT	**	**	**
REL x ANT	**	**	**
NON x REL			

P4 *Delta*	**EPow**	**WPow**	**PLI**
TYPE	**	**	**
NON x ANT	**	**	**
REL x ANT	**	**	**
NON x REL			

Table 4.11. Main effects of TYPE and pairwise comparisons for electrodes Pz and P4 with regard to the three measures applied for the delta frequency band (frequency bins: 1.0-3.0 Hz; time window 100-500 ms). For post hoc single comparisons, all significance values are adjusted according to the modified Bonferroni procedure (Keppel, 1991) (** = < .01).

Figure 4.6 shows that, as for Experiment 2, there was also a stimulus-evoked *increase* in lower theta band activity (~3-5 Hz) between 300 and 600 ms. This increase was roughly in the same time range as (i.e. temporally overlapped with) as the delta EPow, WPow and PLI *decrease* (cf. Figure 4.5).

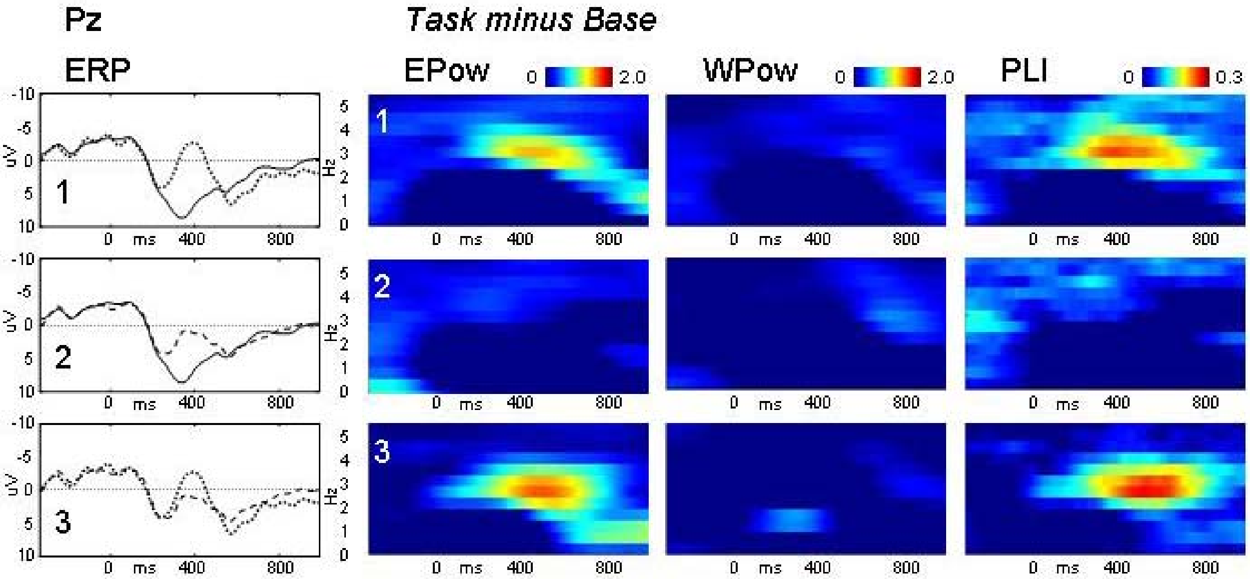

Figure 4.6. Grand average ERPs and Gabor wavelet-based time-frequency difference plots in the lower theta band (~3-5 Hz) for the non-related (Fig. 4.6.1) and related category violations (Fig. 4.6.2) in comparison to the antonym condition at electrode PZ (N=17). In terms of EPow- and PLI-differences, the non-related category violations (Fig. 4.6.1) but not the related category violations (Fig. 4.6.2) showed an EPow and PLI increase in comparison to the control condition. With regard to WPow, no power difference was observable at all; Note that the antonym condition was subtracted from each of the category violation conditions, thereby indicating *relative increases* in activity for the latter (cf. Exp. 1).

The statistical analysis indeed revealed a significant main effect of TYPE for EPow in the lower theta band (averaged frequency bins: 3.0-4.5 Hz) between 300 and 600 ms (*PZ*: *F* (2,32) = 4.22, $p < .05$; *P4*: *F* (2,32) = 6.07, $p < .01$). The resolution of the main effect showed that this effect was due to a significant increase in EPow for non-related category violations in comparison to antonyms (*PZ*: *F* (1,16) = 6.71, $p < .05$; *P4*: *F* (1,16) = 4.46, $p < .05$), whereas there was no significant difference for related category violations opposed to antonyms ($F < 1$).[22] Additional analyses showed that there was no significant main effect of TYPE with regard to WPow (*PZ*: *F* (2,32) = 1.68, $p < .3$; *P4*: $F < 1$). However, the global analysis for the PLI revealed a significant main effect (*PZ*: *F* (2,32) = 6.05, $p < .01$; *P4*: *F* (2,32) = 8.97, $p < .01$). Subsequent single comparisons unveiled that the increase in evoked power for non-related category violations compared to antonyms was due to an increase in phase-locking for the former (*PZ*: *F* (1,16) = 8.40, $p < .01$; *P4*: *F* (1,16) = 7.47 $p < .05$). Again, there was no significant difference for related category violations in comparison to antonyms ($F < 1$), but for related in comparison to non-related category violations (PZ: *F* (1,16) = 10.85, $p < .01$; P4: *F* (1,16) = 33.24, $p < .01$). A schematic overview of the results is given in Table 4.12.[23]

Pz ***Lower Theta***	**EPow**	**Wpow**	**PLI**
TYPE	*		**
NON x ANT	*		**
REL x ANT			
NON x REL	*		**

P4 ***Lower Theta***	**EPow**	**WPow**	**PLI**
TYPE	**		**
NON x ANT	*		**
REL x ANT			
NON x REL	**		**

Table 4.12. Main effects of TYPE and pairwise comparisons for electrodes Pz and P4 with regard to the three measures applied for the lower theta frequency band (frequency bins: 3.0-4.5 Hz; time window 300-600 ms). For post hoc single comparisons, all significance values are adjusted according to the modified Bonferroni procedure (Keppel, 1991) (* = < .05, ** = < .01).

To compare the frequency-correlates of the late positivities observed here with the upper delta findings from Experiment 2, we also analysed the time-frequency matrices in the later time range. However, because the time window for the frontal positivity effect (450-600 ms) completely overlapped with the time window for the enhanced lower theta activity (300-600

---

[22] Furthermore, there was a significant difference between related and non-related category violations (*PZ*: *F* (1,16) = 7.70, $p < .01$; *P4*: *F* (1,16) = 23.75, $p < .01$).

[23] Again, the remaining electrodes showed the same pattern (cf. Appendix E2).

ms) and, furthermore, the lower theta frequency range (3.0-4.5 Hz) partially overlapped with the upper delta frequency range (2.0-3.5 Hz), we only analysed the late *posterior* positivity between 600 and 800 ms. Indeed, the statistical analysis revealed a significant main effect of TYPE in the upper delta band (2.0-3.5 Hz) for EPow (*PZ*: F (2,32) = 8.89, $p < .001$; *P4*: F (2,32) = 7.95, $p < .005$) and PLI (*PZ*: F (2,32) = 14.09, $p < .001$; *P4*: F (2,32) = 11.32, $p < .001$). The resolution of the main effects showed that these effects were due to a highly significant enhancement of EPow (*PZ*: F (1,16) = 9.53, $p < .01$; *P4*: F (1,16) = 8.59, $p < .01$) and PLI (*PZ*: F (1,16) = 18.34, $p < .005$; *P4*: F (1,16) = 11.94, $p < .005$) for the non-related category words in comparison to antonyms. There was no significant effect for the related category words in comparison to antonyms ($F < 1$). Furthermore, an analysis of electrode sites Fz and Cz revealed that the enhanced upper delta EPow for non-related category words was more pronounced at posterior than at central or frontal electrode sites, analogous to the pattern observed for the late posterior positivity (cf. Table 4.13).

Fz ***Upper delta***	**EPow**	**Wpow**	**PLI**
TYPE	#		#
NON x ANT	*		*
REL x ANT			
NON x REL			

Cz ***Upper delta***	**EPow**	**WPow**	**PLI**
TYPE	*		**
NON x ANT	*		**
REL x ANT			
NON x REL	*		*

Pz ***Upper delta***	**EPow**	**Wpow**	**PLI**
TYPE	**		**
NON x ANT	**		**
REL x ANT			
NON x REL	**		**

P4 ***Upper delta***	**EPow**	**WPow**	**PLI**
TYPE	**		**
NON x ANT	**		**
REL x ANT			
NON x REL	**		**

Table 4.13. Main effects of TYPE and pairwise comparisons for electrodes Fz, Cz, Pz and P4 with regard to the three measures applied for the upper delta frequency band (frequency bins: 2.0-3.5 Hz; time window 600-800 ms). For post hoc single comparisons, all significance values are adjusted according to the modified Bonferroni procedure (Keppel, 1991) (* = < .05, ** = < .01).

Summary

As for Experiment 2, we can distinguish three different EPow effects in comparison to the observed ERP pattern: (i) Both category violation conditions led to a decrease of stimulus-evoked activity in the delta band (1-3 Hz) in relation to the antonym condition. This decrease in EPow was due to a simultaneous decrease of whole power and phase locking. Most importantly, this decrease of delta activity was restricted to the time range in which the N400 effect was elicited. Furthermore, there was no significant difference between the two violation conditions in the delta band. (ii) In the lower theta band (3-4.5 Hz), solely the non-related category violation condition led to a significantly higher degree of stimulus-evoked activity in comparison to antonyms. This increase in EPow was due to an increase of phase-locking, whereas there was no effect with respect to WPow. With regard to the time range, this lower theta band EPow and PLI increase largely overlapped with the observed delta effect, and furthermore appeared almost simultaneously with the N400. However, as for Experiment 2, this lower theta EPow increase for non-related category violations extended at least until 700 ms post-onset of the critical word (i.e. until the time range of the late positivity), and furthermore showed a slight tendency to slow down in the later time range. Hence, the EPow modulation overlapped with the biphasic ERP pattern, thereby again rendering an unambiguous attribution to the N400 effect difficult. (iii) There was an increase in the upper delta band for the non-related category violation condition in comparison to antonyms in the P600 time range. This increase was clearly more pronounced at *posterior* electrode sites. However, in comparison to Experiment 2, there was no significant upper delta effect for related category violations. Moreover, although the ERP pattern clearly showed a small but significant *frontal* positivity for both category violations, we couldn't dissociate a respective correlate in the frequency domain due to a high degree of overlap with the preceding lower theta activity.

In sum, these findings strongly support the previous observations from Experiment 2 that, with regard to the N400 effect, there are two clearly distinguishable frequency bands which behaved rather differently with regard to their underlying frequency characteristics. On the one hand, there was a strong EPow modulation in the delta frequency band for antonyms in comparison to both category violation conditions. This EPow modulation was due to a parallel power and phase-locking increase. On the other hand, there was an increase of the lower theta frequency for non-related category violations, which was due to an increase in phase-locking.

4.2.5 Discussion

It was the declared aim of the present experimental manipulation, 1) to confirm the results from the previous experiment with regard to the N400 effect and its observed underlying frequency dynamics, and 2) in contrast to Experiment 2, to elicit a monophasic N400 effect. Because the stimuli were presented as word pairs, possible influences of syntactic processing were thought to be eliminated. The present task manipulation was based on the assumption that the late positivity in Experiment 2 might have been a reflection of enhanced evaluation or integration processes due to the restrictive sentence frame. Therefore, it was predicted that presenting word pairs instead of whole sentences should result in a disappearance of the late positivity complex.

Indeed, the present findings again clearly showed the expected graded N400 effect. However, there was still a late positivity complex, although the respective amplitudes were substantially attenuated. Thus, two conclusions can be drawn. Firstly, with respect to the N400 effect, the present findings fully supported the results from the previous experiment. In addition, it was shown that the presentation mode (sentences vs. word pairs) did not affect the size or morphology of the N400 effect. Also, with regard to the results from the frequency domain, both antonymy verification tasks elicited the same overall pattern. Hence, the present findings provide further evidence for the proposed distinction between an increased delta activity for antonyms, as a reflection of an embedded positive component, and an increased lower theta activity for non-related in comparison to related category violations, as a reflection of a reduced negativity. Secondly, the previously observed late positivity complex was still observable, despite the fact that the stimuli were presented out of sentence contex as word pairs. Nevertheless, although there was no *qualitative* difference between both experimental manipulations with regard to the late positivity complex, there clearly was a *quantitive* difference, i.e. sentence context had a clear influence on the amplitude of the late positivities. Presenting the antonyms as word pairs instead of in sentence context significantly reduced the positivity effect. In the final paragraph of the preceding chapter, we speculated that the explicit task instruction associated with the antonymy sentence verification task might have been an additional factor contributing to the elicitation of the late positivities. That is, the late positivities might be regarded as a reflection of *task* or *instruction*-specific processes. In both experiments, subjects were explicitly instructed to judge the well-formedness of the presented antonym relations. As already pointed out earlier, in the previous experiment, this task-dependent effect was possibly enhanced by the restrictive stereotype sentence frame. But what exactly does this mean? In both experiments, subjects were introduced to the task extensively on the basis of practice material and therefore should have had no difficulties in accomplishing the task correctly under either task instruction. Therefore, there should be no differences between both tasks with regard to the overall performance. This objection is supported by the very low error rates in both tasks (there were no significant differences between both tasks with regard to accuracy). However, there was a crucial difference with regard to the *restrictiveness* of the tasks. In both experiments, the task instruction gave a specification of the aim and the optimal 'outcome' of the task, that is, it limited the scope of possibilities with regard to the *end result* of the performance (word pairs were *either* antonyms/targets *or* not). Yet, the task instruction per se left it to the subjects to choose which *strategy* they could use to accomplish the task correctly. Certainly, this was the case for the word pair experiment. However, the situation was more restrictive for the antonym sentence experiment. The restrictive sentence frame *The opposite of X is* ... drastically narrowed down the scope of possibilities for the subjects.[24] The syntactic structure of the sentence frame not only restricted the processing of the sentence with regard to the upcoming and appropriate word category, but furthermore urged subjects to process the sentence embedded antonym relation in a very specific way, that is with only one correct possible outcome for the sentence final word.[25]

One could speculate that this restrictiveness *automatically* leads to an *anticipation* of the sentence-final word (as, for example, in cloze probability tasks). However, this must not be the case with word pairs. Although the antonym word pair relations could be processed in a *quasi-syntactic* way (that is, analogous to the sentences), alternative processing strategies could also be applied. However, with the quasi-syntactic strategy, the processing of the first word might (inevitably) generate a specific expectation with regard to the second word of the

---

[24] Note that this would have been the case even if these sentences would have been presented to subjects without the *explicit* instruction to perform the antonymy sentence verification task, i.e. simply by instructing them to read the sentences.

[25] In the word pair task, related and non-related category words are, strictly speaking, not category violations, but simply *non*-targets. However, in the sentence task, both clearly *violate* the sentence proposition.

antonym relation. Hence, the actual appearance of the target item would lead to a mapping or final evaluation of the anticipated and the presented item. Yet, the task could also be perfored perfectly without any predictive or anticipatory strategy, that is, according to a motto like '*wait and see*'. Subjects could wait until the presentation of the second word, and then evaluate the presented word pair semantically, that is with respect to its 'antonymy'. Note that, although a semantic analysis is necessary in both scenarios, this semantic processing is guided and restricted through *anticipatory processes* reinforced through the sentence structure only in the former.

However, the above distinctions suggest that we should find different correlates for the respective processing scenarios. If we proceed from the assumption that, in the sentence task, subjects had no choice with respect to their strategy and that this strategy involved anticipatory processes which are somehow mirrored in the late positivity, we arrive at the prediction that we should find different processing correlates in the word-pair task at least for some subjects. Indeed, the evaluation of the single subject ERPs in the word pair task revealed that there was no unique ERP pattern, in clear contrast to the sentence task, where all subjects uniformly showed a biphasic N400-P600 pattern. Whereas eight subjects (out of seventeen) clearly showed a biphasic N400-P600 pattern analogously to the sentence task, the other nine only showed an N400 but *no late positivity*. Hence, we grouped the subjects according to whether they showed a late positivity (group B) or not (group A), and calculated grand averaged ERPs for each groups. The results clearly revealed that subjects who showed *a late positivity* (P600) also had an *early positive peak* for antonyms (cf. Figure 4.7). This pattern was identical (qualitatively and quantitatively) to the one observed in the sentence experiment (cf. Chapter 4.1.2, Fig. 4.1). However, subjects who didn't show a late positivity also didn't show an early positive shift for antonyms.[26] In contrast, the processing of antonym relations in the sentence context elicited an early positive shift for antonyms as well as a late positivity for non-antonyms for *every single subject*. Furthermore, comparing grand averaged ERPs from group *B* (biphasic ERPs) of the word pair experiment with the ERP pattern of the sentence experiment revealed no differences with respect to amplitude or effect size. In other words, viewed from an ERP perspective, it appeared as if subjects who showed a late

---

[26] Furthermore, a comparison of the mean reaction times between group A and B revealed that group B showed an approximately 60 ms faster mean reaction time for all word category conditions than group A (*antonyms*: 59,2 ms; *related*: 73,4 ms; *non-related*: 55,3 ms). However, there was no difference between both groups with regard to accuracy.

positivity in the word pair task processed antonym word pairs in the same way as subjects who processed antonym word pairs in sentence context.

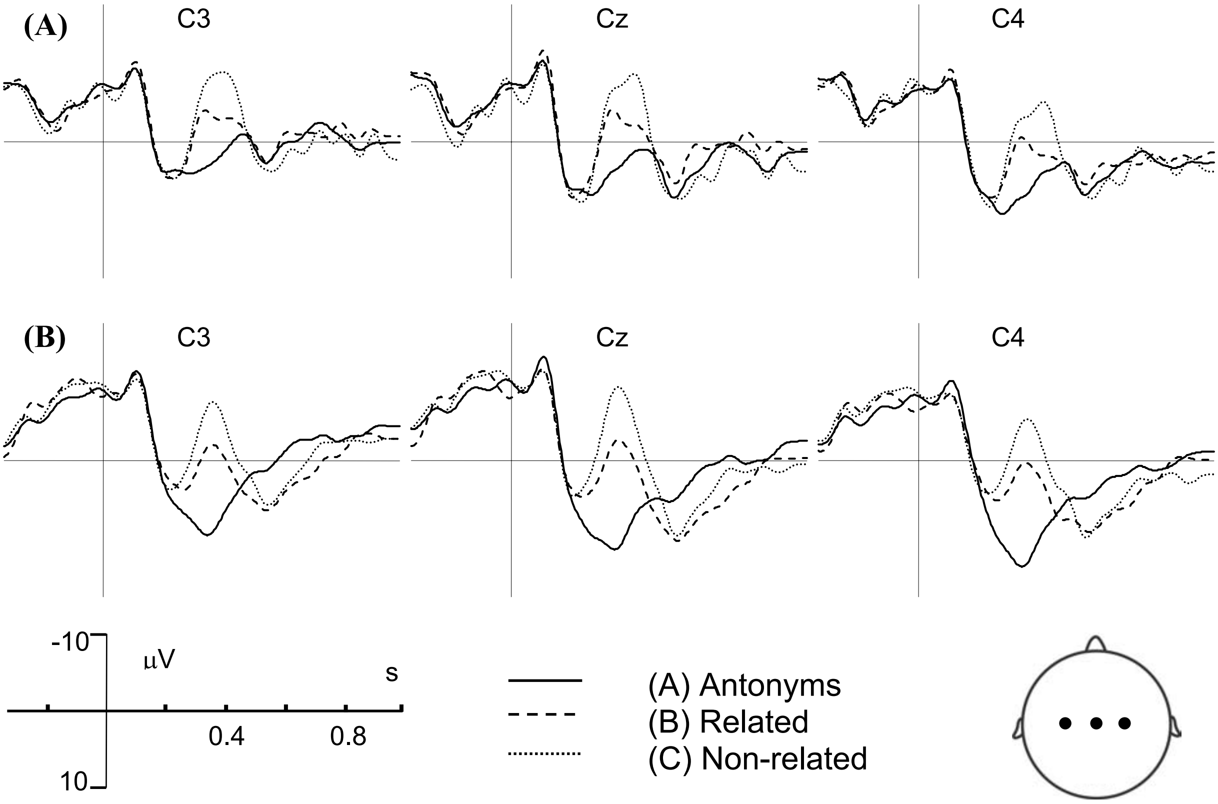

Figure 4.7 Two groups of grand averaged ERPs for antonyms, related and non-related category violations in Experiment 3 (onset at the vertical bar). (A) Grand averaged ERPs for subjects (Vp = 9) who showed no late positivity. (B) Grand averaged ERPs for subjects (Vp = 8) who clearly showed a late positivity. The results revealed that subjects who showed a late positivity also had an early positive peak for antonyms. Negativity is plotted upwards.

In light of the above considerations, we assume that the late positivity complex observed in both antonymy verification tasks might have been a product of anticipatory processes. Hence, we predicted that task-related instructions leading to a processing strategy which excludes anticipatory processes would lead to an abolishment of the late positivities. However, to first test whether an alternative task manipulation which does not involve the explicit instruction to process antonym relations would still lead to the elicitation of a graded processing effect, we first performed a behavioural study.

4.3 Experiment 4: Antonym questionnaire study

Experiments 2 and 3 gave rise to the assumption that the processing of the presented word pair relations was influenced by the *instructions* subjects obtained. In both experiments, it was explicitly stated that participants should focus on the acceptability of the presented sentences or word pairs, respectively, with regard to the antonym relation of the second word in comparison to the first word (via an *antonymy verification task*; see Chapter 4.1.1). We argued that this explicit instruction led to an anticipation of the antonym after the presentation of the first word. In Experiment 2, this instruction-related tendency was reinforced by the sentence context.[27] That is, even without an explicit instruction to judge the acceptability of the sentence with regard to antonymy, the restrictive sentence frame triggers the expectation for a suitable antonym (cf. discussion in Chapter 4.1 and 4.2).

However, in both experiments the processing of the word pair relations might have been influenced by expectation-based processes due to the specific instructions subjects received. Hence, these processes might also have affected the ERP-pattern observed in Experiments 2 and 3. Yet, the constitutive aim of performing both experiments was to elicit a clear monophasic, semantically triggered N400. However, in Experiment 2 as well as in Experiment 3 we obtained a pronounced biphasic N400-P600 pattern (although with a much smaller positivity in Exp. 3), thereby rendering the interpretation with regard to the underlying frequency characteristics difficult (cf. the discussion in Chapter 3, Experiment 1).

One consideration regarding the processing nature of the late positivities (i.e. their functional significance) was the hypothesis that the positivities might be a reflection of final evaluative (or integrative) processes triggered by the instruction-based expectancy with respect to the second word (antonym) of the word-pair. Under this assumption, it was expected that an alteration of the task-related instruction to the effect that a build up of specific expectancies is highly improbable would also influence the processing of antonym relations, thereby possibly avoiding the elicitation of a late positivity.[28]

---

[27] More precisely, the expectation is built up on basis of the proposition of the stereotype sentence frame "*Das Gegenteil von ... [X ist Y]*" ("*the opposite of ... [X is Y]*").

[28] There is ample evidence that the P600 is highly correlated with task instruction or task manipulation (Gunter & Friederici, 1999; Gunter et al., 1997; Hahne & Friederici, 1997, 1998, 1999)

To investigate whether the processing of antonym relations is sensitive to a manipulation of task formulation at all, we first performed a behavioural experiment by means of a questionnaire study with two different instructions.

The experimental participants, who were randomly assigned to two equally sized groups, filled in a questionnaire with identical stimulus material for each group. Both groups only differed with regard to the instruction given. One group (*A*) achieved an instruction equivalent to that for Experiments 2 and 3, i.e. participants were explicitly instructed to judge the degree of antonymy between two successive words (e.g. “black – white” vs. “black – yellow”). On the contrary, the second group (*B*) was explicitly briefed to rate the semantic *relatedness* of the presented word pairs (again, e.g. “black – white” vs. “black – yellow”).

Under the hypothesis that judging the degree of antonymy exerts a task-specific, expectation-based influence on the processing of word pair relations, whereas estimating the relatedness of two successive words involves different processes, the two groups should show disparate performance patterns (with regard to the assigned rating scores).

4.3.1 Method

Participants

Twenty-two students of the University of Leipzig participated in Experiment 4 (13 female, 9 male). Participants were randomly assigned to two equally sized groups (Group A: 5 female; mean age 25.5 (*sd*: 2.62); age range from 21 – 29 years; Group B: 8 female; mean age 23.4 (*sd*: 3.59); age range from 17 – 28 years). There was no significant difference with regard to age between group A and B (F (1,10) = 2.06, $p < .19$).

Materials

The critical conditions for Experiment 4 were identical to those used in Experiment 3 (cf. Appendix A1). Each questionnaire comprised 80 randomised word pairs, of which 40 were antonym pairs (ANT), 20 were related category word pairs (REL) and 20 were non-related category word pairs (NON). Four different versions were constructed (on the basis of the eighty triplets from Experiment 3) such that no single word was repeated within a list and, over all four lists, every word pair combination was presented once (antonyms were presented twice). Each participant filled out one questionnaire (consisting of only one list). Lists were identical for groups *A* and *B* and the questionnaires differed solely in instruction.

Procedure

Both groups were instructed to read a given word pair carefully and to subsequently gauge the relationship between the two words on a seven-point scale by encircling a number between 1 and 7. Whereas group *A* was instructed to judge the *degree of antonymy*, i.e. whether a given word pair is an antonym pair or not (1 = *optimal antonym*, 7 = *not at all an antonym*), group *B* had to judge the *degree of relationship* between the two words (1 = *very strong relation*, 7 = *no relation*).

Data Analysis

For the statistical analysis, mean rating points were calculated for each critical condition per subject per group. Repeated measures ANOVAs with the critical within subjects factor CONDITION (antonyms vs. related vs. non-related category words) and between subjects factor GROUP (instruction A vs. instruction B) and the random factors subjects (F_1) and items (F_2) were computed.

4.3.2 Results

The mean rating scores for both groups are presented in Table 4.13 below. The statistical analysis of the questionnaire rating score revealed main effects of GROUP (F_1 (1,10) = 7.29, $p < .02$; F_2 (1,79) = 35.56, $p < .01$) and CONDITION (F_1 (2,20) = 448.06, $p < .01$; F_2 (2,158) = 1327.78, $p < .01$), and a significant interaction GROUP x CONDITION (F_1 (2,20) = 31.26, $p < .01$; F_2 (2,158) = 83.56, $p < .01$).

	GROUP *A* *(antonym-task)*	GROUP *B* *(relation-task)*
CONDITION	mean scores (standard dev.)	mean scores (standard dev.)
Antonyms	1.21 (0.19)	2.10 (0.83)
Related	4.80 (0.73)	3.05 (0.77)
Non-related	6.93 (0.16)	6.35 (0.61)

Table 4.13. Mean rating scores for the two judgment tasks of the questionnaires in Experiment 4. The scale for the rating scores spans from 1 (= *optimal*) to 7 (= *not at all*).

In the light of the hypothesis that the manipulation of instructions between Group *A* and *B* would mainly affect the rating of the antonym and related category conditions, thereby leading to a closer approximation with regard to rating scores in the relation task than in the antonym task, we additionally calculated a 2-way interaction with the critical within subject factor CATEGORY (antonyms vs. related category) and the between subject factor GROUP. We found a significant interaction CATEGORY x GROUP (F_1 (1,10) = 41.55, $p < .01$; F_2 (1,79) = 153.11, $p < .01$). Nevertheless, a resolution of the interaction by GROUP revealed that the difference between antonym and related category rating scores was significant for both Group A (F_1 (1,10) = 231.41, $p < .01$; F_2 (1,79) = 585.42, $p < .01$) and Group B (F_1 (1,10) = 8.18, $p < .02$; F_2 (1,79) = 55.73, $p < .01$).[29] However, an evaluation of the F-values indicated that the significant interaction CATEGORY x GROUP was due to a much smaller difference between both categories under the relation task instruction in comparison to the antonym task instruction.

---

[29] Note that the significance values of the single comparisons are alpha-adjusted.

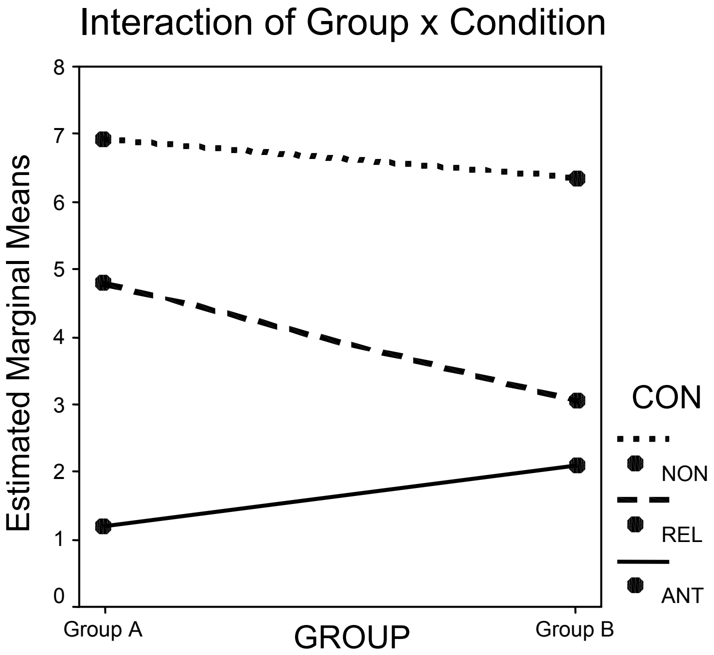

Figure 4.8. Graphical presentation of the results from the questionnaire study. There was a significant interaction between GROUP (*A* vs. *B*) and the two semantically related conditions (antonyms vs. related category condition).

4.3.3 Discussion

Although both groups judged the identical stimulus material, they clearly showed different judgment patterns as a function of the task specific instructions. The instruction to assess the degree of antonymy between two successively presented words on a rating scale ranging from 1 (= *optimal candidate*) to 7 (= *not at all an antonym*) led to a clear gradation of the three different stimulus conditions (cf. Figure 4.8, *Group A*). Antonyms were consistently rated as nearly optimal candidates (∅ = 1.21), whereas non-related category words were consistently associated with the highest rating scores (∅ = 6.93). Almost in between, with a slight tendency towards the higher end of the scale and, most importantly, significantly different from antonyms, were the related category words (∅ = 4.80). However, when subjects were instructed to assess the degree of relation between word pairs, again on a seven-point scale (1 = *very strongly related*; 7 = *not at all related*), the relation among the three conditions changed dramatically, although the same *sequential* gradation between the three category conditions emerged (cf. Figure 4.7, *Group B*). This effect was indicated by the highly significant interaction GROUP x CATEGORY. Note again that both groups (*A* and *B*) judged completely identical stimulus materials.

Post-hoc single comparisons revealed that the GROUP x CATEGORY interaction was due to a difference between the relation of antonyms and related category words in both groups. However, although both groups showed a significant difference between the rating scores for the antonym and the related category condition, the comparison of the respective *F*-values revealed that there was an essentially smaller difference between the rating scores for antonyms and related category words in the relation-instruction group (*B*) in comparison to the antonym-instruction group (*A*) (F_1: 231.41 vs. 8.18; F_2 : 585.42 vs. 55.73).

Hence, the results are twofold. There was a clear task (i.e. instruction) specific impact on the rating of the semantic relation between word pairs. Firstly, when participants were instructed to judge the *degree of antonymy* between two successive words, they clearly distinguished antonyms from related category words, regardless of the semantic 'closeness' of the related category words. Nevertheless, there was obviously an influence of category affiliation to the effect that non-related category words were rated significantly higher than related category words. Secondly, when participants were instructed to solely judge the *relation* between the presented word pairs, antonyms and related category words were rated much more similar than in the antonym task. This, of course, is not surprising from the perspective that they belong to the same semantic category. Nevertheless, there was still a significant difference between antonyms and related category words. However, crucially, with regard to semantic relatedness, there seems to be no reason to assume that antonym word pairs are somehow more closely related to each other than other words from the same 'within' category (why should *black* be more closely related to *white* than *grey* or *yellow*?).[30] Therefore, we must assume that antonyms are subject to further and/or different influences, for example associative processes.

Our results clearly showed that task-related instructions influenced the processing of word pair relations on a purely behavioural level. It is therefore expected that a different instruction/task might also influence the processing of antonym relations with regard to their

---

[30] Note that Murphy & Andrew (1993) argue for a conceptual basis of antonymy. Murphy (2003) proposes that antonymy is not a *intralexical* property, but instead is due to *metalexical* information "...which is not contained in the [mental] lexicon, even though it may be information about words" (2003:9).

electrophysiological correlates. Hence, we assumed that, under experimental manipulations where the task-related focus is shifted away from a relational processing of the word pairs by means of a more neutral and shallow processing demand, the P600 effect should either disappear completely or at least be significantly attenuated. Note that previous ERP findings suggest that the N400 effect with regard to semantic priming is not influenced by task demands as long as sufficient semantic processing is guaranteed (e.g. Kutas et al, 1984). For example, the N400 effect is not sensitive to the sentence truth value in *sentence verification tasks* and, therefore, seems to reflect non-decisional and non-propositional aspects of semantic processing (Kounios & Holcomb, 1992). Furthermore, some authors (e.g. Brown & Hagoort, 1993; Chwilla et al., 1995) argued that the N400 is only sensitive to semantic priming if there is sufficiently 'deep' processing of words (in the sense of Craik & Lockhard, 1972) via a 'controlled' or 'conscious' processing (as for example in lexical decision tasks). However, in the recent literature, there is plenty of evidence for unconscious N400 semantic priming effects (e.g. Rolke, Heil, Sterb, & Hennighausen, 2001; Deacon, Hewitt, Yang, & Nagata, 2000; Kiefer, 2002; Kouider & Dupoux, 2001; Brualla, Romero, Serrano, & Valdizán, 1998).

Therefore, altering the task demands should not affect the N400 amplitude, at least with respect to that portion of the N400 effect which is related to semantic priming. However, replacing the antonymy verification task by means of a more neutral task should clearly affect processes which rely on expectancy based priming (cf. Becker, 1980; Neely, 1977). Consequently, as indicated by the results from the present questionnaire study, we expected a reduced difference between antonyms and related category items with regard to the overall N400 effect (i.e., as a function of the task, a reduction or disappearance of that portion of the N400 which is related to expectancy priming was predicted; e.g. Kounios & Holcomb, 1992; see also Chapter 4.1).

4.4 Experiment 5: ‘Non-conscious’ processing of antonym relations

The present experiment was designed under the assumption that the non-conscious processing of antonym relations should lead to a monophasic N400 effect which is similar to the graded N400 effects observed in the previous experiments, but devoid of the previously observed late positivities. To this end, we introduced a *lexical decision task* to draw the focus of attention away from the processing of antonym relations. Subjects had to decide whether a presented word was a pseudoword or not. Because pseudowords could appear in either the first or the second position of a presented word pair, lexical-semantic processing of every single word was ensured (cf. Table 4.14). Furthermore, the task didn’t require any relational processing of the presented word pairs. In this way, we assumed that the processing of antonym relations should not be subject to expectation or even anticipation-based processes. In addition, there should be no target-related effect for antonyms in comparison to non-antonym relations.

The five critical conditions for the present experiment are shown in Table 4.14 below.

Condition	**Example**
A. *Antonyms*	schwarz - weiss black - *white*
B. *Related*	schwarz - gelb black - *yellow*
C. *Non-related*	schwarz - nett black - *nice*
D. *Pseudo1*	zwarschen - hinfallen *zwarschen - tumbling*
E. *Pseudo2*	langsam - klenck *slow - klenck*

Table 4.14. Example word pairs for each of the experimental conditions. The critical word is underlined. Abbreviations used: Pseudo1 (‘pseudoword in first position’), Pseudo2 (‘pseudoword in second position’).

4.4.1 Method

Materials

The stimulus material for Experiment 5 comprised the same material as for Experiment 3 (cf. Experiment 2), plus additional filler items. From eighty triplets (cf. Experiment 2), comprising three critical relational conditions, a set of 240 experimental word pairs was created. Additionally, a set of 160 filler word pairs was constructed, consisting of a pseudoword and a legal German filler word. Half of the pseudowords appeared in the first, the other half in the second word position.[31] These items were assigned to 4 lists of 120 critical word pairs (40 for the antonyms, 40 for the two mismatch conditions each), plus 80 filler word pairs in a counterbalanced manner such that each participant saw 40 complete triplets of a given set plus 80 filler word pairs from the pseudoword condition. For a complete set of materials, see the critical items from Experiment 2 (listed in Appendix A1) and the filler items in Appendix A2. Word pairs were presented in 5 blocks of 40 word pairs, resulting in 200 word pairs (trials) per subject.

Participants

Seventeen undergraduate students from the Philipps-University of Marburg participated in the Experiment (11 female; mean age 24.6 years; age range 20-31 years). None of the participants had taken part in any one of Experiments 1 to 4.

Procedure

The word pairs were presented as in Experiment 3, that is in a word-by-word manner. The first word (prime) was presented for 400 ms with an interstimulus interval (ISI) of 400 ms, whereas the second word (target) was presented for 350 ms and an ISI of 650 ms. Unlike in Experiment 3, participants were required to complete a *lexical decision task* after each word pair, which involved judging whether one of the presented words was a pseudoword or not.

---

[31] Each pseudoword was a pronounceable permutation of the letters of the first word from the set of triplets used in Experiment 2 and 3. The second word in a pseuword word pair was taken from the respective related and non-related category items. There was no overlap of word pairs and pseudoword pairs, i.e., for example: when a subject saw a list constructed of the triplets 1-40, pseudowords and fillers were constructed from triplets 41-80.

Subjects had to respond by pressing the left mouse button for 'yes'. As for the previous experiments, the time window for the button press was restricted to 3000 ms, whereas the subsequent trial started immediately after the button press. For each participant, the lexical decision task included 80 word pairs comprising a pseudoword (out of 200 word pairs). Between the trials there was an inter-trial interval (ITI) of 1400 ms. The experimental session began with a short training session followed by 5 experimental blocks comprising 40 word pairs each. Including electrode preparation, the entire experiment lasted approximately 2 hours.

The EEG was recorded as for Experiments 2 and 3. Average ERPs were calculated per condition per participant from 334 ms prior to the onset of the critical stimulus item (i.e. the second item) to 1000 ms post onset, before grand-averages were computed over all participants. Trials for which the lexical decision task was not performed correctly were excluded from the averaging procedure as well as from the single trial analysis, as were trials containing artefacts (cf. Experiment 2).

Data Analysis

For the behavioural data, error rates and reaction times were calculated for each condition. Incorrectly answered trials were excluded from the reaction time analysis. We computed a repeated measures analysis of variance (ANOVA) involving the critical factors TASK (*antonyms* vs. *related* vs. *non-related* vs. *pseudo1* vs. *pseudo2*) and TYPE (*antonyms* vs. *related* vs. *non-related*) and the random factors subjects (F_1) and items (F_2).

For the statistical analysis of the ERP data, repeated measure ANOVAs involving the critical factors TYPE (antonyms vs. related vs. non-related) and STIMULUS (antonyms vs. pseudowords) were calculated for mean amplitude values per time window per condition in four lateral regions of interest (ROIs) as well as for the midline electrodes. Lateral regions were defined as follows: *left-frontotemporal* (F7, F3, FC5); *left-posterior* (P7, P3, CP5); *right-frontotemporal* (F8, F4, FC6); *right-posterior* (P8, P4, CP6). The midline electrodes were analysed in terms of the factor electrode (ELEC) with three midline electrodes (Fz, Cz, Pz) as levels.

The statistical analysis was carried out as for Experiment 2.

4.4.2 ERP results

Behavioural Data

The statistical analysis of the error rates for the lexical decision task revealed neither significant main effects of TASK (F_1 (4,64) = 1.32, $p < .28$; F_2 (4,316) = 1.88, $p < .12$) nor of TYPE (F_1 (2,32) = 1.32, $p < .29$; F_2 (2,158) = 2.27, $p < .11$).

With regard to the reaction times, there was a main effect of TASK (F_1 (4,64) = 4.49, $p < .004$; F_2 (4,316) = 5.13, $p < .002$) as well as TYPE (F_1 (2,32) = 8.55, $p < .002$; F_2 (2,158) = 7.27, $p < .002$). A resolution of the main effects revealed a significant difference between antonyms and related category items (F_1 (1,16) = 7.04, $p < 0.02$; F_2 (1,79) = 6.45, $p < 0.02$) as well as between antonyms and non-related category items (F_1 (1,16) = 11.52, $p < 0.005$; F_2 (1,79) = 15.34, $p < 0.001$). Furthermore, there was a significant difference between pseudowords in position 1 and pseudowords in position 2 (F_1 (1,16) = 15.55, $p < 0.002$; F_2 (1,79) = 6.96, $p < 0.02$). In addition, non-related category items differed significantly from pseudowords in position 1 (F_1 (1,16) = 7.75, $p < 0.02$; F_2 (1,79) = 11.26, $p < 0.002$), whereas related category items only differed marginally from this condition (F_1 (1,16) = 4.38, $p < 0.06$; F_2 (1,79) = 3.72, $p < 0.06$). Note that there was no difference between antonyms and pseudowords in position 1 (F_1, $F_2 < 1$), as well as between non-related category items and pseudowords in position 2 (F_1, $F_2 < 1$). Hence, we obtained the following scale with regard to the graduation in reaction time:

ANT <	REL <	NON
PS-1		PS-2

An overview of the behavioural results with regard to error rates and reaction times is given in Table 4.15. As for the prior experiments, the very low error rates indicated that participants had no problem in performing the lexical decision task. Note that the reaction times were measured from the onset of the question mark, which served as a cue for the performance of the lexical decision task (cf. Experiment 2).

task	error rates (%)		reaction times (ms)	
	average	sd	average	sd
antonyms	0.73	1.47	467.88	204.71
related	0.88	1.23	506.96	251.24
non-related	1.62	2.49	524.94	245.58
pseudo1	1.47	1.78	471.32	271.07
pseudo2	2.06	2.54	519.56	288.45

Table 4.15. Percentages of error rates and mean reaction times for the lexical decision task in Experiment 5.

ERPs

A complete overview of the statistical results is listed in Appendix C3. Figure 4.9 shows grand-average ERPs for the three critical conditions (a more extensive selection of electrodes is presented in Appendix B4). Visual inspection indicated that, for the two category conditions (related and non-related category), the critical items elicited a broad, centro-parietal negativity between approximately 300 and 500 ms. This effect was less pronounced for the related category conditions (= REL) than for the non-related category conditions (= NON). In contrast to Experiment 2 and 3, there was no evidence for a positive shift for antonyms in comparison to non-antonyms. In addition, there were no late positivity effects, neither for related nor for non-related category conditions in comparison to antonyms.

Repeated measure ANOVAs in twenty-four successive 50 ms time windows from -200 ms to 1000 ms (t1 – t24), confirmed these observation. The global analysis revealed significant main effects of TYPE for ROIs between 300 and 550 ms (*300-350 ms*: F (2,32) = 8.47, p < .01; *350-400 ms*: F (2,32) = 24.45, p < .01; *400-450 ms*: F (2,32) = 22.09, p < .01; *450-500 ms*: F (2,32) = 15.40, p < .01; *500-550 ms*: F (2,32) = 4.56, p < .05) and for midline electrodes between 250 and 550 ms (*250-300 ms*: F (2,32) = 3.57, p < .05; *300-350 ms*: F (2,32) = 8.47, p < .01; *350-400 ms*: F (2,32) = 29.53, p < .01; *400-450 ms*: F (2,32) = 22.64, p < .01; *450-500 ms*: F (2,32) = 19.00, p < .01; *500-550 ms*: F (2,32) = 3.94, p < .05). All of these effects were due to a more negative waveform for non-related and related category conditions in comparison to the antonym condition. Furthermore, single comparisons revealed that the negativity for the non-related category conditions was significantly stronger than that for related category conditions (cf. Table 4.16 for an overview of separate analyses for each of the four ROIs and the three midline electrodes).

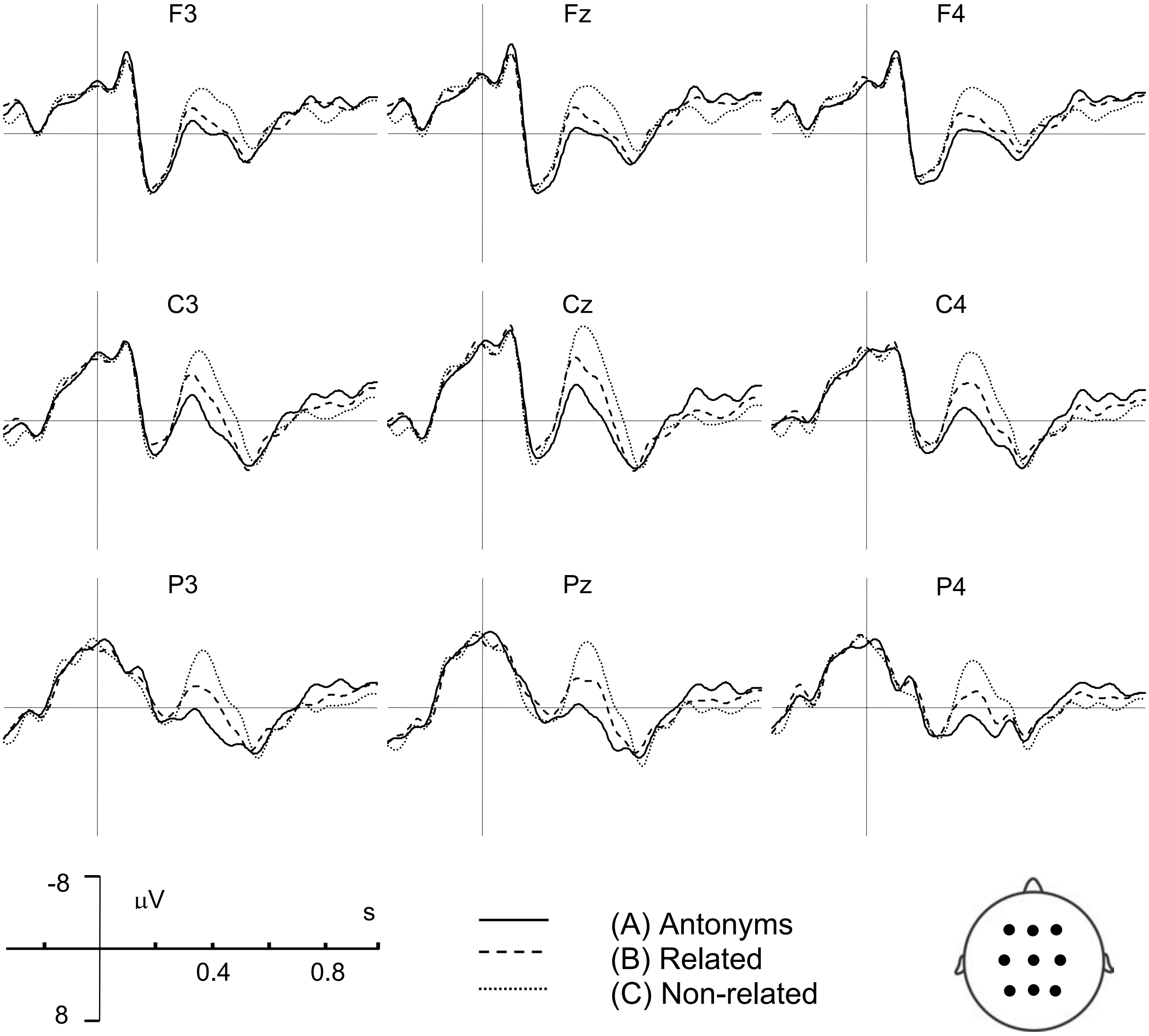

Figure 4.9. Grand average ERPs for antonyms, related and non-related category conditions (onset at the vertical bar) in Experiment 5. Negativity is plotted upwards.

Furthermore, the resolution of the marginally significant interaction ROI x TYPE between 350 and 400 ms (F (6,96) = 2.09, $p < .07$), the significant interaction between 400 and 450 ms (F (6,96) = 4.04, $p < .01$) and the significant interaction ELEC x TYPE between 350 and 450 ms (*350-400 ms*: F (4,64) = 4.47, $p < .01$; *400-450 ms*: F (4,64) = 3.94, $p < .01$) revealed that the negativity was more pronounced at posterior regions for both category conditions.

ROIs		time windows in ms															
		t9	t10	t11	t12	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24
		200 250	250 300	300 350	350 400	400 450	450 500	500 550	550 600	600 650	650 700	700 750	750 800	800 850	850 900	900 950	950 999
FroL	Type				**	**	**	*									
	rel																
	non				**	*	*										
	with				*	*	**	*									
Fz	Type		*	**	**	**	**	*					*				
	rel		*	*													
	non		*	**	**	**	**	*					*				
	with				**	**	**										
FroR	Type			*	**	**	**	*									
	rel																
	non			*	**	**	**	*									
	with				*	**	**										
Cz	Type		*	**	**	**	**	*					**		**		
	rel		*	**	**	*	*						*				
	non		*	**	**	**	**	*					**		*		
	with				**	**	**	*									
PosL	Type			**	**	**	**	*					**				
	rel			*	**	**	*						**				
	non			**	**	**	**	*					**				
	with				**	**	**	*									
Pz	Type			**	**	**	**						**		**		
	rel			**	**	**	*						*		*		
	non			**	**	**	**						**		**		
	with				**	**	**										
PosR	Type			**	**	**	**						**				
	rel			**	**	**											
	non			**	**	**	**						**				
	with				**	**	**										

Table 4.16. Overview of the significant effects of TYPE in each of the 4 ROIs (*frontal-left* = FroL; *frontal-right* = FroR; *posterior-left* = PosL; *posterior-right* = PosR) and 3 midline electrodes (Fz, Cz, Pz) in 24 successive 50ms time windows (t1 – t24) from -200 ms to 1000 ms post-onset of the critical items. All post hoc significance values were adjusted according to the modified Bonferroni procedure (Keppel, 1991) (* = < .05; ** = < .01). There was no significant effect for any comparison in time windows t1-t8 (-200 to 200 ms).

In addition, there were significant main effects of TYPE between 750 and 800 ms for ROIs (*F* (2,32) = 7.15, $p < .01$), which were due to a positivity in left- and right-posterior regions for both category conditions in comparison to antonyms, and between 750 and 800 ms (*F* (2,32) = 8.32, $p < .01$) and 850 to 900 ms (*F* (2,32) = 5.83, $p < .01$) for the midline electrodes, again due to a positivity for both category conditions compared with the antonym condition at electrodes CZ and PZ.

Figure 4.10 shows grand average ERPs for pseudowords (in second word-position) in comparison to the antonym and non-related category conditions.

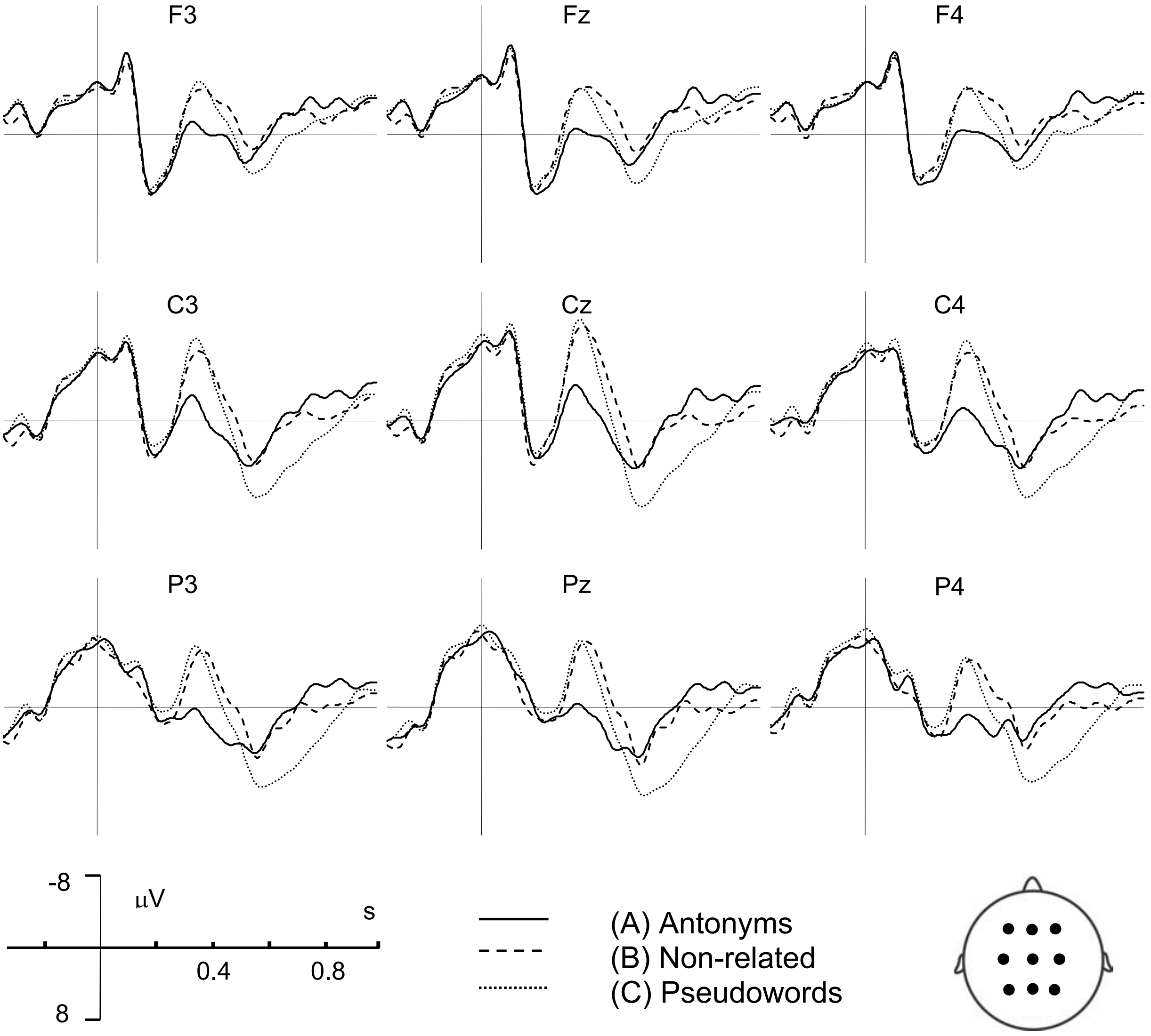

Figure 4.10. Grand average ERPs for pseudowords in second position, antonyms, and non-related category conditions (onset at the vertical bar) in Experiment 5. Negativity is plotted upwards.

As is evident from Figure 4.10, pseudowords elicited a pronounced biphasic pattern in comparison to the antonym condition: the visual inspection revealed a negativity between approximately 300-500 ms and, additionally, a strong positivity between approximately 500-800 ms. Furthermore, it was obvious that there was *no difference* between pseudowords and the non-related category condition with regard to the negativity. These observations were supported by the statistical analyses. As for the non-related category condition in comparison to the antonym condition, the analyses revealed significant main effects of STIMULUS between 250 and 450 ms for ROIs (*250-300 ms*: F (1,16) = 5.34, $p < .05$; *300-350 ms*: F (1,16) = 25.44, $p < .01$; *350-400 ms*: F (1,16) = 38.24, $p < .01$; *400-450 ms*: F (1,16) = 17.22, $p < .01$) and midline electrodes (*250-300 ms*: F (1,16) = 4.89, $p < .05$; *300-350 ms*: F (1,16) = 20.74, $p < .01$; *350-400 ms*: F (1,16) = 38.57, $p < .01$; *400-450 ms*: F (1,16) = 11.06, $p < .01$). All effects were due to a more pronounced negativity for pseudowords in comparison to antonyms. Moreover, there were significant main effects of STIMULUS between 550 and 900 ms for ROIs (*550-600 ms*: F (1,16) = 5.83, $p < .05$; *600-650 ms*: F (1,16) = 12.85, $p < .01$; *650-700 ms*: F (1,16) = 17.52, $p < .01$; *700-750 ms*: F (1,16) = 21.73, $p < .01$; *750-800 ms*: F (1,16) = 30.21, $p < .01$; *800-850 ms*: F (1,16) = 14.33, $p < .01$; *850-900 ms*: F (1,16) = 8.36, $p < .05$) and between 550 and 850 ms for midline electrodes (*550-600 ms*: F (1,16) = 6.73, $p < .05$; *600-650 ms*: F (1,16) = 12.38, $p < .01$; *650-700 ms*: F (1,16) = 14.51, $p < .01$; *700-750 ms*: F (1,16) = 15.79, $p < .01$; *750-800 ms*: F (1,16) = 17.39, $p < .01$; *800-850 ms*: F (1,16) = 6.24, $p < .05$). These effects were due to an enhanced positivity for pseudowords in comparison to antonyms (cf. Table 4.17 for an overview of the main effects which were resolved with regard to ROIs and midline electrodes). Furthermore, resolutions of the significant interactions STIMULUS x ROI between 550 and 850 ms (*550-600 ms*: F (3,48) = 2.99, $p < .05$; *600-650 ms*: F (3,48) = 7.88, $p < .01$; *650-700 ms*: F (3,48) = 6.60, $p < .01$; *700-750 ms*: F (3,48) = 10.20, $p < .01$; *750-800 ms*: F (3,48) = 7.60, $p < .01$; *800-850 ms*: F (3,48) = 5.67, $p < .01$) and STIMULUS x ELEC between 600 and 850 ms (*600-650 ms*: F (2,32) = 11.87, $p < .01$; *650-700 ms*: F (2,32) = 8.28, $p < .01$; *700-750 ms*: F (2,32) = 9.00, $p < .01$; *750-800 ms*: F (2,32) = 5.27, $p < .05$; *800-850 ms*: F (2,32) = 4.15, $p < .05$) revealed, that this positivity was more pronounced and longer lasting at posterior regions (cf. Table 4.17).

A	**PSW x ANT** time windows in ms															
	t9	t10	t11	t12	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24
ROIs	200 250	250 300	300 350	350 400	400 450	450 500	500 550	550 600	600 650	650 700	700 750	750 800	800 850	850 900	900 950	950 999
FroL			*	**	**			*	**	**	*	*				
Fz			*	**				*	*	*	*	*				
FroR			*	**	*	*					*	**	*			
Cz		*	**	**	**			*	**	**	**	**	*			
PosL		*	**	**	**				**	**	**	**	**	**		
Pz			**	**	**			*	**	**	**	**	*			
PosR		*	**	**	*			*	**	**	**	**	**	**		

Table 4.17. Significant main effects of STIMULUS (*pseudowords* = PWS vs. *antonyms* = ANT) in each of the 4 ROIs and the 3 midline electrodes (Fz, Cz, Pz) in 24 successive 50ms time windows (t1 – t24) starting at -200 ms post-onset of the critical items (* = < .05; ** = < .01). There was no significant effect for any comparison in time windows t1-t8 (-200 to 200 ms).

A pairwise comparison of the pseudoword condition with the non-related category condition revealed that there was no significant difference between both conditions in the N400 time window between 250 and 450 ms for ROIs (*250-300 ms*: F (1,16) = 1.09, $p < .32$; *300-350 ms*: F (1,16) = 1.63, $p < .23$; *350-400 ms*: F (1,16) = 1.15, $p < .30$; *400-450 ms*: F (1,16) < 1) and between 250 and 400 ms for midline electrodes ($F < 1$). However, there was a significant effect for midline electrodes between 400 and 450 ms (F (1,16) = 5.00, $p < .05$). Post hoc single comparisons revealed that this effect was due to the circumstance that, at electrode FZ, the onset of the positivity for pseudowords interacted with the consisting negativity. As a consequence, there appeared to be an earlier onset of the significant difference between pseudowords and the non-related category condition (compared with other electrode sites) (cf. Table 4.18). Between 500 and 750 ms, single comparisons revealed significant main effects for ROIs (*500-550 ms*: F (1,16) = 7.59, $p < .05$; *550-600 ms*: F (1,16) = 8.27, $p < .05$; *600-650 ms*: F (1,16) = 19.05, $p < .01$; *650-700 ms*: F (1,16) = 29.28, $p < .01$; *700-750 ms*: F (1,16) = 19.44, $p < .01$) and midline electrodes (*500-550 ms*: F (1,16) = 8.04, $p < .05$; *550-600 ms*: F (1,16) = 9.85, $p < .01$; *600-650 ms*: F (1,16) = 17.51, $p < .01$; *650-700 ms*: F (1,16) = 18.69, $p < .01$; *700-750 ms*: F (1,16) = 11.41, $p < .01$). All effects were due to a more pronounced positivity for pseudowords in comparison to the non-related category condition. Furthermore, an interaction of STIMULUS x ROI between 650 and 850 ms (*650-700 ms*: F (3,48) = 5.47, $p < .01$; *700-750 ms*: F (3,48) = 8.39, $p < .01$; *750-800 ms*: F (3,48) = 4.83, $p < .01$; *800-850 ms*: F (3,48) = 4.81, $p < .01$) and STIMULUS x ELEC between 600 and 850 ms (*600-650 ms*: F (2,32) = 6.35, $p < .01$; *650-700 ms*: F (2,32) = 9.18, $p < .01$; *700-750 ms*: F (2,32) = 15.65, *p* < .01; *750-800 ms*: *F* (2,32) = 4.84, *p* < .05; *800-850 ms*: *F* (2,32) = 6.14, *p* < .01) revealed that this positivity was stronger and more enduring at posterior electrodes (cf. Table 4.18 for an overview of the significant single comparisons).

B	**PSW x NON** time windows in ms															
	t9	t10	t11	t12	t13	t14	t15	t16	T17	t18	t19	t20	t21	t22	t23	t24
ROIs	200 250	250 300	300 350	350 400	400 450	450 500	500 550	550 600	600 650	650 700	700 750	750 800	800 850	850 900	900 950	950 999
FroL							*	**	**	**	*					
Fz					*		**	**	**	*						
FroR							*	*	**	*	*					
Cz							*	**	**	**	**					
ParL							*		**	**	**	**	**			
Pz							*	*	**	**	**	*				
ParR						*	*	*	**	**	**	*				

Table 4.18. Significant differences between pseudowords (PWS) and the non-related category condition (NON) in each of the 4 ROIs and at the 3 midline electrodes (Fz, Cz, Pz) in 24 successive 50ms time windows (t1 – t24) starting at -200 ms post-onset of the critical items (* = < .05; ** = < .01). There was no significant effect for any comparison in time windows t1-t8 (-200 to 200 ms).

4.4.3 Interim discussion

It was the aim of the present experimental manipulation to elicit a monophasic graded N400 effect in response to the processing of antonym relations. As is evident from Figure 4.9 and Table 4.17, non-related and related category words elicited a clear N400 effect in comparison to antonyms. This N400 effect was more pronounced for non-related category words than for related category words. However, in contrast to Experiments 2 and 3, there was no obvious positive shift for antonyms in comparison to the non-antonym conditions. Most importantly, there were also no late positivity effects for either of the non-antonym categories in comparison to antonyms. Hence, with respect to the aim of the present experiment, the task manipulation succeeded. In contrast to findings for the word stimuli, pseudowords (in second position) elicited a pronounced N400 effect in comparison to antonyms. This N400 effect was not distinguishable from the N400 effect for non-related category words. In addition, and more importantly, pseudowords gave rise to a very strong late positivity in comparison to words.

As already pointed out above, there was no observable positive shift for antonyms in comparison to non-antonyms. Instead, the morphology of the N400 component appeared quite similar for all three conditions. The gradedness of the N400 effect only seemed to be due to the strength of the N400 amplitude. Hence, with regard to the N400 effect, there only seemed to be a quantitive difference between the different conditions, but no qualitative difference.

Because the present experimental task manipulation did not involve the explicit processing of relational word information, we assumed that anticipatory or predictive processes would play no role in the elicitation of the N400 effect. Under this assumption, the observed graded N400 effect must be a reflection of lexical-semantic priming processes, which are more or less automatic. Yet, we cannot entirely exclude that subjects became aware of the fact that some words were related and some words were not related to each other (despite of the primary demands of the lexical decision task). Therefore, strictly speaking, the present N400 effects must not necessarily reflect ‘unconscious’ automatic priming processes, but could also be a reflection of ‘smart’ subjects who, in addition to the primary task demands, processed the presented word pairs relationally.

However, the graded N400 effect was a desired result with respect to the central aim of the present chapter, namely to obtain an unequivocal frequency-analytical characterisation of a ‘classical’ lexical-semantic N400 effect. One further interesting aspect of the present findings concerns the question of what might have been the cause of the N400 effect between antonyms and related category words. The previous questionnaire study already indicated that antonyms are even processed differently than highly related words from the same word category (under task demands which didn’t involve antonymy judgments, but only judgments with regard to relatedness). The present findings of a graded N400 effect provide additional neurophysiological evidence for the special status of antonyms. Because both antonyms and related category words were non-targets, the reduced N400 for antonyms must reflect processes which are related to the organisation or representation of lexical-semantic information. However, it is not at all obvious how this difference could be formulated, for example, in terms of semantic networks, featural overlap, or spreading activation.[32]

---

[32] The crucial question is: what exactly does it mean to state that X is the opposite of Y? It seems to be quite unclear how one could capture the difference between ‘*grey - dark grey’* and ‘*black - white’* solely in terms of the degree of semantic feature overlap. Murphy (2003) proposed that antonymy is not based on intralexical

Unfortunately, it is beyond the scope of this thesis to further discuss implications or conclusions based on the present findings in relation to current lexical-semantic theories or priming mechanisms.

A second main finding of the present experiment is the observation that, in contrast to Expriments 2 and 3, there are no late positivities for the related and non-related category conditions in comparison to antonyms. Moreover, there was also no observable positive shift for antonyms in comparison to non-antonyms embedded in the N400. This ERP pattern, however, is reminiscent of the monophasic N400 effect from the group comparisons of Experiment 2. Recall that, in Experiment 2, approximately half of the subjects showed a pronounced biphasic N400-P600 pattern in addition to a pronounced positive shift for antonyms. This ERP pattern was virtually indistinguishable from the ERP findings of Experiment 1. Yet, the other half of the subjects *only* showed a monophasic graded N400 effect with no concurrent positive shift for antonyms. In comparison to the findings from Experiment 1, we therefore argued that this group difference in Experiment 2 might be the reflection of two distinct processing strategies. Together, both experimental results were taken as first evidence for the hypothesis that the observed positivities are merely a reflection of anticipatory task-dependent processes. However, the present finding that the presumabely unattended processing of antonym relations in a lexical decision task ‘failed’ to elicit the positivity complex clearly supports the hypothesis that both the early embedded and the late positivities are task dependent. This issue will be discussed in more detail in the final section of this chapter.

In sum, it can be stated that the lexical decision task finally led to an elicitation of the desired graded monophasic lexical-semantic N400 effect. Hence, after all, we can analyse this N400 effect with regard to its underlying frequency characteristics in the subsequent paragraph, thereby tackling the second crucial question of the present thesis (cf. Introduction).

---

properties, but has its origin in metalexical information. Nevertheless, associative processes might also play a role.

4.4.4 EEG frequency analysis

Methods

The applied frequency-based measures are equivalent to those used in Experiment 3 (cf. Chapter 4.2). The analyses are based on the calculation of evoked power (EPow), whole power (WPow) and phase locking index (PLI), determined by Gabor wavelet analyses in frequency bins of 0.5 Hz (time window from –334 to 1000 ms).

The statistical analysis of the frequency band characteristics comprised the computation of multi factorial analyses of variance (MANOVAs) with the critical factor TYPE (antonyms vs. related vs. non-related vs. pseudowords) per averaged time-frequency bins for the electrodes FZ, CZ, PZ, P3 and P4.

As for the previous experiments, the statistical analysis was carried out as in Experiment 1.

Results

As is evident from Figure 4.11, in the lower theta band (~3-4.5 Hz), the non-related category condition showed an increased EPow and PLI in comparison to the antonym condition in the N400 time range (200-500 ms). For the related category condition, there only seemed to be a slight increase in PLI but no concurrent increase in EPow. The statistical analysis revealed a main effect of TYPE at electrode PZ not only for EPow (F (2,32) = 25.79, $p < .001$) and PLI (F (2,32) = 17.25, $p < .001$), but also for WPow (F (2,32) = 16.29, $p < .001$). Furthermore, these main effects were also observable at electrode P4 (*EPow*: F (2,32) = 32.77, $p < .001$; *PLI*: F (2,32) = 19.58, $p < .001$; *WPow*: F (2,32) = 13.13, $p < .001$), as well as at the other electrode sites under investigation (cf. Appendix E3).

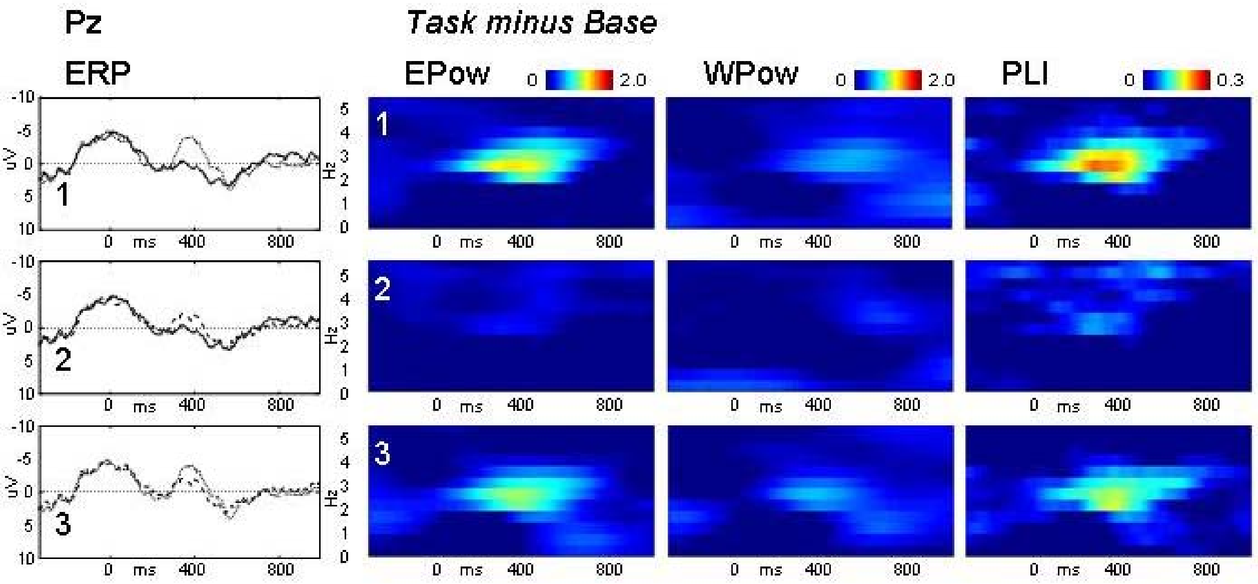

Figure 4.11. Grand average ERPs and Gabor wavelet-based time-frequency plots in the lower theta band (~3-5 Hz) for the non-related category conditions (Fig. 4.11.1) and related category conditions (Fig. 4.11.2) in comparison to the antonym condition at electrode PZ (N=17). The ERPs show N400 differences (300-500 ms) in both comparisons (Fig. 4.11.1 and 4.11.2). In terms of EPow, WPow and PLI, the non-related category condition (Fig. 4.11.1) showed a significant increase in comparison to the control condition. For the related category condition (Fig. 4.11.2), statistical analyses revealed that there was only a marginally significant increase in PLI.

Single comparisons for each category condition in comparison to the antonym condition only revealed a significant difference for non-related category words in EPow (F (1,16) = 44.80, $p < .001$), WPow (F (1,16) = 25.83, $p < .001$) and PLI (F (1,16) = 32.69, $p < .001$). That is, the EPow increase was due to a concurrent increase in whole power and PLI (cf. Table 19 for a schematic overview of the significant results). However, a resolution of the main effects for the related category condition solely revealed a marginally significant difference for PLI which was confined to electrode PZ (F (1,16) = 3.30, $p < .09$), but no significant effect for EPow (F (1,16) = 2.20, $p < .16$) or WPow ($F < 1$). For the non-related category condition the same pattern as for PZ was found at electrode P4 (*EPow*: F (1,16) = 58.75, $p < .001$; *WPow*: F (1,16) = 19.26, $p < .001$; *PLI*: F (1,16) = 31.57, $p < .001$), whereas there was no significant effect for the related category condition (*EPow, WPow, PLI*: $F < 1$).

Pz ***Lower Theta***	**EPow**	**WPow**	**PLI**
TYPE	**	**	**
NON x ANT	**	**	**
REL x ANT			#
NON x REL	**	**	*

P4 ***Lower Theta***	**EPow**	**Wpow**	**PLI**
TYPE	**	**	**
NON x ANT	**	**	**
REL x ANT			
NON x REL	**	**	**

Table 4.19. Main effect of TYPE and pairwise comparisons for electrodes Pz and P4 with regard to the three measures applied for the lower theta frequency band (frequency bins: 3.0-4.5 Hz) (time window 200 – 500 ms). For post hoc single comparisons, all significance values were adjusted according to the modified Bonferroni procedure (Keppel, 1991) (# = marginally significant (< 0.9); * = < .05; ** = < .01).

In contrast to Experiments 2 and 3, visual inspection of Figure 4.12 revealed no eye-catching evidence for a lower delta power and/or PLI decrease in one of the two category conditions (in comparison to the antonym condition). This first evaluation was supported by the statistical analysis: there were no significant differences with regard to EPow, WPow, and PLI for the time and frequency range equivalent to Experiments 2 and 3 (averaged frequency bins 1.0-3.0 Hz, time window 100 - 400 ms).

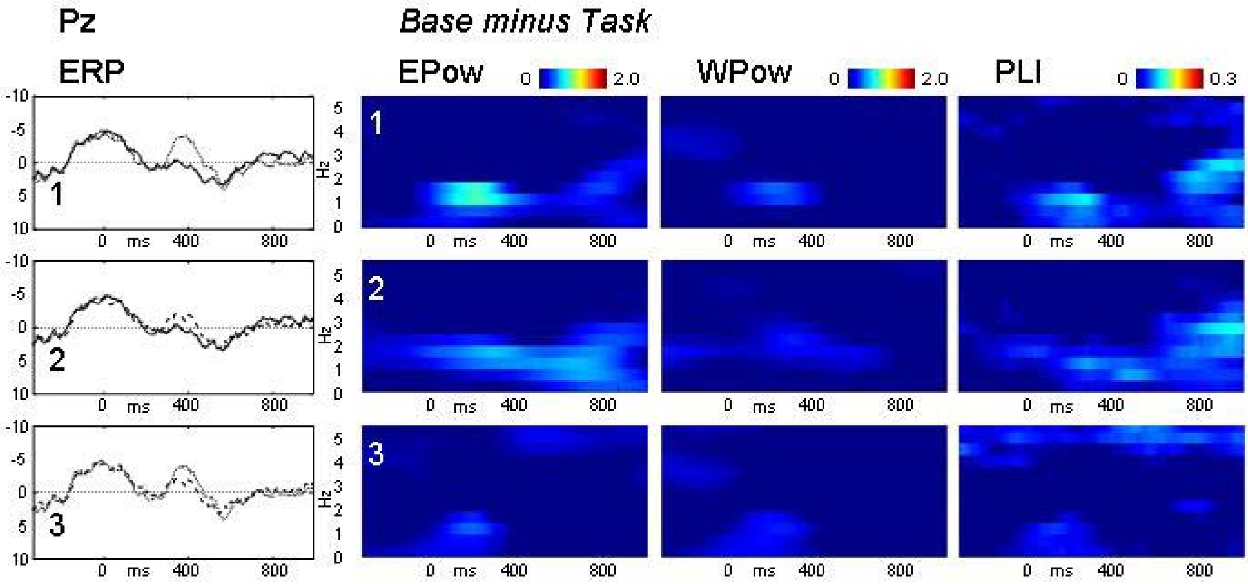

Figure 4.12. Grand average ERPs and Gabor wavelet-based time-frequency plots in the delta band (1-2 Hz) for the related category (Fig. 4.12.2) and non-related category conditions (Fig. 4.12.1) in comparison to the antonym condition at electrode PZ (N=17).

However, on the basis of the visual inspection of Figure 4.12, a more fine grained analysis of the small frequency band between 1.0 – 1.5 Hz confined to the time window between 200 – 400 ms, revealed significant main effects for EPow and PLI (*EPow*: *F* (1,16) = 4.54, *p* < .02; *PLI*: *F* (1,16) = 3.44, *p* < .05). Yet, there was no significant main effect for WPow (*F* (1,16) = 1.80, *p* < .19). A resolution of the significant main effects showed that both significant main effects were due to an increased activity in the delta frequency for antonyms in comparison to related category words (*EPow*: *F* (1,16) = 6.14, *p* < .03; *PLI*: *F* (1,16) = 8.33, *p* < .02) and non-related category words (*EPow*: *F* (1,16) = 5.48, *p* < .04; *PLI*: *F* (1,16) = 4.51, *p* < .05). Furthermore, there was no significant difference between both categories (*EPow*: *F* (1,16) = 1.01, *p* < .33; *PLI*: *F* < 1).

Turning now to the time-frequency analysis of pseudowords in second word position in comparison to antonyms and non-related category words, the power and PLI time-frequency difference matrices are shown in Figure 4.13.

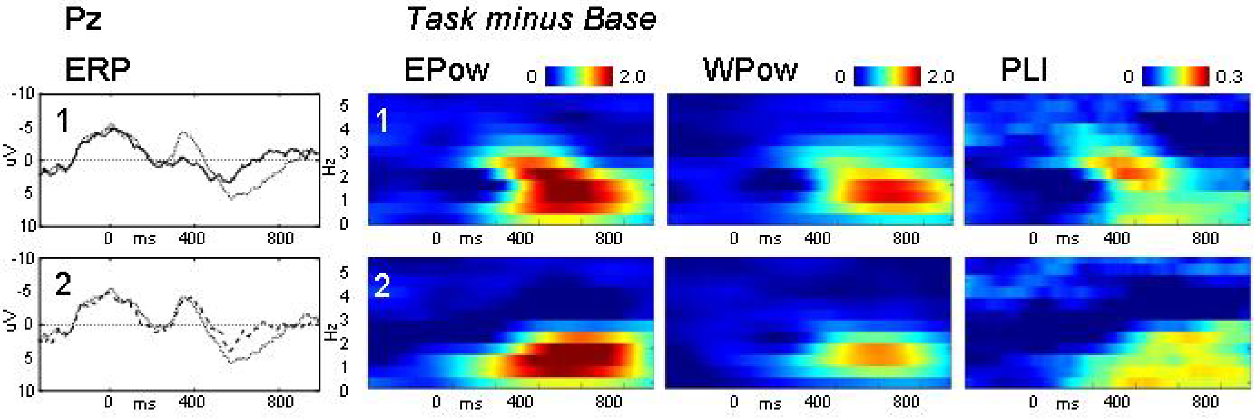

Figure 4.13. Grand average ERPs and Gabor wavelet-based time-frequency plots in the delta band for the pseudoword condition in comparison to the antonym condition (Fig. 4.13.1) and the non-related category condition (Fig. 4.13.2) at electrode PZ (N=17). The ERPs showed P600 differences (500-800 ms) in both comparisons (Fig. 4.13.1. and 4.13.2), whereas an N400 difference is only observable in relation to the anonym condition (Fig 4.13.1). In terms of EPow, WPow and PLI, the pseudoword condition showed a significant increase in comparison to the antonym control condition for both the lower theta and the delta band (Fig. 4.13.1). However, in comparison to the non-related category condition there only was a significant increase in delta band (Fig 4.13.2).

It is obvious from the visual inspection of Figure 4.13 that pseudowords showed the same pattern with regard to the lower theta frequency band in the N400 time window as non-related category conditions. In comparison to antonyms, pseudowords elicited an increase of EPow, WPow and PLI (cf. Figure 4.13).

The statistical analysis supported this observation (cf. Table 4.20). Post hoc single comparisons revealed significant main effects for all three measures for both, electrode PZ (*EPow*: *F* (1,16) = 23.05, *p* < .001; *WPow*: *F* (1,16) = 25.48, *p* < .001; *PLI*: *F* (1,16) = 16.09, *p* < .001) and P4 (*EPow*: *F* (1,16) = 26.95, *p* < .001; *WPow*: *F* (1,16) = 23.48, *p* < .001; *PLI*: *F* (1,16) = 18.33, *p* < .001). Furthermore, there was no significant difference between pseudowords and non-related category conditions with regard to EPow (*PZ, P4*: *F* < 1) and PLI (*PZ*: *F* < 1; *P4*: *F* < 1). However, there was a significant difference with respect to WPow (*PZ*: *F* (1,16) = 5.38, *p* < .04; *P4*: *F* (1,16) = 8.12, *p* < .02).[33]

Pz **Lower Theta**	**EPow**	**WPow**	**PLI**
ANT x NON	**	**	**
ANT x PSW	**	**	**
PSW x NON		*	

P4 **Lower Theta**	**EPow**	**WPow**	**PLI**
ANT x NON	**	**	**
ANT x PSW	**	**	**
PSW x NON		*	

Table 4.20. Post hoc pairwise comparisons for pseudowords (PSW) in comparison to antonyms (ANT) and non-related category words (NON) at electrodes Pz and P4 for the lower theta frequency band (frequency bins: 3.0-4.5 Hz) (time window 200 – 500 ms). All significance values were adjusted according to the modified Bonferroni procedure (Keppel, 1991) (# = marginally significant (< 0.9); * = < .05; ** = < .01).

In addition to the lower theta band power and phase-locking increase, Figure 4.13 shows a very pronounced EPow, WPow and PLI increase for the delta band (1.0-2.5 Hz) in the P600 time range (400-800 ms). This very pronounced delta band increase was not only observable in comparison to the antonym condition (Fig. 4.13.1), but also in comparison to the non-related category condition (Fig. 4.13.2). Consequently, it must be regarded as a clear cut correlate of the P600 in the frequency domain. Planned pairwise comparisons revealed significant main effects for EPow (*PZ*: *F* (1,16) = 16.61, *p* < .01; *P4*: *F* (1,16) = 12.67, *p* < .01), WPow (*PZ*: *F* (1,16) = 25.26, *p* < .001; *P4*: *F* (1,16) = 26.63, *p* < .001) and PLI (*PZ*: *F*

---

[33] Note that this putative difference in whole power could be due to a superposition of WPow activity related to the lower theta band and delta band, respectively. That is, the high degree of delta activity, which is obviously related to the pronounced late positivity, could overlay and boost the less pronounced lower theta activity.

(1,16) = 9.76, $p < .01$; *P4*: *F* (1,16) = 9.66, $p < .01$). All effects were due to an increase for pseudowords relative to the antonym condition (cf. Table 4.21).

P600 ***Delta band***	**EPow**	**WPow**	**PLI**
Fz	*	*	**
Cz	**	**	**
Pz	**	**	**
P3	**	**	**
P4	**	**	**

Table 4.21. Post hoc pairwise comparisons between pseudowords and antonyms with regard to the three measures applied for the delta frequency band (frequency bins: 1.0-2.5 Hz) (time window 400 – 800 ms).

Visual inspection of Figure 4.14 revelead no evidence for any low frequency decrease in EPow, WPow or PLI for pseudowords in comparison to antonyms. Indeed, the statistical analysis supported this observation: there were no significant effects, neither for the N400 time range nor for the P600 time range.

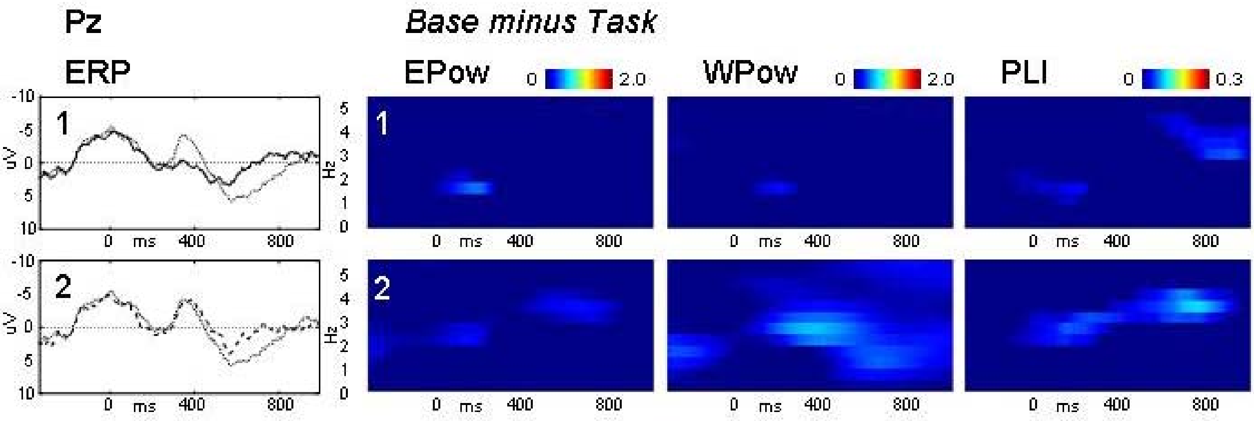

Figure 4.14. Grand average ERPs and Gabor wavelet-based time-frequency difference plots in the delta band (1-3 Hz) for pseudowords in comparison to the antonym condition (Fig. 4.14.1) and the non-related category condition (Fig. 4.14.2) at electrode PZ (N=17). There were no significant differences in any of the applied measures.

4.4.5 Summary

The original aim of the present experimental manipulation was to elicit a monophasic graded N400 effect in order to obtain an unequivocal characterisation of its underlying frequency dynamics. However, although we finally succeeded in eliciting the desired effects, the most important findings of the present experiment are based on effects which *didn't* show up.

Nevertheless, in the following section we first briefly will summarize the two basic findings with regard to the observed N400 effect. (i) There was a pronounced lower theta EPow increase in the N400 time range for non-related category words *and* pseudowords in comparison to the related category condition and antonyms. This EPow increase was due to a concurrent WPow and PLI increase. Although it is not possible to quantify the *relative contributions* of WPow and PLI activity to the respective EPow in a specific frequency band on the basis of the present analysis, the examination of the time-frequency plots suggested that the EPow increase in lower theta activity was mostly due to an increased phase locking. This observation is supported by the results of the previous experiments. In both antonymy judgment tasks, non-related category violations elicited a pronounced increase in lower theta evoked power in comparison to related category violations and antonyms which was due to an enhanced phase locking. (ii) There was a small but nevertheless significant evoked power increase in the delta frequency for antonyms in comparison to related and non-related category words. This increased delta EPow was due to enhanced phase locking. Taken together, both the lower theta increase for non-related categories and the concurrent small delta increase for antonyms can explain the observed graded N400 effect. Because related category words didn't reveal any pronounced in- or decreases of activity in comparison to non-related categories or antonyms, it has to be assumed that the *relative increase* in lower theta evoked power for non-related category words is a reflection lexical-semantic priming processes. However, the interpretation of the *relative increase* in delta evoked power for antonyms is less clear. For example, the increased delta activity could be a reflection of processes which are specific to the lexical-semantic organisation of antonyms (e.g. lexical associations or conceptual priming; cf. Murphy & Andrew, 1993).[34] However, in order to ascribe a more detailed functional interpretation further experimental evidence is needed.

---

[34] However, on the basis of the present experiment we cannot entirely exclude that the delta increase might be a reflection of strategic processes due to the task manipulations (in this case, the present delta increase could be regarded as a highly attenuated instance of the large delta increase for antonyms in Experiment 2 and 3)

As already pointed out above, the most important findings of the present experiment are based on effects which didn't show up. In section 4.4.2 we already stated on the basis of the ERP results that the positive shift for antonyms, which was previously observed in Experiments 2 and 3, was not observable with the present task manipulation. However, on the basis of the findings of Experiments 2 and 3, we linked this positive shift with the concurrent pronounced increase in evoked delta activity for antonyms in comparison to non-antonyms. Furthermore, we hypothesised that both effects might be a reflection of a positive component which is embedded in the N400 effect. Hence, the present finding that there is *no* such delta increase in the *absence* of a positive shift further supports the idea that both effects are closely linked and might reflect the same distinct component. In addition, we didn't observe any late positivities for related and non-related category words. This is again supported by the frequency analyses. There were no significant activity changes for both category conditions in comparison to antonyms in the time range of the late positivities. This double-dissociation with regard to the early and late positivities is also compatible with the differential group pattern observed in Experiment 2 (i.e. the observation that the early embedded positivity was dependent on the presence of the late positivities). Moreover, the absence of the early and late positivities as well as their respective correlates in the frequency domain clearly revealed the task-dependency of the effects (we will discuss this issue in more detail in Chapter 4.5).

Finally, with regard to the processing of pseudowords, there was a strong evoked delta power increase for pseudowords in comparison to words in the P600 time range. This increase was due to a concurrent increase in WPow and PLI. However, most importantly, this delta increase was highly similar to the delta EPow increase for antonyms found in Experiments 2 and 3. Both effects not only comprised the same frequency range, but also involved the same underlying frequency dynamics (im terms of WPow and PLI). We therefore suggest that both delta increases are reflections of the same processes. Because in the present experiment pseudowords were clearly task-relevant (in the sense that they were targets), as was also the case for antonyms in both antonymy verification tasks, it is evident that the delta evoked power increase must be regarded as a reflection of task-dependent processes.

4.5 General Discussion

The basic findings of the three EEG experiments are graphically summarised in Table 4.22.

Task		***ERPs***		***Frequency (EPow)***			
		early	*late*	*early*		*late*	
		N400 effect	Late Positivity	Lower Theta	Delta increase		Upper delta
Antonymy sentence verification task	sentence processing	**	**	**	**		**
Antonymy word pair verification task	word pairs	**	*	**	**		*
	group B	**	**	**	**		**
	group A	**		**			
Lexical decision task (pseudowords)	‘word’ processing	**		**			
	pseudoword processing	**	**	**		**	

Table 4.22 Graphical illustration of the basic results from all three EEG experiments. Note that two stars (**) refer to a pronounced effect, whereas one star (*) refers to a relatively weak effect; furthermore ‘early’ refers to the N400 time range, wheras ‘late’ refers to the time range of the late positivity.

As is apparent from the table, the frequency-analytical investigation of the present event-related potentials clearly showed that the present lexical-semantic N400 effect cannot be regarded as a monolithic effect. In contrast, our findings suggest that (at least) two different processing correlates can be distinguished from each other, both of which exert a different influence on the overall appearance of N400 effect. In addition, we will propose that, under specific task demands, a large portion of the N400 effect can be attributed to an embedded positive component. In the following, we will briefly summarise the findings from the three EEG experiments before proposing a scenario capable of integrating the observed ERP and frequency effects.

Lower theta increase and the N400 effect

Regardless of the task demands, i.e. judging antonym relations in sentence context (Experiment 2) or as word pairs (Experiment 3), or performing a lexical decision task (Experiment 5), non-related category words elicited a pronounced increase in lower theta evoked power in comparison to antonyms *and* related category words. However, *pseudowords* also showed the same evoked lower theta power increase in comparison to antonyms. Furthermore, there was no difference between pseudowords and non-related category words. In all of these cases, the increased evoked theta power was observable in the N400 effect time range.

Delta increase and the early positivity

The explicit instruction to judge antonym relations led to a task-specific increase in delta evoked power for *antonyms* in comparison to both related and non-related category violations in the antonymy sentence verification task (Experiment 2). A similar effect obtained one group of participants *(group B)* in the antonymy word pair verification task (Experiment 3). In both cases, the evoked delta power increase was elicited in the N400 time range and, furthermore, was due to a concurrent increase in whole power and phase locking. However, there was no comparable evoked delta power increase for antonyms in the lexical decision task (Experiment 5) and for the second group *(group A)* in the antonymy word pair verification task (Experiment 3). This led us to conclude that the evoked delta power increase for antonyms is a reflection of task-specific processes and must not be regarded as a correlate of lexical-semantic processes per se. This hypothesis was confirmed through the finding that pseudowords in the lexical decision task (Experiment 5) also elicited a pronounced evoked delta power increase, due to the same underlying mechanisms (in terms of whole power and phase locking increase), although in a later time window which was *subsequent* to the N400 effect. Yet, the crucial point is that the common denominator for the occurrence of the pronounced evoked delta increase not only seemed to be task-dependency but more specifically seemed to be related to the fact that, in all cases, the critical stimuli were *targets* of the task.

Furthermore, in both Experiment 2 and Experiment 3, antonyms showed a pronounced *positive shift* with a clear posterior distribution in comparison to both related and non-related category violations. This positive shift occurred almost simultaneously with the N400 effect.[35] This observation led us to propose that the positive shift might be due to a *positive component* which is embedded in the N400, thereby contributing to a major portion of the observed N400 effect for related and non-related category violations in comparison to antonyms. This assumption was supported through the finding that the positive shift was correlated with the concurrent *increase* in evoked delta power for antonyms in comparison to non-antonyms. This link between both the embedded positivity and the increase in delta was further corroborated through the results from Experiment 5. There was no positive shift and also no concurrent increase in evoked delta power for antonyms in comparison to non-antonyms. However, there was a pronounced increase in evoked delta power for *pseudowords* in comparison to words. This delta power increase was unambiguously correlated with a pronounced late positivity for pseudowords. Because, in Experiment 5, this late positivity was only observable for pseudowords in comparison to words, it was interpreted as a reflection of task-related processes or, more specifically, as a correlate of processes related to target detection. Moreover, because this positivity had a clear centro-posterior distribution, it was taken as an instance of a late P300-like positivity. However, the crucial point was that the pronounced evoked delta increase was the unequivocal reflection of a positivity. Hence, by analogy, this observation further supports the hypothesis that the enhanced positive shift for antonyms in Experiment 2 and 3 was due to an embedded positivity. Yet, it can only be speculated whether this embedded positivity can also be regarded as an instance of a P300 (analogous to the positivity for pseudowords in Experiment 5). However, if (for the sake of the argument) both effects are taken as a reflection of the *same* underlying processes, one has to account for the large latency differences between the early delta increase (the embedded positivity) and the late delta increase (the P300-like positivity). We will come back to this issue in the final paragraph of this chapter.

Upper delta increase and late positivities

The findings of Experiment 3 in comparison to those of Experiment 2 clearly showed that the *late positivity complex* for related and non-related category violations in comparison to antonyms *only* showed up in combination with the early positive shift for antonyms (cf. Experiment 2, 3, 5). Moreover, the observation that, in Experiment 3, there was no difference

---

[35] In fact, visual inspection of Figures 4.1 and 4.4 revealed that the positive peak for antonyms occurred slightly earlier than the N400 peak for related and non-related category violations.

in accuracy between subjects who showed both positivities and subjects who only showed an N400 led us to argue that the distinct ERP patterns might be a reflection of two distinct processing strategies. Furthermore, starting from the observation that, in the antonymy sentence verification task, every single subject showed both positivities, we hypothesised that the subjects showing both positivities in the antonymy word pair task in Experiment 3 processed the antonym relations analogously to the antonym sentence task, i.e. in a '*quasi-syntactic*' way. The frequency analysis revealed that the late positivity complex was due to an increased evoked upper delta power. Hence, the frequency correlate for the late positivity complex was clearly different from the evoked delta power effect which appeared in correlation with the late positivity for pseudowords in Experiment 5. Moreover, both evoked power effects not only had a different topographical distribution (frontal and posterior vs. posterior) but were also due to different underlying processing dynamics (increased phase locking vs. increased whole power and phase locking). This strengthens the assumption that the late frontal and posterior positivity for related and non-related category violations belong to a different 'class' and, hence, reflect different processes.

Conclusion

The above findings suggest that the N400 effect which was observed in the antonymy verification task must be attributed to (at least) two different underlying processes: Firstly, an increase in lower theta activity which presumably reflects the 'true' N400 priming effect and secondly, a pronounced increase in evoked delta activity which was interpreted as the reflection of an embedded positive component. However, with regard to the above findings and considerations, we suggest the following scenario.

The explicit instruction to judge the sequentially presented word pairs with regard to their antonymy led to the anticipation of the second word, i.e. the critical antonym. As in Experiment 2, this task-related processing strategy can be enforced through the restrictive sentence frame *The opposite of X is …* to the effect that subjects are 'urged' to anticipate the correct antonym (cf. the discussion in Chapter 4.2.5). Yet, anticipation in this very restrictive context not only means that subjects generate a specific *expectation* with regard to the upcoming word, but also that they might already retrieve (or at least preactivate) the specific word from semantic long-term memory (LTM). Hence, when the actual antonym was presented to the subject, the respective word form was already available and, therefore, the highly expected target could be easily identified. This *target effect* showed up as an early pronounced P300-like positivity (cf. the extensive literature supporting the view that the P300 is a reflection of voluntary detection of a task relevant target stimulus; e.g. Verleger, 1988). In contrast, non-related category words were neither anticipated (hence no P300-like positivity) nor expected. Nevertheless, they had to be identified. The increased processing effort due to the initation of lexical-semantic processes was reflected in an increased lower theta evoked power (cf. Experiment 2, 3, 5). In contrast, although related category words were also not expected (hence no P300-like positivity), they were semantically related to the *prime* to a very high degree. Therefore, they were subject to a substantial semantic priming effect (due to an almost complete feature overlap) which resulted in a pronounced reduction of the N400 component. Note that, in comparison to antonyms, no significant increase in evoked lower theta power was observable. Yet, this is predicted under the assumption that antonyms are subject to virtually the same degree of semantic priming.[36] Moreover, the evident gradedness of the N400 effect (between related and non-related category words as well as between antonyms and related category words) follows naturally from the combined effects of an increased evoked lower theta power for non-related category words and an increased evoked delta power for antonyms. From the considerations with regard to the P300-like positivity, it is predicted that the processing of antonym relations under task demands which do not entail anticipatory processes and where antonyms are not subject to 'target' effects should *not* lead to the elicitation of an early positivity. This is exactly what happened in the lexical decision task. Because the focus of the task was on the detection of pseudowords, antonyms were neither anticipated nor 'targets'. Hence, they were processed similarly to related category words in the antonymy verification tasks (i.e. they were subject to automatic semantic priming processes leading to a reduced lower theta activity in comparison to non-related words). However, in both the antonymy sentence verification task and group *B* of the antonymy word pair verification task, there was also a *late positivity complex,* which was reflected in an increased evoked upper delta power. As mentioned above, the positivity complex was regarded as a reflection of structural processes in both cases, i.e. as a reflection of final evaluation processes with regard to the well-formedness of a sentence (cf. Chapter 4.1.6). In the antonymy sentence verification task, the related and non-related category words not only did not match with the default antonym relation, but furthermore *violated* the entire proposition. We therefore suggest that the late positivity complex which is reflected in an

---

[36] Recall that the present results are based on differential analysis. Hence, the observation that there is no relative increase in lower theta does not entail that there also is no absolute increase.

evoked upper delta power increase is similar to the repair-related P600 which has been observed, for example, in response to phrase structure violations or verb argument violations (cf. Chapter 3). Of course, this suggestion also extends to the positivity complex observed in Experiment 3 for group *B*.[37]

Yet, we still have to explain the pattern for the pseudowords in Experiment 5, especially with regard to the latency difference of the observed late positivity for pseudowords (in comparison to the much earlier positivity for antonyms in Experiment 2 and 3). Evidently, pseudowords elicited a pronounced N400 effect in comparison to antonyms. This was not surprising because there is ample evidence that pseudowords, as word-like nonwords, elicit a large N400 (e.g. Holcomb & Neville, 1990).[38] Therefore, it has been suggested, in a lexical decision task, pseudowords are treated as words (at least some of the time) before they are rejected (e.g. Deacon, Dynowska, Ritter, & Grose-Fifer, 2004). Of course, pseudowords cannot be subject to semantic priming processes and hence they showed no difference in comparison to non-related category words with regard to the N400 effect or evoked lower theta activity. In addition, pseudowords couldn't be anticipated (like antonyms) although they were clearly specified as target-items of the lexical decision task. Yet, before they could be identified as targets, they first had to undergo lexical-semantic 'processing'. Hence, the target-related P300-like positivity necessarily *had* to follow the N400. These considerations furthermore predict that non-word-like nonwords which are orthographically illegal strings and for which it has been shown that they can be rejected out of hand, should - instead of showing a biphasic N400/P300-like patter - elicit a monophasic *early* P300-like positivity.[39]

However, one possible caveat with regard to the above scenario is the finding from Experiment 5 that related category words in comparison to antonyms showed a significant N400 effect. As predicted on the basis of the above considerations, this N400 difference didn't show up in an increased lower theta activity. Instead, the fine-grained analysis of the delta band revealed a circumscribed increase in evoked delta power for antonyms in comparison to related and non-related category words. This slight increase was due to a significant increase in phase-locking. With regard to the functional interpretation of this delta

---

[37] When we assume that subjects processed the antonym relations in a *quasi-syntactic* way by 'mentally treating or spelling out the antonym relations as a sentence proposition'.

[38] In contrast, non-word-like nonwords do not elicit an N400 (Holcomb & Neville, 1990).

[39] This prediction is borne out in findings from Holcomb & Neville (1990); see also Donchin & Coles (1988).

effect we suggest that it might be a reflection of associative or categorical processes which are specifically connected to the processing of antonyms (cf. Murphy & Andrew, 1993; Cruse, 1991).[40]

In sum, we suggest the following hypothesis with regard to a functional interpretation of the observed ERPs and frequency effects:

(i) the ‘true’ lexical-semantic N400 effect is reflected in an increase in lower theta activity;

(ii) a large portion of the pronounced N400 effect for antonyms (in both antonymy verification tasks) appeared to be task-related and has to be attributed to an embedded P300-like positive component;

(iii) structural evaluation processes are reflected in evoked upper delta power, which superficially shows up as a late positivity complex (as a frontal and a posterior positivity).

To conclude, the present chapter provided extensive evidence for the hypothesis that the ERP effects, and more specifically the N400 effect, can be precisely characterised by means of underlying frequency dynamics. Whereas superficially (i.e. from an ERP perspective) the present N400 effects could only be distinguished quantitatively but not qualitatively (cf. Table 4.22 *left panel*), the complementary findings from the applied frequency-analysis clearly revealed that the observed effects were due to different underlying processes (cf. Table 4.22 *right panel*). Moreover, the present findings from the frequency domain not only allowed us to distinguish different instances of the observed N400 effects from one another, and additionally, to functionally dissociate superficially similar late positivities. Furthermore, they even provided some evidence that - at least under specific circumstances - a large portion of superficially *distinct* ERP effects or components (N400, late positivity) might actually be due to the same underlying processes (and hence might be functionally equivalent).

---

[40] However, as already discussed in Chapters 4.4.3 and 4.4.5, we cannot exclude that subjects became aware of the fact that they were presented with antonym relations. Hence, in addition to the primary task demands, subjects might have developed some anticipatory strategies with regard to a relational processing of the presented word pairs. In this case, the increased evoked delta activity could be a minor instance of the increased delta evoked power in the antonymy verification task.

Chapter 5

The N400 and Reanalysis

5.1 Experiment 6: Processing of subject-object ambiguities

In the final *experimental* chapter of the present thesis, we will address the third of the three questions posed in the introduction, i.e. whether it is possible, on the basis of the findings from the experiments in the previous chapters, to distinguish a ‘classical’ lexical-semantic N400 effect from an N400 effect which cannot be attributed to semantic-interpretative processes but unambiguously reflects structural processes. To this end, we reanalysed the data of an ERP study reported by Bornkessel (2002), in which an N400 effect was observed in response to the disambiguation of temporarily case ambiguous sentences (cf. Table 5.1).[1]

Condition	**Example** *Gestern wurde erzählt, ...* *Yesterday, someone said ...*
A. *SO*	… dass Maria Sängerinnen folgt, obwohl … … that Maria$_{\text{NOM/ACC/DAT.SG}}$ singers$_{\text{NOM/ACC/DAT.PL}}$ follows$_{\text{SG}}$, although …
B. *OS*	… dass Maria Sängerinnen folgen, obwohl … … that Maria$_{\text{NOM/ACC/DAT.SG}}$ singers$_{\text{NOM/ACC/DAT.PL}}$ follow$_{\text{PL}}$, although …

Table 5.1. Example sentences for each of the critical conditions in Experiment 6.

In sentences (A) and (B) of Table 5.1, both arguments of the subordinated complement clause are three-way ambiguous with respect to case (nominative, accusative, dative). Whereas in (A), the structure is disambiguated towards a subject-initial (SO) structure by the number agreement information of the clause-final verb, in (B) it is disambiguated towards an object-initial (OS) structure at the same position. Note that, in contrast to the English subject–verb–object (SVO) word order, the finite verb is always placed in clause final position in German

---

[1] This experiment was originally conducted with the aim to show - in support of the proposed *argument dependency model* - that argument processing is based on two independent processing routes: thematic and syntactic processing (Bornkessel, 2002).

subordinate clauses. In this way, both subject (S) and object (O) noun phrase precede the verb, either in the preferred SOV or in the less-preferred OSV order. However, it is crucial that, due to the case ambiguity of the arguments which precede the verb, the arguments of both sentences (A) and (B) are ambiguous between subject and object until they are disambiguated by the number marking of the sentence final verb.

There is overwhelming behavioural evidence that subject-object ambiguities are quickly resolved in favour of a subject-initial reading both in German (e.g. Bader & Meng, 1999; Schlesewsky, Fanselow, Kliegl, & Krems, 2000; Schriefers, Friederici, & Kühn, 1995) and in other languages (e.g. Dutch, cf. Frazier & Flores d'Arcais, 1989; and Italian, cf. de Vincenzi, 1991). Hence, in both conditions (A) and (B), the first argument '*Maria*' is assigned the subject grammatical function and the second argument '*Sängerinnen*' the object grammatical function. These assignments are confirmed if the clause final verb is singular ('*folgt*'). However, if the sentence is concluded by a plural verb ('*folgen*'), the disambiguating number agreement indicates that the clause is, in fact, object-initial and therefore a reanalyis becomes necessary.

5.1.1 Method

Materials

The two critical conditions for Experiment 6 are shown in Table 5.1 above. Note that the stimulus material was originally part of a larger set of sentences which consisted of eight conditions (cf. Bornkessel, 2002). In this way, each participant saw 320 sentences (40 per condition), of which 80 belonged to the two critical conditions of the present analysis (for more details see Chapter 4.1.1 in Bornkessel, 2002).

Participants

Sixteen undergraduate students from the University of Leipzig participated in Experiment 6 (8 female; mean age 23.1 years; age range 20 – 27 years). All Participants were right-handed and monolingual native speakers of German. None of the participants had taken part in any of the other Experiments (1-5).

Procedure

Sentences were presented visually in the centre of a computer screen. Each trial began with the presentation of an asterisk (300 ms plus 300 ms interstimulus interval, ISI) in order to fixate participants' eyes at the centre of the screen and to alert them to the upcoming presentation of the sentence. Single words were presented for 450 ms and phrases for 500 ms with an ISI of 100 ms. After the presentation of a sentence, there was a 1000 ms pause before participants were required to complete a comprehension task. For each participant the comprehension task comprised the answer 'yes' equally as often as the answer 'no' in each of the experimental conditions.

Participants were asked to avoid movements and to blink their eyes between their response to the comprehension task and the presentation of the next sentence. The experimental session began with a short training session followed by 8 experimental blocks comprising 40 sentences each, between which the participants took short breaks. The entire experiment (including electrode preparation) lasted approximately 2 hours (due to the remaining experimental conditions which will not be reported here; cf. Bornkessel, 2002 for more details).

The EEG was recorded by means of 58 AgAgCl-electrodes fixed at the scalp by means of an elastic cap (Easy Cap International). The ground electrode was positioned above the sternum. Recordings were referenced to the left mastoid, but re-referenced to linked mastoids offline. The electrooculogram (EOG) was monitored by means of electrodes placed at the outer canthus of each eye for the horizontal EOG and above and below the participant's right eye for the vertical EOG. Electrode impedances were kept below 5 kOhm.

All EEG and EOG channels were amplified using Neuroscan Synamps amplifiers (DC to 50 Hz) and recorded continuously with a digitisation rate of 250 Hz. The plots of grand average ERPs were smoothed off-line with a 10 Hz low pass filter, but all statistical analyses were computed on unfiltered data.

Average ERPs were calculated per condition per participant from 334 ms prior to the onset of the critical stimulus item (i.e. the verb) to 1000 ms post onset, before grand-averages were computed over all participants. Trials for which the comprehension task was not performed correctly were excluded from the averaging procedure as well as the single trial analysis, as were trials containing ocular or other artefacts (the EOG rejection criterion was 40µV).

Data Analysis

Because the present experiment was a reanalysis of data already published in Bornkessel (2002), we did not analyse the behavioural data.

For the statistical analysis of the ERP data, repeated measures ANOVAs involving the critical factor ORDER (subject- vs. object-initial) were calculated for mean amplitude values per time window per condition in four lateral regions of interest (ROIs) as well as two central ROIs. Lateral regions were defined as follows: *left-frontotemporal* (F9, F7, F5, FT9, FT7, FC5); *left-posterior* (TP9, TP7. CP5, P9, P7, P5); *right-frontotemporal* (F10, F8, F6, FT10, FT8, FC6); *right-posterior* (TP10, TP8, CP6, P10, P8, P6). Central regions were defined as: *central-anterior* (F3, FZ, F4, FC3, FCZ, FC4); *central-posterior* (CP3, CPZ, CP4, P3, PZ, P4).

The statistical analysis was carried out in a hierarchical manner (cf. Experiment 2).

5.1.2 ERP results

ERPs

Figure 5.1 shows grand-average ERPs for subject- vs. object-initial active verbs. The visual inspection indicated that object-initial verbs elicited a broad, centro-parietal negativity between approximately 400 and 600 ms post onset of the critical verb.

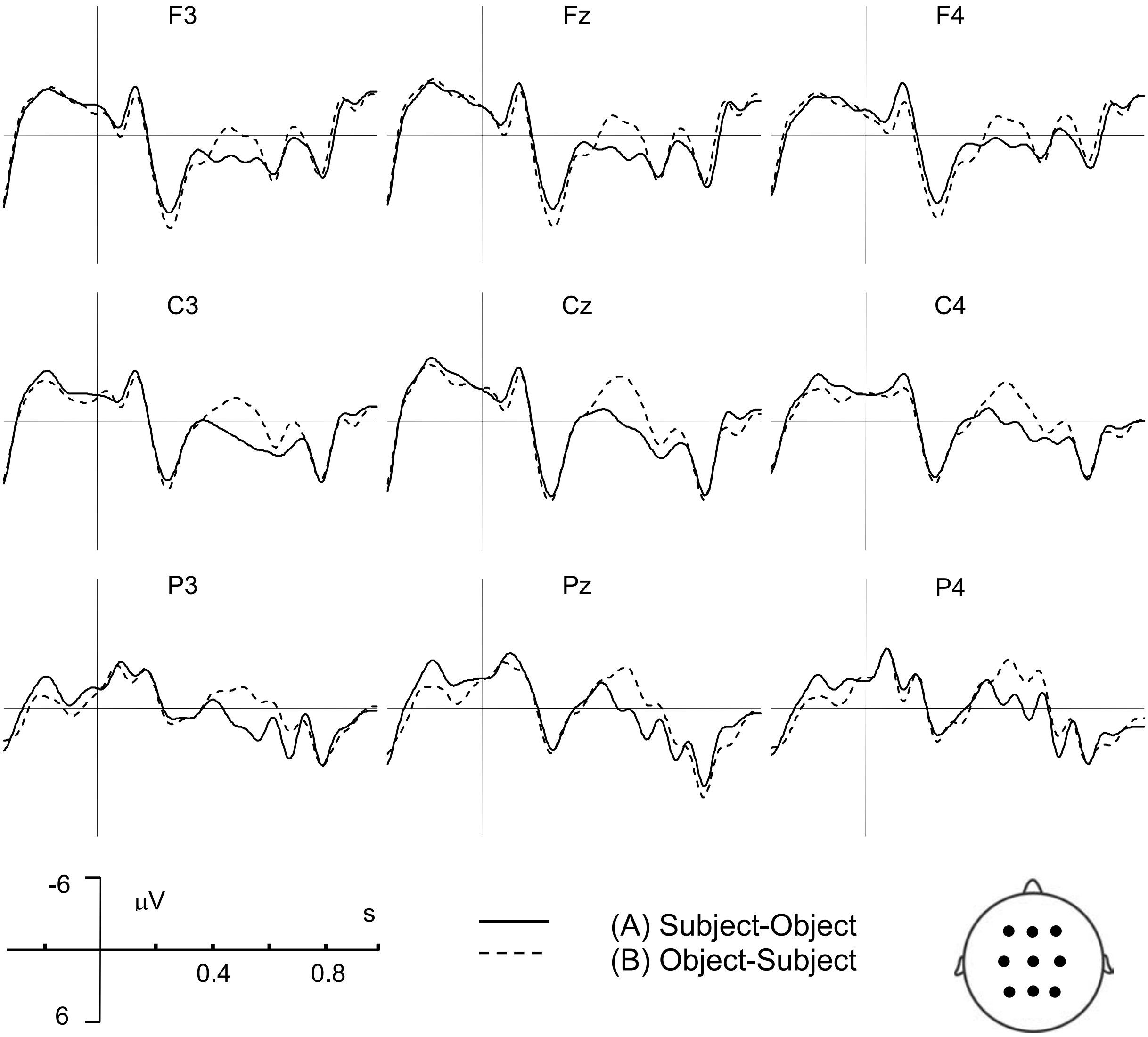

Figure 5.1. Grand average ERPs for object- vs. subject-initial case ambiguous structures at the position of the verb (onset at the vertical bar) in Experiment 6 (cf. Experiment 1 in Bornkessel, 2002). Negativity is plotted upwards.

The statistical analysis, carried-out for twenty-four successive 50 ms time windows beginning at -200 ms to 1000 ms (t1 – t24), confirmed these observation. There was a significant main effect of ORDER between 450 and 600 ms (450-500 ms: F (1,15) = 18.49, $p < .01$; 500-550 ms: F (1,15) = 24.81, $p < .01$; 550-600 ms: F (1,15) = 9.97, $p < .01$), as well as a significant interaction ORDER x ROI between 450 and 650 ms (450-500 ms: F (5,75) = 3.81, $p < .01$; 500-550 ms: F (5,75) = 3.43, $p < .01$; 550-600 ms: F (5,75) = 5.64, $p < .01$; 600-650 ms: F (5,75) = 8.04, $p < .01$). All significant effects were due to an enhanced negativity for object-initial in comparison to subject-initial structures. Resolution of the interactions revealed that there was no significant N400 effect at left-frontotemporal regions, and only a small effect between 450 and 550 ms at right-frontotemporal regions (450-500 ms: F (1,15) = 6.45, p < .05; 500-550 ms: F (1,15) = 4.49, p < .09). In addition, the negativity was most pronounced centro-parietally and lasted until 600 ms at left-posterior regions (450-500 ms: F (1,15) = 19.04, p < .01; 500-550 ms: F (1,15) = 14.14, p < .01; 550-600 ms: F (1,15) = 12.39, p < .01), and even until 650 ms at central-posterior (450-500 ms: F (1,15) = 20.22, p < .01; 500-550 ms: F (1,15) = 21.17, p < .01; 550-600 ms: F (1,15) = 21.19, p < .01; 600-650 ms: F (1,15) = 5.89, p < .05) and right-posterior regions (450-500 ms: F (1,15) = 26.91, p < .01; 500-550 ms: F (1,15) = 18.89, p < .01; 550-600 ms: F (1,15) = 21.91, p < .01; 600-650 ms: F (1,15) = 6.89, p < .05). A schematic overview of the significant results is shown in Table 5.2.

ROIs	time windows in ms															
	t9	t10	t11	t12	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24
	200 250	250 300	300 350	350 400	400 450	450 500	500 550	550 600	600 650	650 700	700 750	750 800	800 850	850 900	900 950	950 999
FroL		#														
CenA		#				**	**									
FroR						*	#									
PosL						**	**	**								
CenP						**	**	**	*							
PosR						**	**	**	*							

Table 5.2. Overview of the significant main effects of ORDER in each of the 6 ROIs (*frontal-left* = FroL; *frontal-right* = FroR; *central-anterior* = CenA; *central-posterior* = CenP; *posterior-left* = PosL; *posterior-right* = PosR) in 24 successive 50ms time windows (t1 – t24) starting at -200 ms till 1000 ms post-onset of the critical verbs (# = marginally significant (< 0.9); * = < .05; ** = < .01). There was no significant effect for any comparison in the time windows t1-t8 (-200 to 200 ms).

5.1.3 Interim discussion

As already pointed out above, object-initial active verbs in comparison to subject-initial verbs elicited a broad, centro-parietal negativity between 450 and 650 ms post onset of the critical verb. However, the finding of an N400 for object-initial structures is somewhat surprising because previous studies investigating the reanalysis of subject-object ambiguities in complement clauses showed a P600 (Friederici & Mecklinger, 1996; Friederici et al., 2001).[2]

---

[2] Furthermore, for ambiguous object-initial structures in *relative clauses*, a P345 has been observed (Mecklinger, Schriefers, Steinhauer, & Friederici, 1995).

Nevertheless, the present N400 effect was interpreted as an index of reanalysis (for supporting evidence from an SAT-study see Chapter 4.2 in Bornkessel, 2002). In a study by Hopf et al. (1998), the dispreferred resolution of accusative-dative ambiguities in German also gave rise to an N400-like effect. It has been argued that this negativity is the reflection of a lexical reaccess, which is required in order to assign dative case instead of the preferred accusative case. However, this line of argumentation cannot account for the present N400 effect, because both critical conditions involved the assignment of dative case *irrespective* of the word order differences.

On the basis of the observation that *dative-nominative* is a basic non-derived word order pattern in German (for example with object-experiencer verbs like '*gefallen*', 'to be appealing to'), Bornkessel (2002) suggested that the reanalysis to this word order might proceed without operations pertaining to the syntactic structure. Hence, the observed N400 effect would be a reflection of *enhanced processing costs* due to a reanalysis *that does not involve any restructuring operations whatsoever*.

5.1.4 EEG frequency analysis

As in the previous experiments (1-3, 5) we applied the three frequency-based measures evoked power (EPow), whole power (WPow) and phase locking index (PLI) for the EEG analysis (cf. Chapter 2.5). All measures were determined by Gabor wavelet analyses in frequency bins of 0.5 Hz (time window –334 to 1000 ms plus 50% tapering window). Analyses were confined to lower frequency bands (< 6 Hz) for the midline electrodes FZ, CZ, and PZ. Because the ERP analysis revealed that the observed N400 effect had a centro-parietal distribution with a clear central maximum, the present time-frequency plots were confined to electrode CZ. The statistical analysis was carried out as in Experiment 2.

Results

Figure 5.2 shows that, for object-initial sentences, there was a pronounced increase of evoked upper delta band activity (2-3 Hz) in comparison to subject-initial sentences. This increase was confined to the time range of the N400 effect of the corresponding ERP analysis. Furthermore, there appeared to be a concurrent increase in upper delta phase locking.

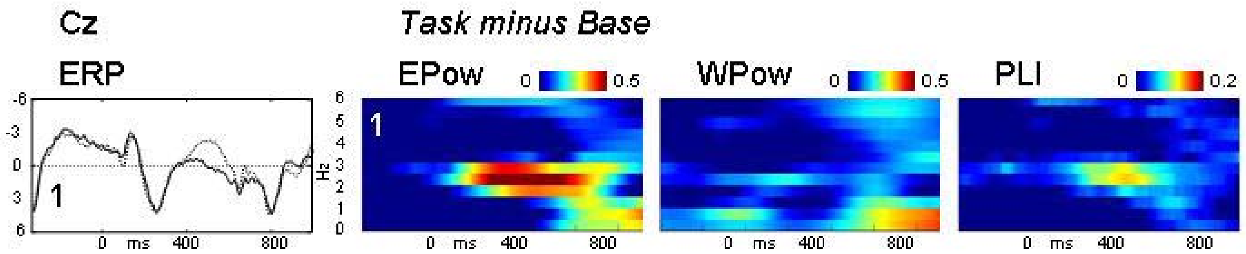

Figure 5.2 Grand average ERPs and Gabor wavelet-based time-frequency difference plots in the delta band (2-3 Hz) for the object-initial sentences in comparison to subject-initial sentences at electrode CZ (N=16). The colour scale depicts the magnitude of the wavelet coefficient differences for EPow and WPow and the PLI value difference for PLI. Note that subject-initial sentences were subtracted from object-initial sentences, thereby indicating *relative increases* in activity for the latter.

The statistical analyses confirmed these observations. For upper delta EPow (averaged frequency bins: 2.0-3.0 Hz; time window: 300-600 ms), there was a significant main effect of ORDER for electrode CZ (F (1,15) = 5.87, $p < .03$). Analyses of the measures WPow and PLI revealed that this upper delta EPow increase was due to a significant increase of PLI (F (1,15) = 7.76, $p < .02$). However, there was no significant effect for WPow ($F < 1$). The same pattern was also observable at electrodes FZ (*EPow*: F (1,15) = 8.54, $p < .02$; *PLI*: F (1,15) = 12.44, $p < .005$; *WPow*: $F < 1$) and PZ (*EPow*: F (1,15) = 3.98, $p < .07$; *PLI*: F (1,15) = 3.95, $p < .07$; *WPow*: F (1,15) = 1.96, $p < .19$). A comparison of the respective F-values revealed that both the significant upper delta EPow and PLI increase were more pronounced at FZ and CZ, but only marginally significant at PZ (cf. Table 5.3; for more details see Appendix E4).

Upper delta *ORDER*	**EPow**	**WPow**	**PLI**
Fz	**		**
Cz	*		*
Pz	#		#

Table 5.3 Significant main effects of ORDER for the electrodes Fz, Cz and Pz with regard to the three measures applied for the upper delta frequency band (frequency bins: 2.0-3.0 Hz; time window 300-600 ms). (# = < .07; * = < .05; ** = < .01).

In addition to the observed evoked upper delta increase for object-initial verbs in comparison to subject-initial verbs, the visual inspection of Figure 5.3 revealed an increase in evoked theta activity for subject-initial sentences in comparison to object-initial sentences.

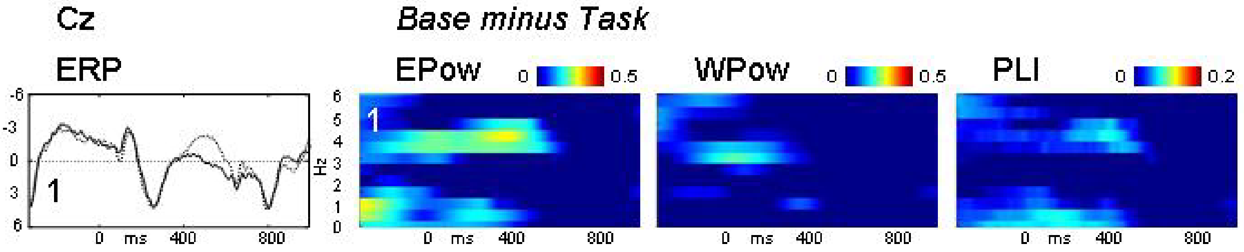

Figure 5.3 Grand average ERPs and Gabor wavelet-based time-frequency difference plots in the theta band (4-5 Hz) for the subject-initial sentences in comparison to object-initial sentences at electrode CZ (N=16). Note that object-initial sentences were subtracted from subject-initial sentences, thereby indicating *relative increases* in activity for the latter.

Indeed, the statistical analyses revealed a significant difference in evoked theta power (averaged frequency bins: 4.0-5.0 Hz; time window: 200-500 ms) for subject-initial verbs in comparison to object-initial verbs at electrode CZ (F (1,15) = 7.29, $p < .02$). As for upper delta this EPow increase was due to a significant enhancement of phase locking (F (1,15) = 5.74, $p < .04$), whereas there was no significant effect with regard to WPow ($F < 1$). Furthermore, the same pattern was observable at electrodes FZ (*EPow*: F (1,15) = 4.00, $p < .07$; *PLI*: F (1,15) = 9.60, $p < .01$; *WPow*: $F < 1$) and PZ (*EPow*: F (1,15) = 10.55, $p < .01$; *PLI*: F (1,15) = 5.92, $p < .03$; *WPow*: $F < 1$). However, in contrast to upper delta activity, the comparison of the respective F-values revealed that the theta effect for subject-initial sentences was more pronounced centro-parietally than at frontal electrode sites (cf. Table 5.4 and Appendix E4).

Theta *ORDER*	**EPow**	**WPow**	**PLI**
Fz	#		**
Cz	*		*
Pz	**		*

Table 5.4 Significant main effects of ORDER for the electrodes Fz, Cz and Pz with regard to the three measures applied for the theta frequency band (frequency bins: 4.0-5.0 Hz; time window 200-500 ms). (# = < .07; * = < .05; ** = < .01).

5.1.5 Conclusion

The analysis of the time-frequency measures applied here clearly revealed that the observed N400 effect for object- in comparison to subject-initial sentences can be attributed to a pronounced increase in upper delta evoked power for object-initial structures. Moreover, this increased upper delta EPow was due to an increased phase locking. Furthermore, in the beginning of the N400 time window, there was a significant but much less pronounced increase in evoked theta power for subject-initial structures.

As already discussed above, the finding of an N400 effect in response to object-initial sentences in case ambiguous sentences was somehow unexpected, because prior investigations of subject-object ambiguities in complement clauses had revealed an enhanced P600 for object- in comparison to subject-initial structures (Friederici & Mecklinger, 1996; Friederici et al., 2001). However, whereas the latter findings were based on the processing of *accusative-nominative* ambiguities, the present stimulus material comprised only structures which were resolved in favour of *dative-nominative* or nominative-dative orders. However, Bornkessel, McElree, Schlesewsky, & Friederici (submitted) argued that both subject-object ambiguity types might have elicited different ERP components because they represent two different types of non-nominative-initial word orders in German. Whereas *accusative-nominative* ambiguities always involve a permuted or derived structure, *dative-nominative* ambiguities can also be interpreted as a base generated *dative-nominative* structure (cf. Haider & Rosengren, 2003), i.e. they can be processed analogously to basic non-derived word orders for object-experiencer verbs such as *'gefallen'* ('to be appealing to'). This observation led Bornkessel (2002) and Bornkessel et al. (submitted) to propose that the N400 effect might be the reflection of *enhanced processing costs* due to non-structural reanalysis. Because all that is required for a successful reanalysis in *dative-nominative* sentences is a reassignment of dative and nominative case to the two arguments, this type of reanalysis would not require any phrase structure revision. However, we will come back to this issue below.

Returning to the findings from the present frequency analysis, the upper delta evoked power increase which was due to an enhanced phase locking clearly is reminiscent of the results obtained in Experiment 2 (cf. also Experiment 3, group *B*). In this experiment, we also observed an evoked power increase in the same frequency band. This upper delta EPow increase was elicited in response to sentence-final words which not only didn't match the expected second word (antonym) of a previously presented antonym prime but, furthermore, violated the proposition of the whole sentence. Crucially, on the surface, this evoked upper delta increase was observable as a *late positivity*, approximately in the time window between 600-800 ms post onset of the critical item. Because the elicitation of the late positivity, and, therefore, also of the underlying upper delta increase, appeared to be dependent on structural processes, we interpreted it as an instance (or a reflection) of a P600-like positivity which might indicate reanalysis processes. More specifically, we proposed that it might reflect final evaluative processes with regard to the *well-formedness* of the sentence. Furthermore, as for the reanalysis N400, the increased EPow was due to an enhanced phase locking without a concurrent increase in whole power. Therefore, we must conclude that both EPow increases were due to (at least) a *partial phase resetting* mechanism (cf. Chapter 2.2). Due to the surprising analogy between both effects (with regard to the functional interpretation in terms of reanalyis, and the underlying frequency dynamics), it is tempting to speculate whether the two instances of the upper delta EPow increase might be a reflection of the *same functional processes*. That is, we could hypothesise that both effects might reflect enhanced processing costs due to a similar reanalysis process.

Yet, a decisive objection with regard to the above speculation is based, firstly, on the obvious fact that, on the surface, both upper delta EPow increases gave rise to different components, i.e. an N400 in contrast to a P600. Secondly, different components are mostly interpreted as clear evidence for the involvement of *qualitatively* different processes, i.e. the appearance of two components would be consistent with the assumption that qualitatively different reanalysis mechanisms were operative. So, how could these observations be compatible with our proposal of a possible functional identity?

The answer is straightforward under the premise that both effects are a reflection of the same underlying *ongoing* oscillatory activity. With regard to the first objection, i.e. the observation of two components with opposite polarity, we have to consider the frequency range of the observed upper delta effects. In both cases, the observed frequency range was between 2.0 – 3.0 Hz, i.e. the approximate centre frequency was around 2.5 Hz. This means that a full oscillatory wave cycle takes approximately 400 ms, whereas a half oscillatory wave cycle (from the maximal negative to the maximal positive peak) will be finished roughly after 200 ms. However, 200 ms is approximately the time difference between the peaks of the observed N400 component and the late positivity from Experiment 2 (cf. Figure 5.1 in comparison to Figure 4.1). In this way, the relation between the earlier negative peak and the later positive peak could simply be regarded as the result of an 180 degree phase shift due to an ongoing upper delta oscillation, i.e. both components could potentially reflect the *up* and *down* of the same upper delta oscillation. Yet, being the possible cause of the observed distinct components is not tantamount to being responsible for the elicitation of two distinct effects. However, both observed ERP *effects* were attributed to an *enhanced phase locking* (or to partial phase resetting). Thus, under the assumption that the same process, namely phase locking of the ongoing oscillation, merely occurred at *different points in time*, the elicitation of distinct effects with different polarities arises quite naturally. Whereas an enhanced phase locking at the beginning of the negative phase cycle will lead to an increased negativity, the same mechanism will give rise to an enhanced positivity during the reversed phase angle. Therefore, it could be speculated that the surface difference in polarity between the two observed ERP effects might actually be due to a *timing difference* in the occurrence of phase locking of the underlying upper delta oscillation. With regard to the second objection, i.e. the apparent incompatibility between a functional identity and a qualitative difference, we have to point out that both assignments clearly refer to distinct processing levels. Whereas – in terms of Marr’s (1982) distinction of different processing levels - the *functional identity* of the presumed underlying processing mechanism of the observed ERP effects refers to the algorithmic level (i.e. pertaining to brain processes, namely the phase locking of oscillatory activity) or possibly even to the implementational level (i.e. pertaining to neural structure), the interpretation that distinct ERP components might reflect *qualitative* differences refers to mental representations (computational level). As already pointed out above, differences in the timing (phase locking) of functionally identical oscillatory processes might be observable as distinct ERP effects on the surface. Hence, the qualitative linguistic difference might be reflected as timing difference in phase locking. Moreover, what might appear as a qualitative difference on a linguistic level of description, might be reflected as a difference in the degree of complexity from a processing perspective. There is ample evidence from behavioural studies that a higher complexity gives rise to increased processing costs in terms of additional processing time. With regard to reanalysis, it is clear that a more complex reanalysis requires a higher degree of recomputation, which in turn requires additional processing time.

So how does the observation that higher processing costs (in the sense of an enhanced recomputation) might lead to additional processing timing relate to finding of a delay in the phase resetting of upper delta oscillations? In Chapter 3 (Experiment 1), we showed that the processing of ungrammatical sentences, which elicited a *processing conflict* due to the presence of two subjects (thereby rendering the sentence uninterpretable) led to an increase in evoked delta power (which was observable on the surface as a pronounced late positivity). Moreover, we suggested that the occurrence of an irresolvable conflict (as for the animate ungrammatical condition), led to an abortion of processing and, thereby, to an immediate reorganisation of the language processing system. This was suggested to result in a more consistent timing across trials, which, in fact, was reflected in a higher degree of phase locking. Yet, the crucial point is that conflict resolution under such a point of view implicates that the relevant information, on which the resolution of the conflict is based, must already be available. This, however, means that *conflict resolution* can basically be regarded as a function of the *temporal availability* of the critical information (as a consequence of the ease of processing). Therefore, the timing of (*partial) phase resetting* as a result or reflection of conflict resolution during language processing might be understood as the *consequence* of the temporal availability of the relevant information, thereby presumably indicating the endpoint of an evaluation process (possibly in the sense of a *diagnosis*; Fodor & Inoue, 1998).

Under the speculative assumption that the timing of upper delta phase locking might indicate the *availability* of information, the findings of an reanalysis N400 for *dative-nominative* orders in comparison to a reanalysis P600 for *accusative-nominative* orders (cf. Bornkessel et al., 2004z) can be elegantly explained. Because, in contrast to *dative-nominative* orders, *accusative-nominative* orders additionally involve the revision of phrase structure, different information types must be taken into consideration in order for the reanalysis to be successful.

However, this leads to a later availability of the information needed for successful conflict resolution. Yet, this latency difference might be reflected in a later onset of phase resetting, thus possibly resulting in a P600 (upper delta phase resetting latency would thereby reflect the ease of conflict resolution possibly in the sense of diagnosis).

Note that the above scenario entails (at least) three predictions: Firstly, there should be no difference between *accusative-nominative* ambiguities (showing up as P600) and *dative-nominative* ambiguities (eliciting an N400) with regard to their underlying frequency dynamics; both should be due to the same degree of upper delta phase locking increase. However, there should be a clear *latency difference* in phase locking (i.e. phase locking for accusative-initial structures should be approximately 200 ms later than that for dative-initial structures). Secondly, we hypothesised that this delay in phase locking might be a reflection of the delayed availability of information for conflict resolution for *accusative-nominative* orders in comparison to *dative-nominative* orders. Yet, this entails that such a processing difference should also be observable in behavioural measures. Previous findings suggest that the processing of object-initial structures with dative verbs may be easier than the processing of similar structures with accusative verbs: In Schlesewsky & Bornkessel (2003), dative-initial structures with active verbs were rated acceptable 85% of the time, whereas Meng & Bader (2000) found that accusative-initial sentences were rated acceptable only 49% of the time. However, with regard to time-sensitive measures such as the speed-accuracy trade-off (SAT) method it is predicted that there should be also a substantial difference in the temporal dynamics between both structures, to the effect that the processing of accusative-initial structures should show slower processing dynamics (e.g. a delayed intercept or slower rate). Thirdly, quantitative differences in the reanalysis N400 or P600 should be observable as differences in the degree of phase locking. As already discussed above, in Chapter 3, we speculated that irresolvable conflicts might lead to an abortion of processing, which would finally be observable in a higher degree of phase locking. This, however, implicates that less severe conflicts should also give rise to a lesser degree of phase locking, especially in cases where additional information for a more successful conflict resolution is available. Remarkably, Bornkessel (2002) and Bornkessel et al. (submitted) observed a reduced reanalysis N400 for object-experiencer verbs in comparison to active verbs in case ambiguous *dative-nominative* constructions. The authors suggested that the lexical information associated with the object experiencer verbs might ease the reanalysis process, thereby reducing the amplitude of the N400 effect.[3] However, this observation perfectly fits the suggested scenario. Thus, it is predicted that the reduced reanalysis N400 for object-experiencer verbs in comparison to active verbs should be due to a *reduced phase locking* in upper delta oscillatory activity.

Leaving the speculations behind and coming back to the present findings, we suggest that the observed reanalysis N400 effect, which was attributed to an upper delta phase locking increase, might be regarded as a manifestation of an integrative conflict resolution process and thereby as an indirect reflection of the temporal dynamics of the *availability* of the different information types (in analogy to the findings from Experiment 2).[4]

In sum, the present findings showed that an N400 effect which was elicited in response to structural manipulations could be clearly distinguished from semantically induced N400 effects on the basis of its underlying frequency characteristics. Moreover, we speculated that even *superficially distinct* ERP effects might be attributed to the *same underlying* processing characteristics. Thereby, the present analysis suggests that presumably disparate findings can be reconciled and simplified with regard to their functional interpretation and their inherent processing dynamics.

---

[3] This view is further supported form findings in a SAT-experiment which showed that object-experiencer verbs gave rise to a higher level of asymptotic performance than dative active verbs. On the basis of these observations, Bornkessel et al. (submitted) hypothesised that dative-nominative structures are more accessible target structures for reanalysis after the processing of object-experiencer verbs.

[4] Note that we haven't yet discussed the differences in theta activity between object and subject-initial verbs. An inspection of the time-frequency plots based on absolute values indicated that the relative theta EPow and PLI increase for subject-initial verbs was in fact due to a more pronounced decrease of evoked theta power and phase locking for object-initial verbs. Furthermore, this EPow and PLI decrease was confined to the onset of the N400 effect and, hence, was superimposed onto the onset of the respective delta increases for object-initial verbs. At the moment we only can speculate about the functional significance of the observed theta decrease. Under the assumption that the increased delta activity (phase locking) for object-initial verbs might be a reflection of processes involved in conflict resolution, the observed theta decrease could be a direct consequence of the reorganisation of the language system. However, further investigations are needed to shed more light on the relation between both processes.

Chapter 6
General Discussion

The primary aim of the thesis was to show that the uncertainty associated with the interpretation of different ERP components, specifically the N400, can be resolved by means of *frequency-analytical* dissociations. To this end, we introduced a new analysis technique for EEG research on human language comprehension, which supplements ERP measures with corresponding frequency-based analyses. Moreover, we argued that this new method not only allows for a differentiation of ERP components on the basis of activity in distinct frequency bands and underlying dynamic behaviour (in terms of power changes and/or phase locking), but also provides further insights with regard to the functional organisation of the language comprehension system and its inherent complexity. Therefore, in the experimental part of the thesis, we focused on investigating and answering the questions (cf. Introduction), (1) whether it is possible to dissociate two N400 components that are indistinguishable on the surface on the basis of their respective underlying frequency characteristics, (2) whether the processing nature of the 'classical' semantic N400 effect can be characterised by means of its underlying frequency characteristics, and (3) whether it is possible to distinguish the semantic N400 effects from an N400-like effect that appears in response to structure-dependent reanalysis.

6.1 Summary of the experimental findings

In Experiment 1, we reanalysed data from Frisch & Schlesewsky (2001), thereby showing that two N400 effects which are indistinguishable from a surface perspective (i.e. in terms of latency and topography) but clearly of distinct linguistic origin could be dissociated on the basis of their corresponding frequency characteristics. On the one hand, we could correlate evoked activity in two clearly separable frequency ranges with an animacy N400 (upper theta) and an ungrammaticality N400 (lower theta). On the other hand, the results from the different applied delta band measures (PLI and WPow) were taken as an indication of the involvement of different conflict resolution strategies in the two ungrammatical conditions. A higher PLI, as evidence for a more consistent timing across events, was interpreted as a more effective and efficient interaction of various subprocesses involved in the processing of conflicting (and probably unresolvable) information, whereas higher WPow, as a reflection of higher neuronal synchronisation, was accounted for in terms of a higher degree of activity of neuronal populations.

In Experiments 2 - 5 we investigated the processing of antonym relations under different task manipulations. Antonym relations were thought to serve as an optimal means of eliciting lexical-semantic processing, in the sense that antonym primes give rise to a substantial priming effect that is observable as an N400 reduction for the antonym targets in comparison to a control condition. The prime motivation was thereby to elicit a clear monophasic lexical-semantic N400 effect in order to obtain an unbiased estimate of its underlying frequency characteristics. Indeed, we found a substantial N400 effect for the processing of antonyms in comparison to non-antonyms for all experimental manipulations. However, a monophasic N400 was only elicited in Experiment 5, whereas for Experiments 2 and 3 we found a biphasic N400/late positivity pattern. More importantly, we showed that the observed N400 effect was not a monolithic effect, but rather due to the superposition of functionally different frequency components. Task-relevant targets elicited a pronounced increase in *evoked delta power,* which superficially showed up as a *P300-like positivity*. For antonyms (Experiment 2 and 3), this positive component appeared almost simultaneously to the N400 deflection for non-related words, thereby giving rise to a substantial N400 effect. In contrast, for pseudowords (Experiment 5), this positivity appeared subsequently to an N400 and therefore showed up as a pronounced biphasic N400/late positivity component. In addition, we found that, irrespective of the task demands, i.e. judging antonym relations in sentence context (Experiment 2) or as word pairs (Experiment 3), or performing a lexical decision task (Experiment 5), non-related words (and pseudowords in Experiment 5) elicited a pronounced increase in *lower theta evoked power* in comparison to antonyms and related category words in the N400 time range. Therefore, the increase in lower theta evoked power was interpreted as the reflection of an enhanced lexical-semantic processing effort and thus, as a correlate of the 'true' *lexical-semantic N400 priming effect*. Furthermore, the analysis of Experiment 5 revealed a circumscribed increase in evoked delta power for antonyms which was due to a significant increase in phase-locking. We suggested that this might be a reflection of associative or *categorical processes* which are specifically linked to the processing of antonyms (Murphy & Andrew, 1993). Finally, it was shown that the *late positivity complex* which was found only for related and non-related *category violations* in comparison to antonyms (Experiment 2 and group B in Experiment 3) was a correlate of an increased *upper delta evoked power* due to an enhanced phase locking. Because the positivity complex was assumed to be a reflection of processes related to structural processing, we suggested that it might be regarded as an instance of the repair-related P600 which was observed in response to the outright structural violations in Experiment 3. Hence, we speculated that the upper delta evoked power and phase locking increase might be interpreted as an index of final evaluative processes linked to reanalysis processes.

In Experiment 6, we reanalysed data from Bornkessel (2002), who found an N400 effect for the disambiguation of ambiguous sentences towards an object-initial rather than a subject-initial order. This N400 effect was interpreted as a reflection of *enhanced processing costs* due to a *reanalysis* that does not involve any restructuring operations. We showed that the observed reanalysis N400 effect was reflected in an increase in *upper delta evoked power* due to an enhanced *phase locking*. This observation further supported the assumptions based on the findings from Experiments 1, 2, and 3 that an increased upper delta phase locking (as a possible reflection of a *phase resetting* mechanism) might be interpreted as a correlate of *conflict resolution* processes during language processing. Furthermore, we proposed that *upper delta phase locking* should be understood as the *consequence* of the temporal availability of information relevant for final evaluation processes, and thereby presumably might indicate the endpoint of an evaluation process.

In sum, in the present experiments we showed that the N400 effect should not be regarded as a monolithic effect. Depending on the respective task manipulations, the N400 effect appeared as the result of the superposition of (at least) three functionally different frequency band activities: (i) a pronounced evoked delta increase for task-related targets which was observable as a P300-like positive component, (ii) an increase in lower theta activity which presumably reflects the ‘true’ lexical-semantic N400 priming effect, and (iii) a circumscribed increase in evoked delta power due to a significant increase in phase-locking, which might be a reflection of categorical (or associative) processes. Furthermore, we speculated that processes which are related to conflict resolution or final evaluative processes (diagnosis or reanalysis) might be reflected in upper delta phase locking, which may be observable superficially as a late positivity complex.

6.2 Evaluation of the experimental findings with regard to the primary aim of the thesis

With regard to the three questions posed in the introductory chapter, the following conclusions can be drawn: (1) in Experiment 1 we showed that two superficially indistinguishable N400 components can be distinguished on the basis of activity in distinct frequency bands; (2) in Experiments 2, 3, and 5 we showed that the 'classical' semantic N400 priming effect must be understood as the result of an interaction or superposition of different processes which, however, can be characterised on the basis of their respective underlying frequency dynamics; thereby we suggested that the portion of the N400 effect which seemed to reflect 'true' lexical-semantic processes might be linked to the lower theta frequency band;[1] (3) finally, in Experiment 5 we showed that an N400 effect which appeared in response to reanalysis processes could be clearly distinguished from a semantic N400 effect by means of its underlying frequency characteristics.

Furthermore, we also argued that the task-related positive shift observed for antonyms in Experiments 2 and 3 might be due to a superimposed positivity which was suggested to be functionally similar to the late positive component which we observed for pseudowords in Experiment 5. These speculations were based on the findings from the corresponding frequency analysis that both effects not only appeared to be due to an evoked power increase in the same frequency band but also revealed the same underlying frequency dynamics in terms of whole power and phase locking increase. Moreover, we speculated that both evoked delta power increases which were observable superficially as positive deflections might be the reflection of a P300-like positivity. However, taking these speculations seriously - at least for the moment – these findings would suggest that superficially distinct ERP effects might 'share' similar underlying processing characteristics, i.e. they might be partially due the same underlying functional processes.

Even more speculative is the proposal from Experiment 6. There, we suggested that two superficially clearly distinct ERP effects, an N400 effect and a late P600-like positivity, might be the reflection of the same underlying frequency dynamics (qualitatively and quantitatively). More specifically, we speculated that the obvious difference in latency and polarity between both components could be explained by a temporal difference in phase

---

[1] In addition, we suggested that there might also be a reflection of conceptual priming processes for antonyms in comparison to related category words (cf. Chapter 4.4).

locking (phase resetting) of the same underlying upper delta frequency activation. However, we must stress that this speculation is only based on theoretical considerations and thus the link between both ERP effects is merely by analogy. Nevertheless, the implications which would follow from these speculations are straightforward: the proposed frequency-analytical measures would not only be able to functionally dissociate superficially indistinguishable ERP effects/components, but, furthermore, they would provide a first clue that two ERP effects/components which appeared superficially as clearly distinct entities, might nevertheless have been due to the same underlying processes. In this way, the superficial distinctiveness would not be a reflection of a mere functional difference but, instead, would index a procedural difference, i.e. in terms of the temporal dynamics (e.g. in terms of availability of information). Such a reinterpretation, however, would also clearly have consequences for models of language processing.

6.3 Open questions and outlook

Although our findings provided ample evidence for the benefit of the proposed frequency-analytical approach, there are clearly several open questions and shortcomings which are, however, beyond the scope of this thesis. Nevertheless, we will discuss some of these in the following.

The focus of this thesis was the investigation of the question whether language-related ERP effects can be dissociated and characterised by means of their underlying frequency dynamics, i.e. the primary aim was clearly a methodological one. Therefore, in a first step, we confined our analysis to the investigation of evoked power changes (as a *direct* estimation of ERP effects in the frequency domain). As pointed out in Chapter 2, ERPs and their respective EPow are insofar equivalent because both measures are representations of the same signal. In the second step, we further described the observed EPow differences as the consequence of amplitude and/or phase modulations. Thus, we didn’t focus on induced activity differences and therefore cannot preclude that, in addition to the present findings, there were differences in induced activations in higher frequency ranges which correlate with our task manipulations, although the visual inspection of the time-frequency difference plots revealed no systematic effects in the higher frequency ranges.

We repeatedly stressed that the individual adjustment of frequency bands is a necessary prerequisite to detect stimulus specific activity changes especially with regard to the alpha frequency range (cf. Chapter 2). However, because the focus of our analysis was the investigation of ERP effects, we argued that an individual adjustment of frequency bands according to IAF might even blur a characterisation of the underlying frequency dynamics. Nevertheless, interindividual differences in IAF might have led to a superposition of functionally different frequencies or sub-bands (e.g. in the alpha range). Note that this objection does not affect the interpretation of the present differential analysis. However, it might have distorted the functional assignment of specific frequency bands, especially with regard to the (upper) theta frequency range.[2] Moreover, due to an antidromic reactivity of different frequency bands in response to stimulus processing (e.g. theta synchronisation vs. alpha desynchronisation), opposite effects might have been cancelled out. Of course, this objection might also concern between-subject comparisons. Hence, one should be cautious to simply equate findings (i.e. 'responsive' frequency bands) from different sub-populations without considering additional parameters (e.g. degree of phase locking).

A further issue that is beyond the scope of this thesis concerns the question of how the present language-related frequency band correlates might relate to findings from other cognitive domains (e.g. with regard to the observed theta frequency effect and findings from memory research).[3]

Finally, we didn't discuss the present findings (and the rather speculative implications based upon) in the light of current models of language processing, neither with regard to a general neurocognitive model of language processing (Friederici, 1999, 2002), nor in relation to more specific models of priming (e.g. Neely, 1991). However, although we believe that even these preliminary findings might entail far-ranging consequences for language processing

---

[2] In Experiment 1, we distinguished an *animacy N400,* which was reflected in the *upper theta band* (~6-7.5 Hz), from an *ungrammaticality N400,* which was reflected in the *lower theta band* (~3.5-5 Hz). Yet, we cannot exclude that the difference in *upper theta* activity actually is confounded with *lower alpha* activity (or even might be due to it). However, this objection would clearly not affect the language-related functional allocation, although it might affect its interpretation with regard to possible underlying cognitive processing mechanisms (i.e. as a possible reflection of memory-related or attentional processes).

[3] One question, for example, would be whether the increased lower theta evoked power for non-related category words in Experiments 2, 3, and 5 might be a reflection of processes which are related to long term memory (access, search, or retrieval) or to working memory processes.

modelling, we concede that their interpretation is still open to speculations and, therefore, we acknowledge that it is much too early to arrive at cogent conclusions. Therefore, to obtain a more exact frequency-analytical classification and specification of the observed findings in order to arrive at a more detailed functional interpretation, further experimental investigations are necessary.

References

Altenmüller, E. O. and Gerloff, C. (1999). Psychophysiology and the EEG. In: E. Niedermeyer & F. Lopes da Silva (Eds.), *Electroenecphalography: basic principles, clinical applications, and related fields* (4th ed.). Baltimore: Williams & Wilkins.

Andersen, P. & Andersson, S.A. (1968). *Physiological Basis of the Alpha Rhythm*. New York: Appleton-Century-Crofts.

Bader, M. & Meng, M. (1999). Subject-object ambiguities in German embedded clauses: An across-the-board comparison. *Journal of Psycholinguistic Research*, *28*, 121-143.

Ball, G.J., Gloor, P., & Schaul, N. (1977). The cortical electromicrophysiology of pathological delta waves in the electroencephalogram of cats. *Clinical Neurophysiology*, *43*, 346-361.

Balota, D.A. (1994). Visual word recognition. In: M.A. Gernsbacher (ed.), *Handbook of Psycholinguistics* (pp.303-358). Academic Press: New York.

Barlow, J.S. (1957). An electronic method for detecting evoked responses of the brain and for reproducing their average waveforms. *Electroencephalography and Clinical Neurophysiology*, *9*, 340-343.

Barlow, J.S. (1997). The early history of EEG data-processing at the Massachusetts Institute of Technology and the Massachusetts General Hospital. *International Journal of Psychophysiology*, *26*, 443-454.

Barrett, S. E. & Rugg, M. D. (1990). Event-related potentials and the semantic matching of pictures. *Brain and Cognition*, *14*, 201-212.

Basar, E. (1980). *EEG-brain dynamics. Relation between EEG and brain evoked potentials*. Amsterdam: Elsevier.

Basar, E. (1998). *Brain function and oscillations. I. Brain oscillations: Principles and approaches*. Berlin: Springer.

Basar, E. (1999). *Brain function and oscillations. II. Integrative Brain Function. Neurophysiology and Cognitive Processes*. Berlin: Springer.

Basar, E., Hari, R., Lopes da Silva, F.H., & Schürmann, M. (eds.) (1997). Brain Alpha Activity – New Aspects and Functional Correlates. Special issue. *International Journal of Psychophysiology*, *26*.

Basar, E., Basar-Eroglu, C., Karakas, S. & Schürmann, M. (2001). Gamma, alpha, delta, and theta oscillations govern cognitive processes. *International Journal of Psychophysiology*, *39*, 241-248.

Basar-Eroglu, C., Basar, E., Demiralp, T. & Schürmann, M. (1992). P300-response: possible psychophysiological correlates in delta and theta frequency channels. A review. *International Journal of Psychophysiology*, *13*, 161-179.

Bastiaansen, M.C.M. (2000). *Anticipatory attention, an event-related desynchronization approach*. Unpublished doctoral dissertation, University of Brabant.

Bastiaansen, M.C.M., van Berkum, J.J.A., & Hagoort, P. (2002a). Event-related theta power increases in the human EEG during online sentence processing. *Neuroscience Letters*, *323*, 13-16.

Bastiaansen, M.C.M, van Berkum, J.J.A., & Hagoort, P. (2002b). Syntactic processing modulates the θ rhythm of the human EEG. *NeuroImage*, *17*, 1479-1492.

Beck, A. (1890a). Die Bestimmung der Localisation der Gehirn- und Rückenmarksfunctionen vermittelst der elektrischen Erscheinungen. *Centralblatt für Physiologie*, *4*, 473-476.

Beck, A. (1890b). Die Ströme der Nervencentren. *Centralblatt für Physiologie*, *4*, 572-573.

Becker, C.A. (1980). Semantic context effects in visual word recognition: An analysis of semantic strategies. *Memory & Cognition*, *8*, 493-512.

beim Graben, P., Saddy, J.D., & Schlesewsky, M. (2000). Symbolic dynamics of event-related brain potentials. *Physical Review E*, *62*, 5518-5541.

Bendat, J.S. & Piersol, A.G. (1986) *Random Data: Analysis and Measurement Procedures*. 2nd ed. New York: Wiley.

Bentin, S., McCarthy, G. & Wood, C.C. (1985). Event-related potentials, lexical decision and semantic priming. *Electroencephalography and Clinical Neurophysiology*, *60*, 343-355.

Berger, H. (1929). Über das Elektroenkephalogramm des Menschen. 1. Mitteilung. *Archiv für Psychiatrie*, *87*, 527-570.

Berger, H. (1932). Über das Elektroenkephalogramm des Menschen. 4. Mitteilung. *Archiv für Psychiatrie*, *97*, 6-26.

Berger, H. (1938). *Das Elektroenkephalogramm des Menschen*. Halle: Nova Acta Leopoldina. Abhandlungen der kaiserlich-carolinisch deutschen Akademie der Naturforscher, Neue Folge, Bd. 6., *38*, 173-309.

Bertrand, O. & Tallon-Baudry, C. (2000). Oscillatory gamma activity in humans: a possible role for object representation. *International Journal of Psychophysiology*, *38*, 211-223.

Besson, M. & Macar, F. (1987). An event-related potential analysis of incongruity in music and other non-linguistic contexts. *Psychophysiology*, *24*, 14-25.

Bizas, E., Simos, P.G., Stam, C.J., Arvanitis, S., Terzakis, D., & Micheloyannis, S. (1999). EEG correlates of cerebral engagement in reading. *Brain Topography*, *12*, 99-105.

Bland, B.H. (1986). The physiology and pharmacology of hippocampal formation theta rhythms. *Progress in Neurobiology*, *26*, 1-54.

Bloom, P.A. & Fischler, I. (1980). Completion norms for 329 sentence contexts. *Memory and Cognition*, *8*(6), 631-642.

Bódizs, R., Kántor, S., Szabó, G., Szûcs, A., Erõss, L., & Halász, P. (2001). Rhythmic hippocampal slow oscillation characterizes REM sleep in humans. *Hippocampus*, *11*, 747-753.

Bornkessel, I. (2002). *The Argument Dependency Model: A Neurocognitive Approach to Incremental Interpretation*. Leipzig: MPI-Series in Cognitive Neuroscience.

Bornkessel, I., Schlesewsky, M., & Friederici, A.D. (2002). Grammar overrides frequency: Evidence from the online processing of flexible word order. *Cognition*, *85*, B21-B30.

Bornkessel, I., McElree, B., Schlesewsky, M. & Friederici, A.D. (submitted). Multidimensional contributions to garden path strength: Dissociating phrase structure from case marking. *Journal of Memory and Language*.

Brandt, M.E. (1997). Visual and auditory evoked phase resetting of the alpha EEG. *International Journal of Psychophysiology*, *26*, 285-298.

Brazier, M.A.B. (1960). Some uses of computers in experimental neurology. *Experimental Neurology*, *2*, 123-142.

Brown, C.M. & Hagoort, P. (1993). The processing nature of the N400: evidence from masked priming. *Journal of Cognitive Neuroscience*, *5*, 34-44.

Brown, C.M. & Hagoort, P. (1999). *The Neurocognition of Language*. New York: Oxford University Press.

Brualla, J., Romero, M.F., Serrano, M. & Valdizán, J.R. (1998). Auditory event-related potentials to semantic priming during sleep. *Electroencephalography and Clinical Neurophysiology*, *108*, 283-290.

Bullock, T.H. & Achimowicz, J.Z. (1994). A comparative survey of oscillatory brain activity, especially gamma-band rhythms. In: C. Pantev, T. Elbert, & B. Lütkenhöner (eds.), *Oscillatory Event Related Brain Dynamics* (pp. 11-26). New York: Plenum Press.

Bullock, T.H., McClune, M.C., & Enright, J.T. (2003). Are the electroencephalograms mainly rhythmic? Assessment of periodicity in wide-band time series. *Neuroscience*, *121*, 233-252.

Burgess, A.P. & Gruzelier, J.H. (2000). Short duration power changes in the EEG during recognition memory for words and faces. *Psychophysiology*, *37*, 596-606.

Buzsáki, G. (1998). Memory consolidation during sleep: a neurophysiological perspective. *Journal of Sleep Research*, *7*, 17-23.

Caplan, J.B., Madsen, J.R., Raghavachari, S., & Kahana, M.J. (2001). Distinct patterns of brain oscillations underlie two basic parameters of human maze learning. *Journal of Neurophysiology*, *86*, 368-380.

Caton, R. (1875). The electric currents of the brain. *British Medical Journal*, *2*, 278.

Chang, T.M. (1986). Semantic memory: facts and models. *Psychological Bulletin*, *99*, 199-220.

Chwilla, D.J., Brown, C.M. & Hagoort, P. (1995). The N400 as a function of the level of processing. *Psychophysiology*, *32*, 274-285.

Chwilla, D.J., Kolk, H.H.J., & Mulder, G. (2000). Mediated Priming in the Lexical Decision Task: Evidence from Event-Related Potentials and Reaction Time. *Journal of Memory and Language*, *42*, 314-341.

Clark, W.A. (1987). The LINC was early and small. In: B.I. Blum (ed.), *History of Medical Informatics. Proceedings of ACM conference on History of medical informatics* (pp. 51-73). New York: ACM Press.

Clark, W.A., Brown, R.M., Goldsetin, M.H., Molnar, C.E., O'Brian, D.F., & Zieman, H.E. (1961). The Average Response Computer (ARC): A Digital Device for Computing Averages and Amplitude and Time Histograms of Electrophysiological Responses. *IRE Trans. Biomed. Electronics*, BME-*8*, 46-51.

Clifton, C., Frazier, L., & Rayner, K. (Eds.) (1994). *Perspectives on Sentence Processing*. Hillsdale: Lawrence Erlbaum.

Coenen, A., Zajachkivsky, O., & Bilski, R. (1998). In the footsteps of Beck: the desynchronization of the electroencephalogram. *Electroencephalography and Clinical Neurophysiology*, *106*, 330-335.

Collins, A.M. & Quillian, M.R. (1969). Retrieval time from semantic memory. *Journal of Verbal Learning and Verbal Behaviour*, *8*, 240-247.

Cooley, J.W. & Tukey, J.W. (1965). An algorithm for the machine calculation of complex Fourier series. *Mathematics of Computation*, *19*, 267-301.

Coulson, S., King, J. & Kutas, M. (1998). Expect the unexpected: event-related brain responses of morphosyntactic violations. *Language and Cognitive Processes*, *13*, 21-58.

Craik, F.I. & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, *6*, 671-84.

Cruse, D.A. (1991). Antonymy revisited: Some thoughts on the relationship between words and concepts. In: A. Lehrer & E.F. Kittay (eds.), *Frames, fields, and contrasts: New essays in semantic and lexical organization* (pp. 289-306). Hillsdale, NJ: Erlbaum.

Danilewsky, W.Y. (1877). *Investigations into the physiology of the brain*. Doctoral thesis, University of Charkov.

Davidson, R.J., Chapman, J.P., Chapman, L.J., & Henriques, J.B. (1990). Asymmetrical brain electrical activity discriminates between psychometrically-matched verbal and spatial cognitive tasks. *Psychophysiology*, *27*, 528-543.

Dawson, G. D. (1951). A summation technique for detecting small signals in a large irregular background. *Journal of Physiology*, *115*, 2-3.

Dawson, G. D. (1954). A summation technique for the detection of small evoked potentials. *Electroencephalography and Clinical Neurophysiology*, *6*, 153-154.

de Vincenzi, M. (1991). *Syntactic parsing strategies in Italian*. Dordrecht: Kluwer Academic Publishers.

Deacon, D., Hewitt, S., Yang, C.M. & Nagata, M. (2000). Event-related potential indices of semantic priming using masked and unmasked words: evidence that the N400 does not reflect a post-lexical process. *Cognitive Brain Research*, *9*, 137-146.

Deacon, D., Dynowska, A., Ritter, W. & Grose-Fifer, J. (2004). Repetition and semantic priming of nonwords: Implications for theories of N400 and word recognition. *Psychophysiology*, *41*, 60-74.

Demiralp, T. Ademoglu, A., Schürmann, M., Basar-Eroglu, C., & Basar, E. (1999). Detection of P300 waves in single trials by the wavelet transform (WT). *Brain and Language*, *66*, 108-128.

Dietsch, G. (1932). Fourier-Analyse von Elektroenkephalogrammen der Menschen. *Pflügers Arch. f. d. ges. Physiol.*, *230*, 106-112.

Donchin, E., McCarthy, G., & Kutas, M. (1977). Electroencephalographic investigations of hemispheric specialization. In: J.E. Desmedt (ed.), Language and hemispheric specialization in man: Cerebral ERPs (pp. 212-242). *Prog. Clin. Neurophysiol., vol.3*. Basel: Karger.

Donchin, E. & Coles, M.G.H. (1988). Is the P300 component a manifestation of context updating ? *Behavioral and Brain Science*, *11*, 355-372.

Doppelmayr, M., Klimesch, W., Pachinger, T., & Ripper, B. (1998). Individual differences in brain dynamics: important implications for the calculation of event-related band power. *Biological Cybernetics*, *79*, 49-57.

Doppelmayr, M., Klimesch, W., Schwaiger, J., Stadler, W., & Röhm, D. (2000). The time locked theta response reflects interindividual differences in human memory performance. *Neuroscience Letters*, *278*, 141-144.

Doppelmayr, M., Klimesch, W., Stadler, W., Pöllhuber, D., & Heine, C. (2002). EEG alpha power and intelligence. *Intelligence*, *30*, 289-302.

Dosher, B.A. (1976). The retrieval of sentences from memory: A speed accuracy study. *Cognitive Psychology*, *8*, 291-310.

Eckhorn, R., Bauer, R., Jordan, W., Brosch, M., Kruse, W., Munk, M., & Reitbeck, H.J. (1988). Coherent oscillations: A mechanism of feature linking in the visual cortex? Multiple electrode and correlation analysis in the cat. *Biological Cybernetics*, *60*, 121-130.

Elul, R. (1972). The genesis of the EEG. *International Review of Neurobiology*, *15*, 227-272.

Eulitz, C., Maess, B., Pantev, C., Friederici, A., Feige, B., & Elbert, T. (1996). Oscillatory neuromagnetic activity induced by language and non-language stimuli. *Cognitive Brain Research*, *4*, 121-132.

Eulitz, C., Eulitz, H., Maess, B., Cohen, R., Pantev, C., & Elbert, T. (2000). Magnetic brain activity evoked and induced by visually presented words and nonverbal stimuli. *Psychophysiology*, *37*, 447-455.

Evans, C.R. & Mulholland, T.B. (1969). *Attention in Neurophysiology*. London: Butterworths.

Federmeier, K.D. & Kutas, M. (1999a). A rose by any other name: long-term memory structure and sentence processing. *Journal of Memory and Language*, *41*, 469-495.

Federmeier, K.D. & Kutas, M. (1999b). Right words and left words: electrophysiological evidence for hemispheric differences in meaning processing. *Cognitive Brain Research*, *8*, 373-392.

Fiebach, C.J. (2001). *Working memory and syntax during sentence processing: A neurocognitive investigation with event-related brain potentials and functional magnetic resonance imaging*. MPI-Series in Cognitive Neuroscience, 23.

Fiebach, C.J., 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*, 321-338.

Fischler, I., Bloom, P.A., Childers, D.G., Roucos, S.E., & Perry, N.W. (1983). Brain potentials related to stages of sentence verification. *Psychophysiology*, *20*, 400-409.

Fischler, I., Bloom, P.A., Childers, D.G., Arroyo, A.A. & Perry, N.W. (1984). Brain potentials during sentence verification: late negativity and long-term memory strength. *Neuropsychologia*, *22*, 559-568.

Fitts, P.M. (1954). The information capacity of descrete motor responses. *Journal of Experimental Psychology*, *67*, 103-112.

Fodor, J.A., Bever, T.G., & Garrett, M.F. (Eds.) (1974). The Psychology of Language: An Introduction to Psycholinguistics in Generative Grammar. New York : McGraw-Hill.

Fodor, J.D. & Inoue, A. (1998). Attach anyway. In: J.D. Fodor & F. Ferreira (eds.), *Reanalysis in sentence processing* (pp. 101-141). Dordrecht: Kluwer.

Frazier, L. (1987). Sentence processing. A tutorial review. In: M. Coltheart (Ed.), Attention and Performance XII (pp 559-586). Hove: Lawrence Erlbaum.

Frazier, L. & Flores d'Arcais, G.B. (1989). Filler driven parsing : A study of gap filling in Dutch. *Journal of Memory and Language*, 28, 331-344.

Freeman, W.J. (1975). *Mass action in the nervous system*. New York: Academic Press.

Freeman, W.J. & van Dijk, B.W. (1987). Spatial patterns of visual cortical fast EEG during conditioned refelex in a rhesus monkey. *Brain Research*, *422*, 267-276.

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. (1999).The Neurobiology of Language Comprehension. In: A.D. Friederici (Ed.), *Language Comprehension: A Biological Perspective* (2nd Ed.). Berlin, Heidelberg, New York: Springer, 265-304.

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

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

Friederici, A.D., Hahne, A. & Mecklinger, A. (1996). The temporal structure of syntactic parsing: Event-related potentials during speech perception and word-by-word reading. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *22*, 1219-1248.

Friederici, A.D. & Mecklinger, A. (1996). Syntactic parsing as revealed by brain responses: First pass and second pass parsing processes. *Journal of Psycholinguistic Research*, *25*, 157-176.

Friederici, A.D., Steinhauer, K., Mecklinger, A. & Meyer, M. (1998). Working memory constraints on syntactic ambiguity resolution as revealed by electrical brain responses. *Biological Psychology*, *47*, 193-221.

Friederici, A.D., Mecklinger, A., Spencer, K.M., Steinhauer, K., & Donchin, E. (2001) Syntactic parsing preferences and their on-line revisions: A spatio temporal analysis of event-related brain potentials. *Cognitive Brain Research*, *11*, 305-323.

Friederici, A.D., Hahne, A. & Saddy, D. (2002). Distinct neurophysiological patterns reflecting aspects of syntactic comlexity and syntactic repair. *Journal of Psycholinguistic Research*, *31*, 45-63.

Friederici, A.D. & Meyer, M. (in press). The brain knows the difference. Tow types of grammatical violations. *Cognitive Brain Research*.

Frisch, S. & Schlesewsky, M. (2001). The N400 indicates problems of thematic hierarchizing. *NeuroReport*, *12*, 3391-3394.

Galambos, R. (1992). A comparison of certain gamma band (40 Hz) rhythms in cat and man. In: E. Basar & T.H. Bullock (eds.), *Induced Rhythms in the Brain* (pp 201-216). Basel: Birkhauser.

Galambos, R., Makeig, S., & Talmachoff, P. (1981). A 40 Hz auditory potential recorded from the human scalp. *Proceedings of the National Academy of Sciences USA*, *78*, 2643-47.

Ganis, G., Kutas, M. & Sereno, M.I. (1996). The search for ‘Common Sense’: An electrophysiological study of the comprehension of words and pictures in reading. *Journal of Cognitive Neuroscience*, *8*, 89-106.

Garnsey, S.M. (1993). Event-related brain potentials in the study of language: An introduction. *Language and Cognitive Processes*, *8*, 337-356.

Gevins, A., Smith, M.E., McEvoy, L., & Yu, D. (1997). High-resolution EEG mapping of cortical activation related to working memory: effects of task difficulty, type of processing, and practice. *Cerebral Cortex*, *7*, 374-385.

Giannitrapani, D. (1971). Scanning mechanisms and the EEG. *Electroencephalography and Clinical Neurophysiology*, *30*, 139-146.

Givens, B. (1996). Stimulus-evoked resetting of the dentate theta rhythm: relation to working memory. *NeuroReport*, *8*, 159-163.

Gray, C.M. & Singer, W. (1987). Stimulus-dependent neuronal oscillations in the cat visual cortex area 17. 2nd IBRO-Congrs., *Neuroscience Suppl.*, 1301P.

Gray, C.M., Engel, A.K., König, P., & Singer, W. (1990). Stimulus-dependent neuronal oscillations in cat visual cortex: receptive field properties and feature dependence. *European Journal of Neuroscience*, *2*, 607-619.

Gunter, T.C., Stowe, L.A. & Mulder,G. (1997). When syntax meets semantics. *Psychophysiology*, *34*, 660-76.

Gunter, T.C. & Friederici, A.D. (1999). Concerning the automaticity of syntactic processing. *Psychophysiology*, *36*, 126-37.

Gunter, T.C, Friederici, A.D. & Hahne, A. (1999). Brain responses during sentence reading: visual input affects central processes. *NeuroReport*, *10*, 3175-3178.

Gunter, T.C., Friederici, A.D. & Schriefers, H. (2000). Syntactic gender and semantic expectancy: ERPs reveal early autonomy and late interaction. *Journal of Cognitive Neuroscience*, *12*, 556-568.

Guyton, A.C. (1976). *Organ physiology: structure and function of the nervous system*. London: Saunders.

Haberlandt, K. (1994). Methods in reading research. In: M.A. Gernsbacher (ed.), *Handbook of Psycholinguistics*. San Diego: Academic Press.

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

Hagoort, P., Brown, C.M. & Osterhout, L. (1999). The neurocognition of syntactic processing. In: C.M. Brown & P. Hagoort, P. (eds.), *The Neurocognition of Language*. New York: Oxford University Press.

Hahne, A. (2001). What's different in second-language processing? Evidence from event-related brain potentials. *Journal of Psycholinguistic Research*, *30*, 251-166.

Hahne, A. & Friederici, A.D. (1997). Two stages in parsing: early automatic and late controlled processes. *Experimental Brain Research*, *117*, 47.

Hahne, A. & Friederici, A.D. (1998). ERP-evidence for autonomous first-pass parsing processes in auditory language comprehension. *Journal of Cognitive Neuroscience, Abstracts Supplement*, 125.

Hahne, A. & Friederici, A.D. (1999) Electrophysiological evidence for two steps in syntactic analysis: Early automatic and late controlled processes. *Journal of Cognitive Neuroscience*, *11*, 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*, 199-212.

Hahne, A. & Friederici, A.D. (2002). Differential task effects on semantic and syntactic processes as revealed by ERPs. *Cognitive Brain Research*, *13*, 339-356.

Haider, H. & Rosengren, I. (2003). Scrambling: Nontriggered chain formation in OV languages. *Journal of Germanic Linguistics*, *15*, 203-267.

Haig, A.R., Gordon, E., Wright, J.J., Meares, R.A., & Bahramali, H. (2000). Synchronous cortical gamma-band activity in task-relevant cognition. *NeuroReport*, *11*, 669-675.

Hari, R., Salmelin, R., Mäkelä, J.P., Salenius, S. & Helle, M. (1997). Magnetoencephalographic cortical rhythms. *International Journal of Psychophysiology*, *26*, 51-62.

Harmony, T., Fernandez, T., Silva, J., Bernal, J., Diaz-Comas, L., Reyes, A., Marosi, E., Rodriguez, M., & Rodriguez, M. (1996). EEG delta activity: an indicator of attention to internal processing during performance of mental tasks. *International Journal of Psychophysiology*, *24*, 161-171.

Hill, H., Strube, M. Roesch-Ely, D. & Weisbrod, M. (2002). Automatic vs. controlled processes in semantic priming – differantiation by event-related potentials. *International Journal of Psychophysiology*, *44*, 197-218.

Hobson, J.A. (1988). *The dreaming brain. How the brain creates both the sense and the nonsense of dreams*. New York: Basic Books.

Holcomb, P.J. (1988). Automatic and attentional processing: an event-related brain potential analysis of semantic priming. *Brain and Language*, *35*, 66-85.

Holcomb, P.J. & Neville, H. J. (1990). Auditory and visual semantic priming in lexical decision: A comparison using event-related brain potentials. *Language and Cognitive Processes*, *5*, 281-312.

Hopf, J.-M., Bayer, J., Bader, M. & Meng, M. (1998). Event-related brain potentials and case information in syntactic ambiguities. *Journal of Cognitive Neuroscience*, *10*, 264-280.

Huyn, H. & Feldt, L.S. (1970). Conditions under which the mean square ratios in repeated measurement designs have exact F-distributions. *Journal of the American Statistical Association*, *65*, 1582-1589.

Jemel, B., George, N., Olivares, E., Fiori, N., & Renault, B. (1999). Event-related potentials to structural familiar face incongruity processing. *Psychophysiology*, *36*, 437–452.

Jervis, B.W., Nichols, M.J., Johnson, T.E., Allen, E., & Hudson, N.R. (1983). A fundamental investigation of the composition of auditory evoked potentials. *IEEE Transactions on Biomedical Engineering*, *30*, 43-50.

Jürgens, E. & Rösler, F. (1995). How do alpha oscillations influence gamma band activity? Commentary on Pulvermüler et al. on brain-rhythms. *Psycoloquy*, *6*(09), Brain Rhythms (10).

Jürgens, E., Rösler, F., Hennighausen, E., & Heil, M. (1995). Stimulus induced gamm oscillations: harmonics of alpha activity? *NeuroReport*, *6*, 813-816.

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

Kahana, M.J., Sekuler, R., Caplan, J.B., Kirschen, M., & Madsen, J.R. (1999). Human theta oscillations exhibit task dependence during virtual maze navigation. *Nature*, *399*, 781-784.

Kahana, M.J., Seelig, D. & Madsen J.R. (2001). Theta returns. *Current Opinion in Neurobiology*, *11*, 739-744.

Kalcher, J. & Pfurtscheller, G. (1995). Discrimination between phase-locked and non-phase-locked event-related EEG activity. *Electroencephalography and Clinical Neurophysiology*, *94*, 381-384.

Kaufman, L., Schwartz, B., Salustri, C., & Williamson, S.J. (1989). Modulation of spontaneous brain activity during mental imagery. *Journal of Cognitive Neuroscience*, *2*, 124-132.

Keppel, G. (1991). *Design and analysis: A researchers handbook* (3rd Edition). Englewood Cliffs, NJ: Prentice Hall.

Khader, P., Scherag, A., Streb, J., & Rösler, F. (2003). Differences between noun and verb processing in a minimal phrase context: a semantic priming study using event-related brain potentials. *Cognitive Brain Research*, *17*, 293-313.

Khader, P. & Rösler, F. (2004). EEG power and coherence analysis of visually presented nouns and verbs reveals left frontal processing differences. *Neuroscience Letters*, *354*, 111-114.

Kiefer, M. (2002). The N400 is modulated by unconsciously perceived masked words: further evidence for an automatic spreading activation account of N400 priming effects. *Cognitive Brain Research*, *13*, 27-39.

Kiefer, M., Weisbrod, M., Kern, I., Maier, S. & Spitzer, M. (1998). Right hemisphere activation during indirect semantic priming: evidence from event-related potentials. *Brain and Language*, *64*, 377-408.

Kimball, J. (1973). Seven principles of surface structure parsing in natural language. *Cognition*, *2*, 15-47.

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.

Kirschfeld, K. (1992). Oscillations in the Insect Brain: Do they Correspond to the Cortical γ-Waves of Vertebrates? *Proceedings of the National Academy of Sciences USA*, *89*, 4764-4768.

Kirschfeld, K. (1995). Neuronal oscillations and synchronized activity in the central nervous system: functional aspects. *Psycoloquy*, *6*(36), 1-6.

Klimesch, W. (1996). Memory processes, brain oscillations and EEG synchronization. *International Journal of Psychophysiology*, *24*, 61-100.

Klimesch, W. (1997). EEG-alpha rhythms and memory prcocesses. *Journal of Psychophysiology*, *26*, 319-340.

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain Research Reviews*, *29*, 169-195.

Klimesch, W., Pfurtscheller, G., Mohl, W. & Schimke, H. (1990). Event-related desynchronization, ERD-mapping and hemispheric differences for words and numbers. *International Journal of Psychophysiology*, *8*, 297-308.

Klimesch, W., Schimke, H., Ladurner, G., & Pfurtscheller, G. (1990). Alpha frequency and memory performance. *Journal of Psychophysiology*, *4*, 381-390.

Klimesch, W., Pfurtscheller, G., & Schimke, H. (1992). Pre- and poststimulus processes in category judgment tasks as measured by event-related desynchronization (ERD). *Journal of Psychophysiology*, *6*, 186-203.

Klimesch, W., Schimke, H., Pfurtscheller, G. (1993). Alpha frequency, cognitive load and memory performance. *Brain Topography*, *5*, 1-11.

Klimesch, W., Schimke, H., & Schwaiger, J. (1994). Episodic and semantic memory: an analysis in the EEG theta and alpha band. *Clinical Neurophysiology*, *91*, 428-441.

Klimesch, W., Doppelmayr, M., Pachinger, T., & Russegger, H. (1996). Theta band power in the human scalp EEG and the encoding of new information. *NeuroReport*, *7*, 1235-1240.

Klimesch, W., Doppelmayr, M., Pachinger, T., & Ripper, B. (1997). Brain oscillations and human memory: EEG correlates in the upper alpha and theta band. *Neuroscience Letters*, *238*, 9-12.

Klimesch, W., Doppelmayr, M., Pachinger, T., & Russegger, H. (1997). Event-related desynchronization in the alpha band and the processing of semantic information. *Cognitive Brain Research*, *6*, 83-94.

Klimesch, W., Doppelmayr, M., Schimke, H., & Ripper, B. (1997). Theta synchronization in a memory task. *Psychophysiology*, *34*, 169-176.

Klimesch, W., Doppelmayr, M., Russegger, H., Pachinger, T., & Schwaiger, J. (1998). Induced alpha band power changes in the human EEG and attention. *Neuroscience Letters*, *244*, 73-76.

Klimesch, W., Russegger, H., Doppelmayr, M. & Pachinger, T. (1998). A method for the calculation of induced band power: implications for the significance of brain oscillations. *Electroencephalography and Clinical Neurophysiology*, *108*, 123-130.

Klimesch, W., Doppelmayr, M., Schwaiger, J., Auinger, P., & Winkler, T. (1999). ‚Paradoxical' alpha synchronization in a memory task. *Cognitive Brain Research*, *7*, 493-501.

Klimesch, W., Schack, B., Schabus, M., Doppelmayr, M., Gruber, W., & Sauseng, P. (2004). Phase-locked alpha and theta oscillations generate the P1-N1 complex and are related to memory performance. *Cognitive Brain Research*, *19*, 302-316.

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

Kluender, R. & Kutas, M. (1993b). Subjacency as a processing phenomenon. *Language and Cognitive Processes*, *8*, 573-633.

Kouider, S. & Dupoux, E. (2001). A functional disconnection between spoken and visual word recognition: evidence from unconscious priming. *Cognition*, *82*, B35-B49.

Kounios, J. & Holcomb, P.J. (1992). Structure and process in semantic memory: evidence from event-related brain potentials and reaction times. *Journal of Experimental Psychology*, *121*, 460-480.

Krause, C.M., Sillanmäki, L., Koivisto, M., Saarela, C., Häggqvist, A., Laine, M., & Hämäläinen, H. (2000). The effects of memory load on event-related EEG desynchronization and synchronization. *Clinical Neurophysiology*, *111*, 2071-2078.

Kristeva-Feige, R., Feige, B., Makeig, S., Ross, B., & Elbert, T. (1993). Oscillatory brain activity during motor task. *NeuroReport*, *4*, 1291-1294.

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

Kutas, M. & Hillyard, S. A. (1983). Event-related brain potentials to grammatical errors and semantic anomalies. *Memory and Cognition*, *11*, 539-550.

Kutas, M. & Hillyard, S.A. (1984). Brain potentials during reading reflect word expectancy and semantic association. *Nature*, *307*, 161-163.

Kutas, M., Lindamood, T.E. & Hillyard, S.A. (1984). Word expectancy and event-related brain potentials during sentence processing. In: S. Kornblum & J. Requine (Eds.), *Preparatory states and processes*. Hillsdale, N. J.: Erlbaum.

Kutas, M. & Hillyard, S.A. (1989). An electrophysiological probe of incidential semantic association. *Journal of Cognitive Neuroscience*, *1*, 38-49.

Kutas, M. & Van Petten, C.K. (1994). Psycholinguistics electrified. Event-related brain potential investigations. In: M.A. Gernsbacher (ed.), *Handbook of Psycholinguistics* (pp.83-143). Academic Press: New York.

Kutas, M. & Iragui, V. (1998). The N400 in a semantic catgorization task across 6 decades. *Electroencephalography and Clinical Neurophysiology*, *108*, 456-471.

Kutas, M. & Federmeier, K.D. (2000). Electrophysiology reveals semantic memory use in language comprehension. *Trends in Cognitive Sciences*, *4*, 463-470.

Lachaux, J.P., Rodriguez, E., Martinerie, J. & Varela, F.J. (1999). Measuring phase synchrony in brain signals. *Human Brain Mapping*, *8*, 194-208.

Leutgeb, S. & Mizumori, S.J.Y. (1999). Excitotoxic septal lesions result in spatial memory deficits and altered flexibility of hippocampal single-unit representations. *Journal of Neuroscience*, *19*, 6661-6672.

Llinás, R.R. & Ribary, U. (1993). Coherent 40-Hz oscillation characterizes dream state in humans. *Proceedings of the National Academy of Sciences USA*, *90*, 2078-2081.

Llinás, R.R., Leznik, E., & Urbano, F.J. (2002). Temporal binding via cortical coincidence detection of specific and nonspecific thalamocortical inputs: A voltage-dependent dye-imaging study in mouse brain slices. *Proceedings of the National Academy of Sciences USA*, *99*, 449-454.

Lopes da Silva, F. (1999a). Event-related potentials: Methodology and quantification. In: E. Niedermeyer & F. Lopes da Silva (Eds.), *Electroencephalography. Basic principles, clinical applications and related fields* (pp. 947-957). (4th ed.). Baltimore: Williams & Wilkins.

Lopes da Silva, F. (1999b). Dynamics of EEGs as signals of neuronal populations: models and theoretical considerations. In: E. Niedermeyer & F. Lopes da Silva (Eds.), *Electroenecphalography: basic principles, clinical applications, and related fields* (pp. 958-967) (4th ed.). Baltimore: Williams & Wilkins.

Lopes da Silva, F.H., van Lierop, T.H.M.T., Schrijer, C.F.M., & Storm van Leuwen, W. (1973). Organization of thalamic and cortical alpha rhythm: spectra and coherences. *Electroencephalography and Clinical Neurophysiology*, *35*, 627-639.

Lopes da Silva, F.H. & Pfurtscheller, G. (1999). Basic concepts on EEG synchronization and desynchronization. In: G. Pfurtscheller & F.H. Lopes da Silva (eds.), *Event-Related Desynchronization. Handbook of Electroencephalography and Clinical Neurophysiology, Revised Series, Vol. 6*. (pp. 3-11). Amsterdam: Elsevier.

Lutzenberger, W., Pulvermüller, F., & Birbaumer, N. (1994). Words and pseudowords elicit distinct patterns of 30-Hz activity in humans. *Neuroscience Letters*, *176*, 115-118.

Makeig, S., Westerfield, M., Jung, T.P., Enghoff, S., Townsend, J., Courchesne, E. & Sejnowski, T.J. (2002). Dynamic brain sources of visual evoked responses. *Science*, *295*, 690-694.

Marr, D. (1982). *Vision: A computational investigation into the human representation and processing of viusal information*. New York: W.H. Freeman and Company.

McElree, B. (1993). The locus of lexical preference effects in sentence comprehension. *Journal of Memory and Language*, *32*, 536-571.

McElree, B. & Griffith, T. (1995). Syntactic and thematic processing in sentence comprehension. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*, 134-157.

McKee, G., Humphrey, B., & McAdam, D.W. (1973). Scaled lateralization of alpha activity during linguistic and musical tasks. *Psychophysiology*, *10*, 441-443.

McPherson, W.B. & Holcomb, P.J. (1999). An electrophysiological investigation of semantic priming with pictures of real objects. *Psychophysiology*, *36*, 53-65.

Mecklinger, A., Kramer, A., & Strayer, D. (1992). Event-related potentials and EEG components in a semantic memory search task. *Psychophysiology*, *29*, 104-119.

Mecklinger, A., Schriefers, H., Steinhauer, K. & Friederici, A.D. (1995). Processing relative clauses varying on syntactic and semantic dimensions: An analysis with event-related potentials. *Memory & Cognition*, *23*, 477-494.

Meng, M. & Bader, M. (2000). Ungrammaticality detection and garden path strength: Evidence for serial parsing. *Language and Cognitive Processes*, *15*, 615-666.

Menon, R.S. & Kim, S.G. (1999). Spatial and temporal limits in cognitive neuroimaging with fMRI. *Trends in Cognitive Sciences*, *3*, 207-216.

Meyer, D.E. (1970). On the representation and retrieval of stored semantic information. *Cognitive Psychology*, *1*, 242-299.

Meyer, D.E. & Schvaneveldt, R.W. (1971). Facilitation in recognizing pairs of words: evidence of a dependence between retrieval operations. *Journal of Experimental Psychology*, *90*, 227-234.

Miller, R. (1991). *Cortico-Hippocampal Interplay and the Representation of Contexts in the Brain*. Berlin: Springer.

Morrell, L.K. & Salamy, J.G. (1971). Hemispheric Asymmetry of Electrocortical Responses to Speech Stimuli. *Science*, *174*, 164-66.

Moruzzi, G. & Magoun, H.W. (1949). Brain stem reticular formation and activation of the EEG. *Electroencephalography and Clinical Neurophysiology*, *1*, 455-473.

Münte, T. F., Heinze, H. & Mangun, G. R. (1993). Dissociation of brain activity related to syntactic and semantic aspects of language. *Journal of Cognitive Neuroscience*, *5*, 335-344.

Münte, T. F., Matzke, M., & Johannes, S. (1997). Brain activity associated with syntactic incongruencies in words and pseudo-words. *Journal of Cognitive Neuroscience*, *9*, 318-329.

Mulholland, T.B. (1969). The concept of attention and the electroencephalographic alpha rhythm. In: C.R. Evans & T.B. Mulholland (eds.), *Attention in Neurophysiology* (pp. 100-127). London: Butterworths.

Murphy, G.L. & Andrew, J.M. (1993). The Conceptual Basis of Antonymy and Synonymy in Adjectives. *Journal of Memory and Language*, *32*, 301-319.

Murphy, M.L. (2003). *Semantic Relations and the Lexi*con. Antonymy, Synonymy and other Paradigms. Cambridge: University Press.

Neely, J.H. (1977). Semantic priming and retrieval from lexical memory: roles of inhibitionless spreading activation and limited-capacity attention. *Journal of Experimental Psychology*, *106*, 226-254.

Neely, J.H. (1991). Semantic priming effects in visual word recognition: a selective review of current findings and theories. In: D. Besner & G.W. Humphreys (eds.), *Basic Processes in Reading: Visual Word Recognition*. Lawrence Erlbaum, Hillsdale, NJ, 264-336.

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

Niedeggen, M. & Rösler, F. (1996). N400 effects related to incongruities in mental calculation problems. *Psychophysiology*, *33*, S65.

Niedeggen, M. & Rösler, F. (1999). N400 effects reflect activation spread during retrieval of arithmetic facts. *Psychological Science*, *10*, 271-276.

Niedermeyer, E. (1999). Historical aspects. In: E. Niedermeyer & F. Lopes da Silva (Eds.), *Electroenecphalography: basic principles, clinical applications, and related fields* (4th ed.). Baltimore: Williams & Wilkins.

Nigam, A., Hoffmann, J.E. & Simons, R.F. (1992) N400 to semantically anomalous pictures and words. *Journal of Cognitive Neuroscience*, *4*, 15-22.

Nobre, A. C., Allison, T. & McCarthy, G. (1994). Word recognition in the human inferior temporal lobe. *Nature*, *372*, 260-263.

Nobre, A. C. & Mc Carthy, G. (1995). Language-related field potentials in the anterior-medial temporal lobe: II. Effects of word type and semantic priming. *Journal of Neuroscience*, *15*, 1090-1098.

Nunez, P.L. (1995). *Neocortical Dynamics and Human EEG Rhythms*. Oxford: Oxford University Press.

Nunez, P.L. (2000). Toward a quantitative description of large-scale neocortical dynamic function and EEG. *Behavioral and Brain Sciences*, *23*, 371-437.

O'Keefe, J., Recce, M.L. (1993). Phase relationship between hippocampal place units and the EEG theta rhythm. *Hippocampus*, *3*, 317-330.

Ogawa, S., Lee, T. M., Nayak, A. S. & Glynn, P. (1990). Oxygenation-sensitive contrast in magnetic resonance image of rodent brain at high magnetic fields. *Magnetic Resonance Medicine*, *14*, 68-78.

Ogawa, S., Tank, D. W., Menon, R., Ellermann, J. M., Kim, S.-G., Merkle, H. and Ugurbil, K. (1992). Intrinsic signal changes accompanying sensory stimulation: functional brain mapping using MRI. *Proceedings of the National Academy of Sciences USA*, *89*, 5951-5955.

Oldfield, R.C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97-113.

Osterhout, L. (1997). On the brain responses to syntactic anomalies: Manipulations of word position and word class reveal individual differences. *Brain and Language*, *59*, 494-522.

Osterhout, L. & Holcomb, P.L. (1992): Event-Related Brain Potentials Elicited by Syntactic Anomaly. *Journal of Memory and Language*, *31*, 785-806.

Osterhout, L. & Holcomb, P.L. (1993). Event-related potentials and syntactic anomaly: evidence of anomaly detection during the perception of continuous speech. *Language and Cognitive Processes*, *8*, 413-38.

Osterhout, L., Holcomb, P.J. & Swinney, D.A. (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*, 786-803.

Osterhout, L. & Mobley, L.A. (1995). Event-related brain potentials elicited by failure to agree. *Journal of Memory and Language*, *34*, 739-773.

Pachella, R.G. (1974). The interpretation of reaction time in information processing research. In: B. Kantowitz (Ed.), *Human information processing: Tutorials in performance and cognition* (pp. 41-82). New York: Halstead Press.

Parnefjord, R. & Basar, E. (1995). Delta oscillations as a correlate to accoustical perception at the auditory threshold. *Electroencephalography and Clinical Neurophysiology*, *94*, 43.

Patel, A. D., Gibson, E., Ratner, J., Besson, M. & Holcomb, P. J. (1998). Processing syntactic relations in language and music: An event-related potential study. *Journal of Cognitive Neuroscience*, *10*, 717-733.

Penny, W.D., Kiebel, S.J., Kilner, J.M., & Rugg, M.D. (2002). Event-related brain dynamics. *Trends in Neurosciences*, *25*, 387-389.

Petsche, H., Stumpf, C., & Gogolak, G. (1962). The significance of the rabbit's septum as a relay between the midbrain and the hippocampus. The control of hippocampus arousal activity by septum cells. *Electroencephalography and Clinical Neurophysiology*, *14*, 202-211.

Petsche, H., Pockberger, H. & Rappelsberger, P. (1984). On the search for the sources of the electroencephalogram. *Neuroscience*, *11*, 1-27.

Picton, T.W., Lins, O.G. & Scherg, M. (1995). The recording and analysis of event-related potentials. In: J.C. Boller & J. Grafman (eds.), *Handbook of neuropsychology* (pp. 429-99). Amsterdam: Elsevier.

Pfurtscheller, G. (1994). Event-related desynchronization (ERD) and 40-Hz oscillations in a simple movement task. In: C. Pantev, T. Elbert & B. Lütkenhöner (Eds.), *Oscillatory event-related brain dynamics* (pp. 357-366). New York: Plenum Press.

Pfurtscheller, G. (1999). EEG Event-related Desynchronization (ERD) and Event-related Synchronization (ERS). In: E. Niedermeyer & F. Lopes da Silva (Eds.), *Electroenecphalography: basic principles, clinical applications, and related fields* (4th ed.) (pp. 958-967). Baltimore: Williams & Wilkins.

Pfurtscheller, G. and Aranibar, A. (1977). Event-related cortical desynchronization detected by power measurements of scalp EEG. *Electroencephalography and Clinical Neurophysiology*, *42*, 817-826.

Pfurtscheller, G. & Klimesch, W. (1991). Event-related desynchronization during motor behavior and visual information processing. In: C.H.M. Brunia, G. Mulder, & M.N. Verbaten (Eds.), *Event-related Brain Research*. Electroencephalography and Clinical Neurophysiology (Suppl.) (pp. 58-65). Amsterdam: Elsevier.

Pfurtscheller, G. & Klimesch, W. (1992). Functional topography during a visuoverbal judgment task studied with event-related desynchronization mapping. *Journal of Clinical Neurophysiology*, *9*, 120-131.

Pfurtscheller, G., Neuper, C., & Kalcher, J. (1993). 40-Hz oscillations during motor behaviour in man. *Neuroscience Letters*, *162*, 179-182.

Pfurtscheller, G., Neuper, Ch., Andrew, C., & Edlinger, G. (1997). Foot and hand area mu rhythms. *International Journal of Psychophysiology*, *26*, 121-135.

Pfurtscheller, G. & Lopes da Silva, F.H. (1999). Event-related EEG/MEG synchronization and desynchronization: basic principles. *Clinical Neurophysiology*, *110*, 1842-1857.

Praamstra, P. & Stegeman, D.F. (1993). Phonological effects on the auditory N400 event-related brain potential. *Cognitive Brain Research*, *1*, 73-86.

Práwdicz-Neminski, W.W. (1913). Ein Versuch der Registrierung der elektrischen Gehirnerscheinungen. *Zentralblatt Physiologie*, *27*, 951-960.

Pulvermüller, F. (1996). Hebb's concept of cell assemblies and the psychophysiology of word processing. *Psychophysiology*, *33*, 317-333.

Pulvermüller, F. (1999). Words in the brain's language. *Behavioral and Brain Sciences*, *22*, 253-336.

Pulvermüller, F. (2001). Brain reflections of words and their meaning. *Trends in Cognitive Sciences*, *5*, 517-524.

Pulvermüller, F. & Preissl, H. (1991). A cell assembly model of language. *Network*, *2*, 455-468.

Pulvermüller, F., Preissl, H., Eulitz, C., Pantev, C., Lutzenberger, W., Elbert, T., & Birbaumer, N. (1994). Brain rhythms, cell assemblies, and cognition: Evidence from the processing of words and pseudowords. *Psycoloquy*, **5**,1-30.

Pulvermüller, F., Preissl, H., Lutzenberger, W., & Birbaumer, N. (1995). Spectral responses in the gamma-band: Physiological signs of higher cognitive processes? *NeuroReport*, *6*, 2057-64.

Pulvermüller, F., Eulitz, C., Pantev, C., Mohr, B., Feige, B., Lutzenberger, W., Elbert, T., & Birbaumer, N. (1996). High-frequency cortical responses reflect lexical processing: An MEG study. *Electroencephalography and Clinical Neurophysiology*, *98*, 76-85.

Pulvermüller, F., Preissl, H., Lutzenberger, W. & Birbaumer, N. (1996). Brain rhythms of language. Nouns versus verbs. *European Journal of Neuroscience*, *8*, 937-941.

Pulvermüller, F., Lutzenberger, W., & Preissl, H. (1999). Nouns and verbs in the intact brain: evidence from event-related potentials and high frequency cortical responses. *Cerebral Cortex*, *9*, 497-506.

Ray, W.J. & Cole, H.W. (1985). EEG alpha activity reflects attentional demands, and beta activity reflects emotional and cognitive processes. *Science*, *228*, 750-752.

Rizzuto, D.S., Madsen, J.R., Bromfield, E.B., Schulze-Bonhage, A., Seelig, D., Aschenbrenner-Scheibe, R., Kahana, M.J. (2003). Reset of human neocortical oscillations during a working memory task. *Proceedings of the National Academy of Sciences USA*, *100*, 7931-7936.

Robinson, D.L. (1999). The technical, neurological and psychological significance of ‘alpha’, ‘delta’ and ‘theta’ waves confounded in EEG evoked potentials: a study of peak latencies. *Clinical Neurophysiology*, *110*, 1427-1434.

Rodriguez, E., George, N., Lachaux, J.P., Martinerie, J., Renault, B., & Varela, F.J. (1999). Perception’s shadow: long distance synchronization of human brain activity. *Nature*, *397*, 430-433.

Roehm, D., Klimesch, W., Haider, H., & Doppelmayr, M. (2001). The role of theta and alpha oscillations for language comprehension in the human electroencephalogram. *Neuroscience Letters*, *310*, 137-140.

Roehm, D., Winkler, T., Swaab, T., & Klimesch, W. (2002). The N400 and delta oscillations: Is there a difference? *Journal of Cognitive Neuroscience*, Supplement, 134.

Rösler, F., Pechmann, T., Streb, J., Röder, B. & Hennighausen, E. (1998). Parsing of Sentences in a Language with Varying Word Order: Word-by-Word Variations of Processing Demands Are Revealed by Event-Related Brain Potentials. *Journal of Memory and Language*, *38*, 150-176.

Rolke, B., Heil, M., Sterb, J. & Hennighausen, E. (2001). Missed prime words within the attentional blink evoke an N400 semantic priming effect. *Psychophysiology*, *38*, 165-174.

Rosen, B.R., Buckner, R.L. & Dale, A.M. (1998). Event-related functional MRI: Past, present and future. *Proceedings of the National Academy of Sciences U.S.A. 95*, 773-780.

Rugg, M.D. (1990). Event-related brain potentials dissociate repetition effects of high- and low-frequency words. *Memory & Cognition*, *18*, 367-79.

Rugg, M.D. & Barret, S.E. (1987). Event-related potentials and the interaction between orthographic and phonological information in a rhyme-judgment task. *Brain and Language*, *32*, 336-61.

Rugg, M.D. & Coles, M.G.H. (1995). The ERP and Cognitive Psychology: Conceptual Issues. In: M. D. Rugg & M. G. H. Coles (Eds.), *Electrophysiology of mind* (pp. 27-39). Oxford: Oxford University Press.

Saddy, D., Drehnhaus, H. & Frisch, S. (in press). Processing polarity items: Contrastive licensing costs. *Brain and Language*.

Samar, V.J., Bopardikar, A., Rao, R., & Swartz, K. (1999). Wavelet analysis of neuroelectric waveforms: A conceptual tutorial. *Brain and Language*, *66*, 7-60.

Sarnthein, J., Petsche, H., Rappelsberger, P., Shaw, G.L., & von Stein, A. (1998). Synchronization between prefrontal and posterior association cortex during human working memory. *Proceedings of the National Academy of Sciences USA*, *95*, 7092-7096.

Sayers, B., Beagley, H. A. and Hanshall, W. R. (1974). The mechanisms of auditory evoked EEG responses. *Nature*, *247*, 481-483.

Schack, B., Witte, H., Helbig, M., Schelenz, Ch., & Specht, M. (2001). Time-variant non-linear phase-coupling analysis of EEG burst patterns in sedated patients during electroencephalic burst suppression period. *Clinical Neurophysiology*, *112*, 1388-1399.

Schack, B. & Klimesch, W. (2002). Frequency characteristics of evoked and oscillatory electroencephalic activity in a human memory scanning task. *Neuroscience Letters*, *331*, 107-110.

Schlesewsky, M., Fanselow, G., Kliegl, R. & Krems, J. (2000). The subject-preference in the processing of locally ambiguous wh-questions in German. In: B. Hemforth & L. Konieczny (eds.), *German sentence processing* (pp. 65-93). Dordrecht: Kluwer.

Schlesewsky, M. & Bornkessel, I. (2003). Ungrammaticality detection and garden path strength: A commentary on Meng & Bader's (2000) evidence for serial parsing. *Language and Cognitive Processes*, *18*, 299-311.

Schlesewsky, M., Bornkessel, I. & Frisch, S. (2003). The neurophysiological basis of word order variations in German. Brain and Language, *Brain and Language*, *86*, 116-128.

Schlesewsky, M. & Bornkessel, I. (in press). On incremental interpretation: Degrees of meaning accessed during sentence comprehension. *Lingua*.

Schmidt, A.L., Arthur, D.L., Kutas, M. & Flynn, E. (1989). Neuromagnetic responses during reading meaningful and nonmeaningful sentences. *Psychophysiological Abstracts*, *26*, S6.

Schriefers, H., Friederici, A.D. & Kühn, K. (1995). The processing of locally ambiguous relative clauses in German. *Journal of Memory and Language*, *34*, 499-520.

Schürmann, M. (1998). Mögliche funktionelle Korrelate ereigniskorrelierter α-Oszillationen im EEG. *Klinische Neurophysiologie*, *29*, 280-288.

Schürmann, M., Basar-Eroglu, C., Kolev, V., & Basar, E. (1995). A new metric for analyzing single-trial event-related potentials. Application to human visual P300 delta response. *Neuroscience Letters*, *197*, 167-170.

Schürmann, M., Basar-Eroglu, C. & Basar, E. (1997). A possible role of evoked alpha in primary sensory processing: common properties of cat intracranial recordings and human EEG and MEG. *International Journal of Psychophysiology*, *26*, 149-170.

Schürmann, M., Basar-Eroglu, C., Kolev, V., & Basar, E. (2001). Delta response and cognitive processing: single trial evaluations of human visual P300. *International Journal of Psychophysiology*, *39*, 229-239.

Schütze, C.T. (1996). *The empirical base of linguistics*. Chicago, London: The University of Chicago Press.

Simos, P.G., Basile, L.F.H. & Papanicolaou, A.C. (1997). Source localization of the N400 response in a sentence-reading paradigm using evoked magnetic fields and magnetic resonance imaging. *Brain Research*, *762*, 29-39.

Singer, W. (1990). Search for coherence: a basic principle of cortical self-organization. *Concepts in Neuroscience*, *1*, 1-26.

Singer, W. (1993). Synchronization of cortical activity and its putative role in information processing, *Annual Review of Physiology*, *55*, 349-74.

Sinkkonen, J., Tiitinen, H., & Näätänen, R. (1995). Gabor filters: an informative way for analyzing event-related brain activity. *Journal of Neuroscience Methods*, *56*, 99-104.

Squire, L.R., Ojeman, J.G., Miezin, F.M., Petersen, S.E., Videen, T.O., & Raichle, M.E. (1992). Activation of the hippocampus in normal humans: A functional anatomical study of memory. *Proceedings of the National Academy of Sciences USA*, *89*, 1837-1841.

Srinivasan, R. (2004). Internal and external neural synchronization during conscious perception. *International Journal of Bifurcation and Chaos*, *14*, 825-842.

St. George, M., Mannes, S. & Hoffman, J.E. (1994). Global semantic expectancy and language comprehension. *Journal of Cognitive Neuroscience*, *6*, 70-83.

Steinhauer, K., Mecklinger, A., Friederici, A.D. & Meyer, M. (1997). Wahrscheinlichkeit und Strategie: Eine EKP-Studie zur Verarbeitung syntaktischer Anomalien. *Zeitschrift für experimentelle Psychologie*, *44*, 305-331.

Steriade, M. (1999). Cellular Substrates of Brain Rhythms. In: E. Niedermeyer & F. Lopes da Silva (Eds.), *Electroenecphalography: basic principles, clinical applications, and related fields* (4th ed.). Baltimore: Williams & Wilkins.

Steriade, M., Curró Dossi, R.C., Paré, D., & Oakson, G. (1991). Fast oscillations (20-40 Hz) in Thalamocortical Systems and Their Potentiation by Mesopontine Cholinergic Nuclei in the Cat. *Proceedings of the National Academy of Sciences USA*, *88*, 4396-4400.

Steriade, M., McCormick, D.A., & Sejnowski, T.J. (1993). Thalamocortical oscillations in the sleeping and aroused brain. *Science*, *262*, 679-685.

Tallon, C., Bertrand, O., Bouchet, P., & Pernier, J. (1995). Gamma-range activity evoked by coherent visual stimuli in humans. *European Journal of Neuroscience*, *7*, 1285-1291.

Tallon-Baudry, C., Bertrand, O., Delpuech, C., & Pernier, J. (1996). Stimulus Specificity of Phase-Locked and Non-Phase-Locked 40 Hz Visual Responses in Human. *The Journal of Neuroscience*, *16*, 4240-4249.

Tallon-Baudry, C., Bertrand, O., Delpuech, C., & Pernier, J. (1997). Oscillatory γ-Band (30-70 Hz) Activity Induced by a Visual Search Task in Humans. *The Journal of Neuroscience*, *15*, 722-734.

Tallon-Baudry, C. & Bertrand, O. (1999a). Oscillatory gamma activity in humans and its role in object representation. *Trends in Cognitive Sciences*, *3*, 151-162.

Tallon-Baudry, C. & Bertrand, O. (1999b). Reply (to Pulvermüller, Keil, & Elbert, 1999). *Trends in Cognitive Sciences*, *3*, 252-253.

Tass, P.A. (1999). *Phase Resetting in Medicine and Biology: Stochastic Modelling and Data Analysis*. Berlin: Springer.

Taylor, W.L. (1953). “Cloze” procedure: A new tool for measuring readability. *Journalism Quarterly*, *30*, 415-417.

Tesche, C.D. (1997). Non-invasive detection of ongoing neuronal population activity in normal human hippocampus. *Brain Research*, *749*, 53-60.

Tilhonen, J., Hari, R., & Kajola, M. (1991). Magnetoencephalographic 10 Hz rhythm from the human auditory cortex. *Neuroscience Letters*, *129*, 303-305

Treisman, A. (1999). Solutions to the Binding Problem: Progress through Controversy and Convergence. *Neuron*, *24*, 105-110.

Truccolo, W.A., Ding, M., Knuth, K.H., Nakamura, R. & Bressler, S.L. (2002). Trial-to-trial variability of cortical evoked responses: implications for the analysis of functional connectivity. *Clinical Neurophysiology*, *113*, 206-226.

Tulving, E. (2002). Episodic memory: From mind to brain. *Annual Review of Psychology*, *53*, 1-25.

Van Berkum, J., Hagoort, P. & Brown, C. (1999). Semantic integration in discourse: Evidence from the N400. *Journal of Cognitive Neuroscience*, *11*, 657-671.

Van Petten, C. (1993). A comparison of lexical and sentence-level context effects in event-related potentials [Special issue: Event-related brain potentials in the study of language]. *Language and Cognititive Processes*, *8*, 485-531.

Van Petten, C. & Kutas, M. (1990). Interactions between sentence context and word frequency in event-related brain potentials. *Memory and Cognition*, *18*, 380-393.

Van Petten, C., Kutas, M., Kluender, R., Mitchiner, M. & McIsaac, H.K. (1991). Fractionating the word repition effect with event-related brain potentials. *Journal of Cognitive Neuroscience*, *3*, 131-150.

Van Petten, C. & Rheinfelder, H. (1995). Conceptual relationships between spoken words and environmental sounds: event-related brain potential measures. *Neuropsychologia*, *33*, 485-508.

Verleger, R. (1988). Event-related potentials and cognition: A critique of the context updating hypothesis and an alternative interpretation of P3. *Behavioral and Brain Sciences*, *11*, 343-427.

Villablanca, J. (1974). Role of the thalamus in sleep control: sleep-wakefulness studies in chronic diencephalic and athalamic cats. In: O. Petre-Quadens & J.D. Schlag (eds.), *Basic Sleep Mechanisms* (pp. 51-78). New York: Academic Press.

von Stein, A. & Sarnthein, J. (2000a). Different frequencies for different scales of cortical integration: from local gamma to long range alpha/theta synchronization. *International Journal of Psychophysiology*, *38*, 301-313.

von Stein, A. & Sarnthein, J. (2000b). EEG frequency and the size of cognitive neuronal assemblies. *Behavioral and Brain Sciences*, *23*, 413-414.

Vos, S.H.,Gunter, T.C., Kolk, H.H.J., & Mulder, G. (2001). Working memory constraints on syntactic processing: An electrophysiological investigation. *Psychophysiology*, *38*, 41-63.

Vos, S. M., Gunter, T. C., Schriefers, H., & Friederici, A. D. (2001). Syntactic parsing and working memory: The effects of syntactic complexity, reading span, and concurrent load. *Language and Cognitive Processes*, *16*, 65-103.

Weckerly, J. & Kutas, M. (1999). An electrophysiological analysis of animacy effects in the processing of object relative sentences. *Psychophysiology*, *36*, 559-570.

Weisbrod, M., Kiefer, M., Winkler, S., Maier, S., Hill, H., Roesch-Ely, D. & Spitzer, M. (1999). Electrophysiological correlates of direct versus indirect semantic priming in normal volunteers. *Cognitive Brain Research*, *8*, 289-298.

Weiss, S. & Mueller, H.M. (2003). The contribution of EEG coherence to the investigation of language. *Brain and Language*, *85*, 325-343.

Williamson, S.J., Kaufman, L., Lu, Z.L., Wang, J.Z., & Karron, D. (1997). Study of human occipital alpha rhythm: the alphon hypothesis and alpha suppression. *International Journal of Psychophysiology*, *26*, 63-76.

Wood, C.C., Goff, W.R. & Day, R.S. (1971). Auditory Evoked Potentials during Speech Perception. *Science*, *173*, 1248-51.

Woodworth, R.S. (1899). Accuracy of voluntary movements. *Psychological Review*, *3*, 1-101.

Appendix A

Materials

1. Materials for Experiments 2-5:

The critical constituents are listed in the order:

Prime (antonym1)	*antonym / related / non-related*
01 groß	*klein / dick / grün*
02 krank	*gesund / kränklich / wellig*
03 schwarz	*weiss / gelb / nett*
04 lang	*kurz / hoch / flott*
05 ungenau	*genau / vage / lieblich*
06 schön	*hässlich / normal / müde*
07 leer	*voll / halbvoll / braun*
08 stark	*schwach / halbstark / stumpf*
09 arm	*reich / zufrieden / breit*
10 leicht	*schwer / mittelschwer / doof*
11 lebendig	*tot / halbtot / hohl*
12 billig	*teuer / preiswert / munter*
13 faul	*fleißig / bemüht / rosa*
14 geschlossen	*offen / angelehnt / hager*
15 freundlich	*unfreundlich / höflich / viereckig*
16 links	*rechts / mittig / bunt*
17 oben	*unten / dazwischen / oval*
18 hinten	*vorne / zentral / klebrig*
19 hier	*dort / nebenan / spitz*
20 hell	*dunkel / trüb / grob*
21 glänzend	*matt / streifig / zärtlich*
22 waagerecht	*senkrecht / diagonal / traurig*
23 schmutzig	*sauber / staubig / salzig*
24 kalt	*warm / lau / sanft*
25 gebraucht	*neu / benutzt / geizig*
26 lieben	*hassen / mögen / haarig*
27 schnell	*langsam / bedächtig / holzig*
28 nass	*trocken / feucht / lila*
29 nackt	*bekleidet / halbnackt / blind*

30 süss	*sauer / bitter / kahl*
31 weich	*hart / elastisch / zornig*
32 betrunken	*nüchtern / beschwipst / verbrannt*
33 krumm	*gerade / eckig / ängstlich*
34 schlecht	*gut / mäßig / schlank*
35 Feuer	*Wasser / Wind / Sessel*
36 tolerant	*intolerant / ambivalent / farbenfroh*
37 klug	*dumm / schlau / kühl*
38 Nacht	*Tag / Abend / Hund*
39 Himmel	*Erde / Luft / Ofen*
40 Kind	*Erwachsener / Jugendlicher / Ratte*
41 Ankunft	*Abfahrt / Hinfahrt / Durchfall*
42 geben	*nehmen / behalten / schnarchen*
43 anziehen	*ausziehen / umziehen / hinfallen*
44 öffnen	*schließen / zuhalten / wachsen*
45 einschalten	*ausschalten / betreiben / zuhören*
46 zuknöpfen	*aufknöpfen / abreißen / abwaschen*
47 eingraben	*ausgraben / umgraben / durchlesen*
48 Abend	*Morgen / Mittag / Treppe*
49 Ausgang	*Eingang / Durchgang / Weinglas*
50 Abrüstung	*Aufrüstung / Umrüstung / Federung*
51 passiv	*aktiv / träge / kursiv*
52 jung	*alt / mittelalt / rot*
53 Amateur	*Profi / Experte / Hausschuh*
54 Anfang	*Ende / Mitte / Pflanze*
55 vertraut	*fremd / bekannt / kantig*
56 Berg	*Tal / Hügel / Maus*
57 bergauf	*bergab / voran / musisch*
58 dick	*dünn / füllig / morsch*
59 aufmachen	*zumachen / verpacken / kitzeln*
60 Krieg	*Frieden / Konflikt / Osterei*
61 Freund	*Feind / Kollege / Birne*
62 Sommer	*Winter / Herbst / Plastik*
63 getrennt	*zusammen / angrenzend / gekocht*

64 weinen	*lachen / grinsen / fliegen*
65 schlafend	*wach / dösend / schimmelnd*
66 immer	*nie / manchmal / fröhlich*
67 Mann	*Frau / Kind / Stuhl*
68 vorher	*nachher / jetzt / talwärts*
69 alles	*nichts / manches / oder*
70 Osten	*Westen / Süden / Kissen*
71 ja	*nein / vielleicht / Topf*
72 trinken	*essen / schlürfen / lügen*
73 Vorspeise	*Nachspeise / Hauptgericht / Atommüll*
74 Fußboden	*Decke / Wand / Umfrage*
75 dein	*mein / unser / neun*
76 ledig	*verheiratet / geschieden / chemisch*
77 schreiben	*lesen / hören / flattern*
78 minus	*plus / null / Dativ*
79 rund	*eckig / gerade / blutig*
80 Regen	*Sonne / Nebel / Chinese*

2. Materials for Experiment 5:

The critical constituents are listed in the order:
prime / pseudoword in second position; pseudoword in first position / target

01	*groß*	*neilk*	*sans*	*talwärts*
02	*gesund*	*knark*	*benda*	*stumpf*
03	*gelb*	*zwarsch*	*naugen*	*zuhören*
04	*kurz*	*nalg*	*tärge*	*hohl*
05	*vage*	*nauge*	*noste*	*kahl*
06	*hässlich*	*nösch*	*niewen*	*sanft*
07	*voll*	*erel*	*troden*	*kitzeln*
08	*schwach*	*krast*	*Geren*	*Ratte*
09	*reich*	*mar*	*aratemur*	*rosa*
10	*leicht*	*wersch*	*nünd*	*klebrig*
11	*tot*	*digbenle*	*mauchaf*	*spitz*
12	*teuer*	*libgil*	*knarken*	*schnarchen*
13	*fleißig*	*luaf*	*Wersch*	*Federung*
14	*angelehnt*	*fofen*	*remim*	*haarig*
15	*unfreundlich*	*nulchfried*	*Neim*	*Sessel*
16	*rechts*	*klins*	*digbenle*	*kursiv*
17	*unten*	*nebo*	*nulchfried*	*kantig*
18	*vorne*	*tinneh*	*innelascht*	*lieblich*
19	*hier*	*trod*	*Zänglend*	*Birne*
20	*dunkel*	*lehl*	*aj*	*zornig*
21	*matt*	*zänglend*	*Krenstech*	*Plastik*
22	*diagonal*	*krenstech*	*aubgrecht*	*schimmelnd*
23	*staubig*	*mugzischt*	*fargeub*	*oval*
24	*warm*	*tlak*	*nebo*	*musisch*
25	*neu*	*aubgrecht*	*trantelo*	*chemisch*
26	*hassen*	*neblei*	*mugzischt*	*gekocht*
27	*bedächtig*	*glansam*	*Mar*	*Weinglas*
28	*trocken*	*sans*	*Murmk*	*Atommüll*
29	*nackt*	*teidebelk*	*knötzpfeun*	*müde*

30	süss	reusa	Insum	Hund
31	hart	ichwe	morsmer	traurig
32	nüchtern	knurbenet	erelen	durchlesen
33	gerade	murmk	Neilk	Durchfall
34	gut	tschelch	neblei	fröhlich
35	Wasser	Reufe	prosveise	ängstlich
36	intolerant	trantelo	Klins	Maus
37	dumm	gulk	Tanch	Dativ
38	Abend	Tanch	begen	wellig
39	Erde	Milmeh	Lehl	Osterei
40	Erwachsener	Dink	heinezan	nett
41	Abfahrt	Nuftnak	nalgen	wachsen
42	nehmen	begen	knurben	lügen
43	ausziehen	heinezan	rorveh	lila
44	schließen	fönfen	gühel	bunt
45	ausschalten	innelascht	nurefd	zärtlich
46	aufknöpfen	knötzpfeun	rekig	grob
47	ausgraben	branneig	milmeh	blutig
48	Morgen	Benda	Tschelch	Umfrage
49	Eingang	Sagusgan	Nurd	Ofen
50	Aufrüstung	Strünbaug	Ichwe	Topf
51	passiv	tärge	sella	blind
52	alt	glun	Fofen	Pflanze
53	Experte	Aratemur	tinneh	morsch
54	Ende	Nafgan	Reusa	Kissen
55	fremd	taurvert	nafgan	hager
56	Tal	Gühel	zwarschen	hinfallen
57	bergab	fargeub	lendfasch	geizig
58	füllig	nünd	maun	holzig
59	zumachen	mauchafen	glun	munter
60	Frieden	Rekig	libgil	rot
61	Feind	Nurefd	krinten	verbrannt
62	Winter	Morsmer	sagusgan	breit
63	zusammen	nertgent	nuftnak	grün

64	*lachen*	*niewen*	*strünbaug*	*doof*
65	*wach*	*lendfasch*	*Dink*	*Chinese*
66	*nie*	*remim*	*teidebelk*	*oder*
67	*Kind*	*Maun*	*breischen*	*kühl*
68	*nachher*	*rorveh*	*nertgent*	*salzig*
69	*nichts*	*sella*	*nöschen*	*abwaschen*
70	*Süden*	*Noste*	*taurvert*	*viereckig*
71	*vielleicht*	*aj*	*fönfen*	*flott*
72	*essen*	*krinten*	*Luaf*	*Hausschuh*
73	*Nachspeise*	*Prosveise*	*doßfuben*	*schlank*
74	*Decke*	*Doßfuben*	*Glansam*	*Stuhl*
75	*unser*	*neim*	*digel*	*farbenfroh*
76	*verheiratet*	*digel*	*tlaken*	*fliegen*
77	*lesen*	*breischen*	*gulken*	*flattern*
78	*plus*	*insum*	*reuf*	*neun*
79	*eckig*	*nurd*	*Krast*	*Treppe*
80	*Sonne*	*Geren*	*branneig*	*braun*

Appendix B

Supplementary ERP figures

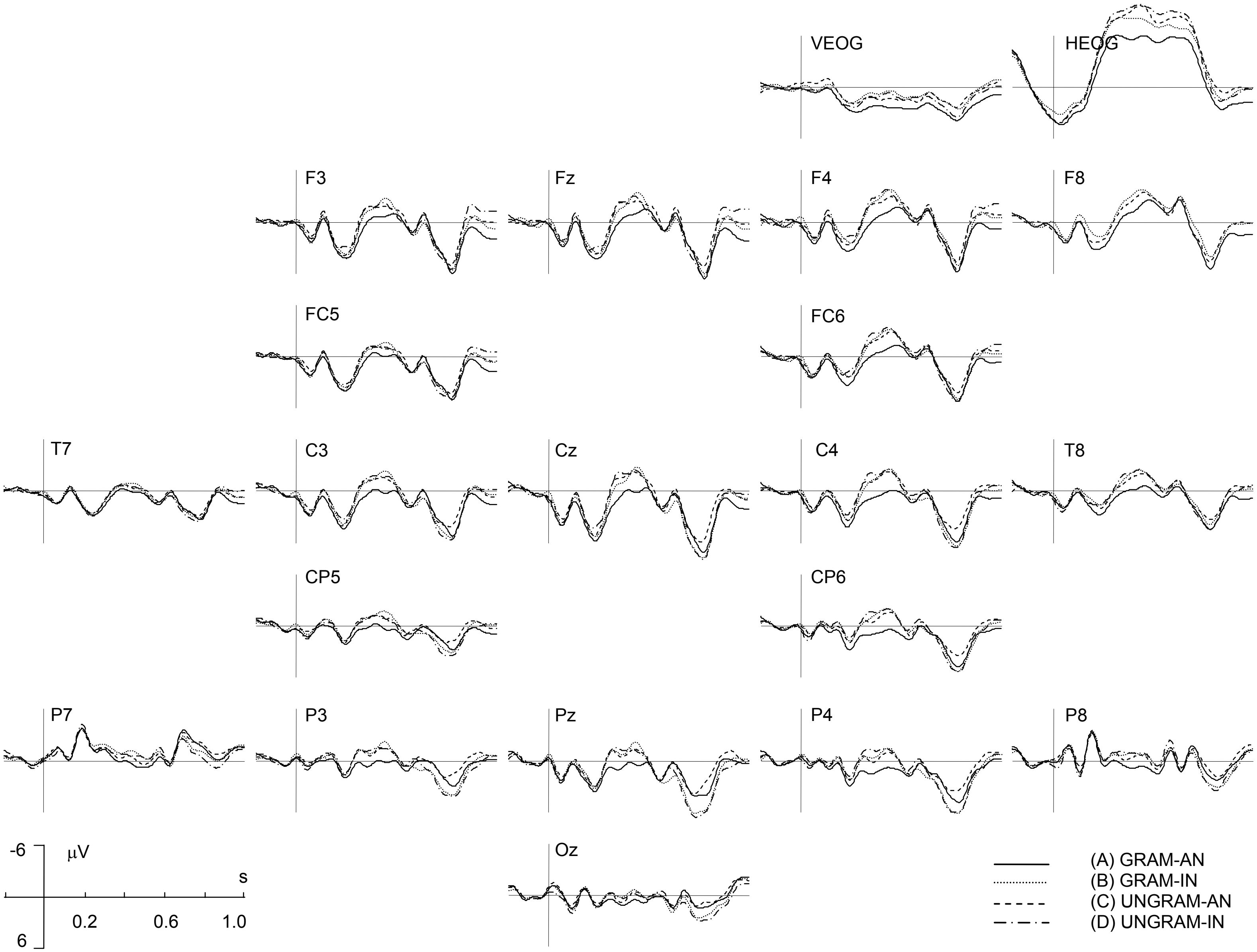

Figure B1. Grammatical-animate vs. grammatical inanimate vs. ungrammatical animate vs. ungrammatical inanimate condition at the position of the second NP in Exp. 1.

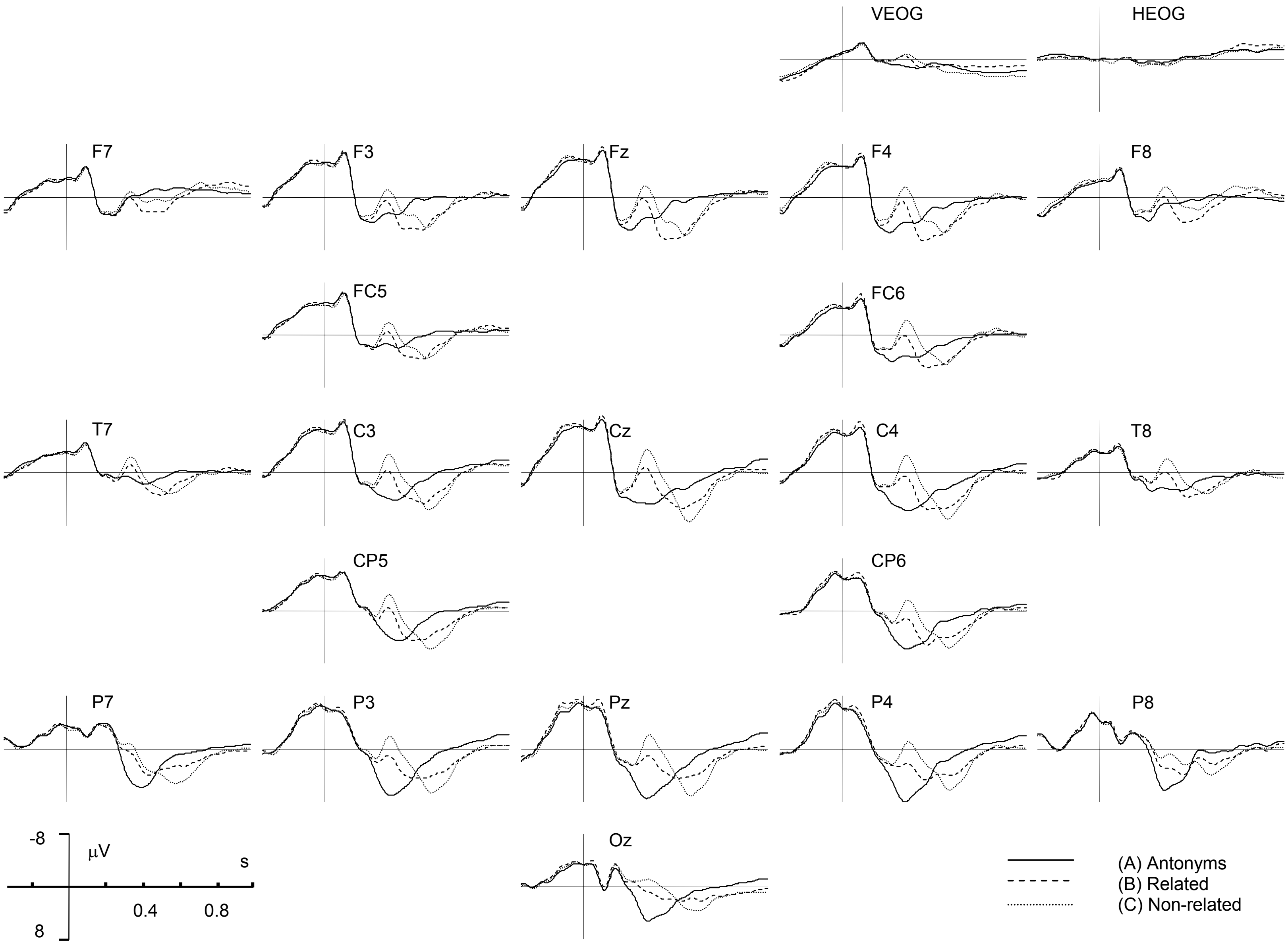

Figure B2. Antonyms vs. related vs. non-related category violations in Exp. 2.

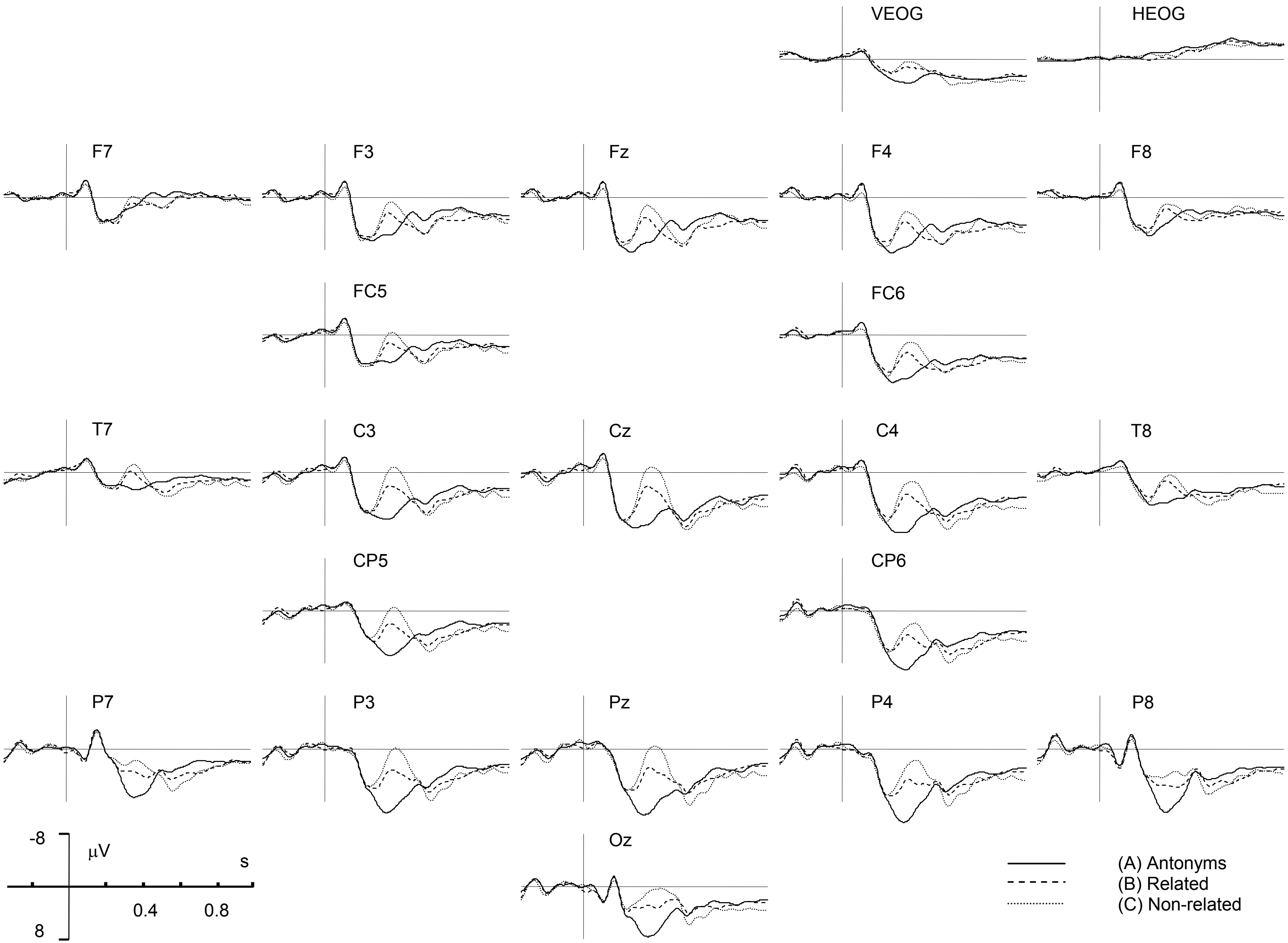

Figure B3. Antonyms vs. related vs. non-related category violations in Exp. 3.

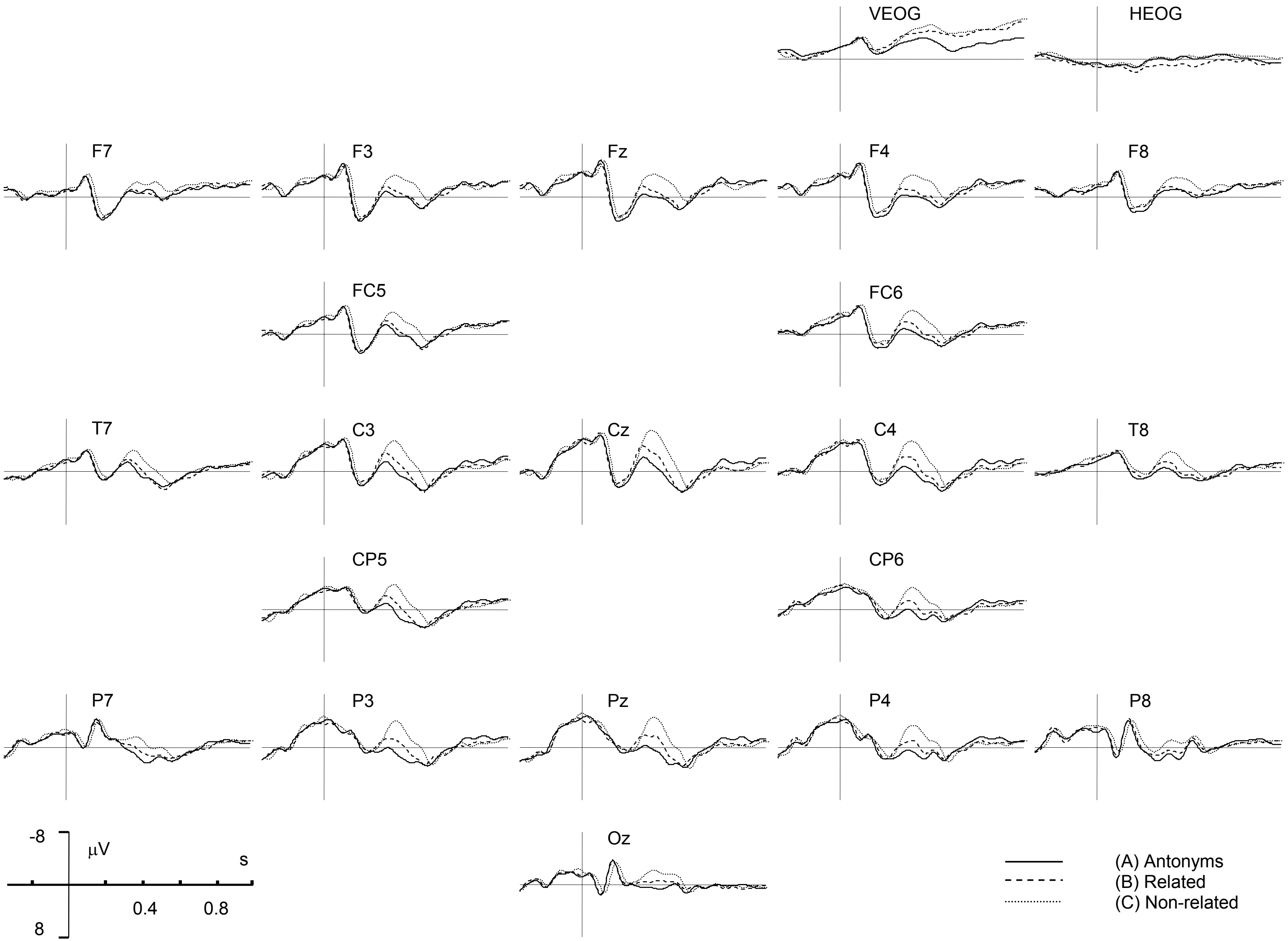

Figure B4. Antonyms vs. related vs. non-related category words in Exp. 5.

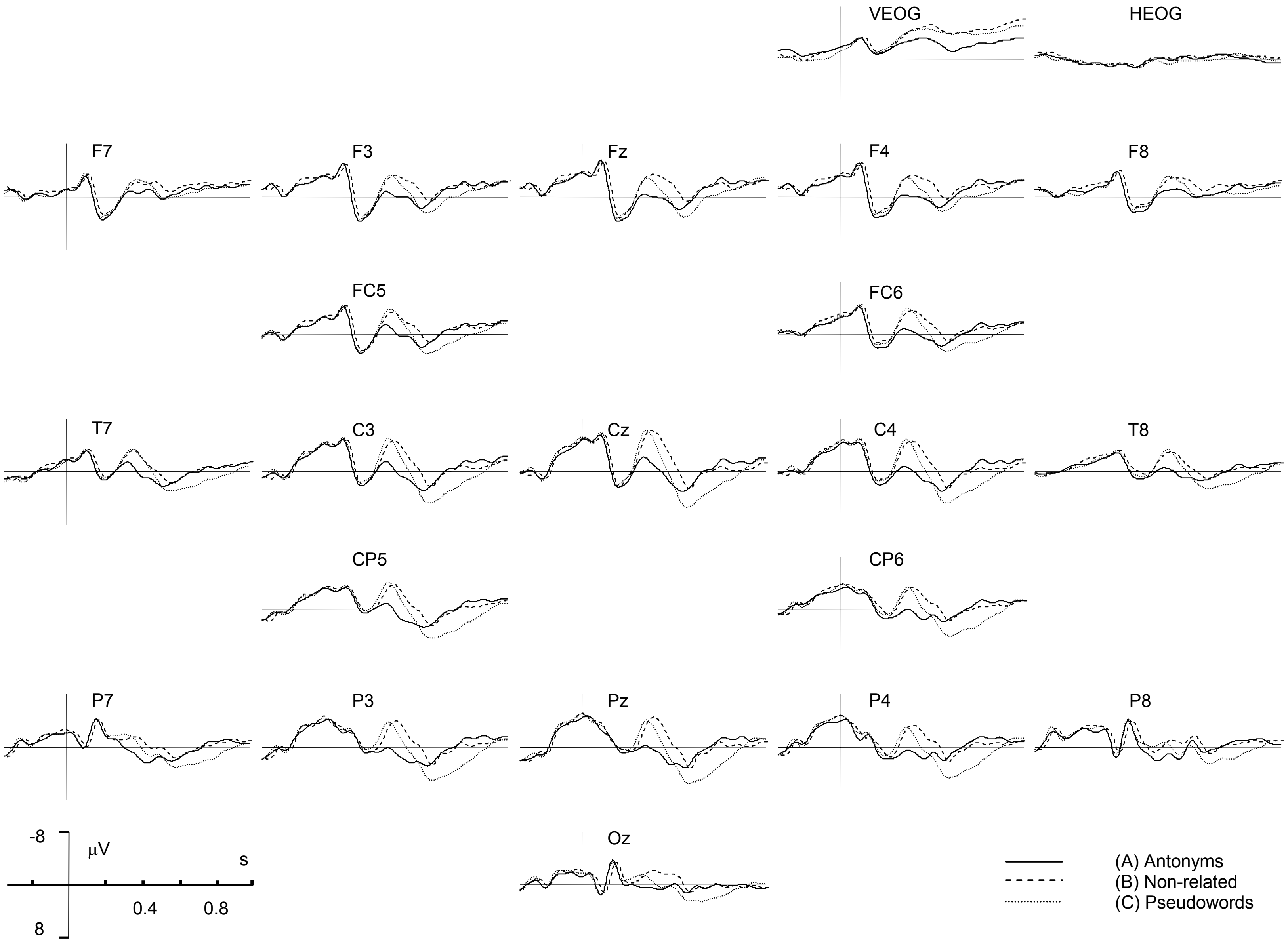

Figure B5. Antonyms vs. non-related vs. pseudowords in Exp. 5.

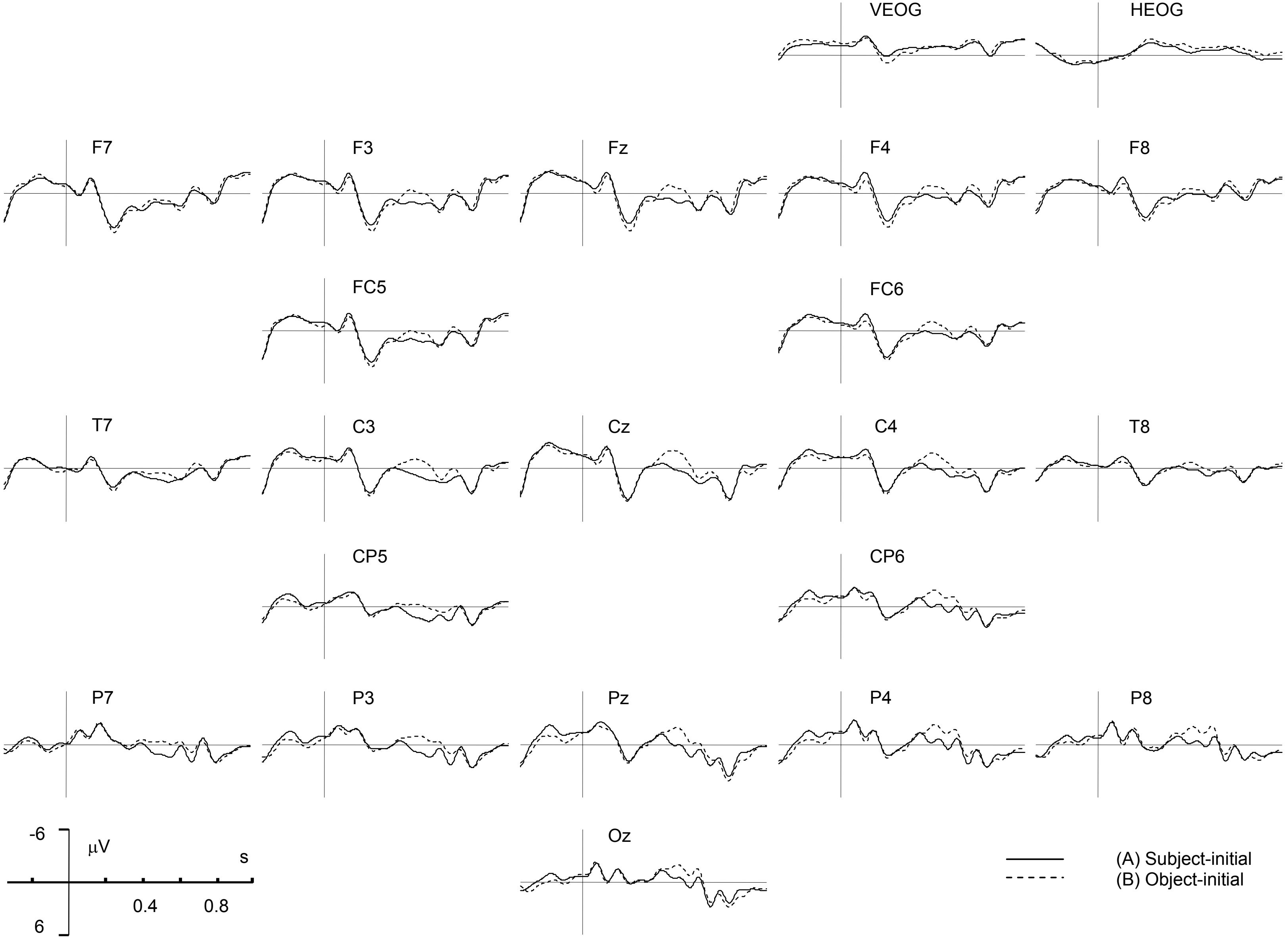

Figure B6. Subject-initial vs. object-initial sentences in Exp. 6.

Appendix C

Statistical Overviews of the ERP Findings

1. Experiment 2

	TIME in ms	ROI *F* (3,48)	*p*	TYPE *F* (2,32)	*p*	ROI x TYPE *F* (6,96)	*p*		FroL *F* (1,16)	*p*	FroR *F* (1,16)	*p*	PosL *F* (1,16)	*p*	PosR *F* (1,16)	*p*
T1	200 – 250	8.5	0.005	1.8	0.182	1.15	0.34	A	---	---	---	---	---	---	---	---
T2	250 – 300	1.34	0.273	9.07	0.001	3.74	0.005	A	1.51	0.236	9.83	0.000	4.50	0.019	18.26	0.000
								t1	----	----	<1	0.602	3.65	0.074	2.85	0.111
								t2	----	----	16.20	0.001	6.38	0.022	28.47	0.000
								t3	----	----	11.28	0.004	1.98	0.178	15.41	0.001
T3	300 – 350	10.47	0.001	43.78	0.000	11.05	0.000	A	6.00	0.006	19.73	0.000	59.25	0.000	58.20	0.000
								t1	4.12	0.059	10.05	0.006	22.80	0.000	17.79	0.001
								t2	8.06	0.012	31.42	0.000	76.69	0.000	82.12	0.000
								t3	3.80	0.069	12.30	0.003	51.84	0.000	54.07	0.000
T4	350 – 400	10.18	0.001	46.2	0.000	26.46	0.000	A	5.44	0.009	16.36	0.000	101.73	0.000	76.62	0.000
								t1	12.72	0.003	22.83	0.000	31.26	0.000	46.39	0.000
								t2	4.24	0.056	22.84	0.000	171.02	0.000	139.91	0.000
								t3	<1	0.708	<1	0.482	78.69	0.000	37.11	0.000
T5	400 – 450	6.16	0.007	13.67	0.000	16.70	0.000	A	7.81	0.002	15.47	0.000	20.42	0.000	16.59	0.000
								t1	13.86	0.002	27.34	0.000	20.86	0.000	34.10	0.000
								t2	<1	0.690	<1	0.453	43.22	0.000	26.58	0.000
								t3	18.69	0.001	17.74	0.001	5.22	0.036	1.66	0.216
T6	450 – 500	7.33	0.003	11.84	0.000	7.54	0.001	A	14.60	0.000	29.57	0.000	1.57	0.223	3.04	0.062
								t1	8.95	0.009	21.98	0.000	----	----	----	----
								t2	5.85	0.028	12.46	0.003	----	----	----	----
								t3	30.57	0.000	46.16	0.000	----	----	----	----
T7	500 – 550	4.07	0.036	24.59	0.000	3.66	0.026	A	26.26	0.000	34.16	0.000	8.58	0.001	8.23	0.001
								t1	4.84	0.043	3.32	0.087	1.02	0.328	<1	0.623
								t2	24.03	0.000	38.98	0.000	11.90	0.003	8.87	0.009
								t3	44.04	0.000	59.12	0.000	9.19	0.008	10.00	0.006
T8	550 – 600	9.44	0.002	49.07	0.000	5.57	0.001	A	30.16	0.000	35.74	0.000	36.52	0.000	33.84	0.000
								t1	<1	0.825	<1	0.919	24.76	0.000	19.66	0.000
								t2	44.48	0.000	45.94	0.000	70.29	0.000	47.17	0.000
								t3	30.72	0.000	67.87	0.000	16.50	0.001	23.11	0.000
T9	600 – 650	13.58	0.000	31.23	0.000	10.00	0.000	A	12.83	0.000	14.50	0.000	41.49	0.000	28.78	0.000
								t1	<1	0.912	<1	0.515	29.44	0.000	8.59	0.010
								t2	16.88	0.001	16.06	0.001	75.01	0.000	35.32	0.000
								t3	15.63	0.001	30.09	0.000	19.84	0.000	34.00	0.000
T10	650 – 700	10.89	0.001	20.89	0.000	10.03	0.000	A	3.25	0.052	5.91	0.007	32.20	0.000	19.61	0.000
								t1	<1	0.635	<1	0.411	14.61	0.002	4.59	0.048
								t2	3.93	0.065	5.30	0.035	47.17	0.000	23.69	0.000
								t3	4.66	0.046	13.87	0.002	23.73	0.000	29.77	0.000
T11	700 – 750	7.83	0.005	6.00	0.006	7.76	0.000	A	1.40	0.261	2.80	0.076	14.22	0.000	7.53	0.002
								t1	----	----	----	----	<1	0.533	<1	0.685
								t2	----	----	----	----	20.14	0.000	7.05	0.017
								t3	----	----	----	----	18.84	0.001	18.30	0.001
T12	750 – 800	2.95	0.092	3.50	0.042	5.18	0.037	A	<1	0.889	1.34	0.276	7.78	0.002	6.97	0.003
								t1	----	----	----	----	<1	0.929	1.10	0.310
								t2	----	----	----	----	9.46	0.007	5.02	0.040
								t3	----	----	----	----	12.02	0.003	17.06	0.001
T13	800 – 850	1.90	0.183	<1	0.448	4.21	0.005	A	<1	0.407	<1	0.721	4.67	0.017	3.88	0.031
								t1	----	----	----	----	<1	0.707	<1	0.335
								t2	----	----	----	----	5.90	0.027	3.03	0.101
								t3	----	----	----	----	6.67	0.020	7.87	0.013
T14	850 – 900	1.28	0.282	<1	0.564	4.55	0.004	A	2.44	0.104	<1	0.751	3.61	0.039	3.96	0.029
								t1	----	----	----	----	<1	0.553	<1	0.614
								t2	----	----	----	----	4.01	0.062	6.77	0.019
								t3	----	----	----	----	4.70	0.045	5.21	0.036

Table 1. Main effects of ROI, TYPE (antonyms vs. related vs. non-related), ROI x TYPE, and effects in each of the 4 ROIs (frontal-left = FroL; frontal-right = FroR; posterior-left = PosL; posterior-right = PosR) in fourteen successive 50 ms time windows (T1-T14) from 200 to 900 ms post-onset of the critical items in Experiment 2. The main effect for the 3 conditions (ANT = antonyms; REL = related category violations; NON = non-related category violations) in each ROI is coded as A = ANT x REL x NON. The 3 single comparisons are: t1= REL x NON, t2 = ANT x NON, and t3 = ANT x REL.

	TIME in ms	ELEC *F* (2,32)	*p*	TYPE *F* (2,32)	*p*	ELEC x TYPE *F* (4,64)	*p*		Fz *F* (1,16)	*p*	Cz *F* (1,16)	*p*	Pz *F* (1,16)	*p*
T1	200 – 250	1.97	0.176	2.23	0.124	<1	0.627	A	---	---	---	---	---	---
T2	250 – 300	1.53	0.236	13.63	0.000	<1	0.528	A	---	---	---	---	---	---
T3	300 – 350	10.05	0.002	56.09	0.000	10.55	0.000	A	15.45	0.000	62.48	0.000	80.29	0.000
								t1	10.52	0.005	23.58	0.000	27.60	0.000
								t2	20.99	0.000	85.26	0.000	121.80	0.000
								t3	10.02	0.006	54.27	0.000	64.78	0.000
T4	350 – 400	1.97	0.169	44.84	0.000	31.56	0.000	A	9.02	0.001	47.66	0.000	95.13	0.000
								t1	22.70	0.000	35.88	0.000	45.70	0.000
								t2	8.28	0.011	79.75	0.000	178.81	0.000
								t3	<1	0.753	20.53	0.000	52.14	0.000
T5	400 – 450	<1	0.814	10.00	0.001	25.68	0.000	A	10.95	0.000	10.16	0.000	18.63	0.000
								t1	14.99	0.001	24.27	0.000	28.94	0.000
								t2	<1	0.457	15.27	0.001	30.94	0.000
								t3	20.36	0.000	<1	0.796	3.56	0.078
T6	450 – 500	1.15	0.317	7.74	0.003	17.78	0.000	A	24.67	0.000	4.60	0.018	2.44	0.103
								t1	11.40	0.004	11.45	0.005	----	----
								t2	16.05	0.001	<1	0.811	----	----
								t3	40.77	0.000	5.90	0.027	----	----
T7	500 – 550	2.22	0.144	16.43	0.000	10.03	0.000	A	38.54	0.000	10.61	0.000	4.45	0.020
								t1	2.36	0.144	<1	0.884	<1	0.896
								t2	50.44	0.000	13.72	0.002	4.96	0.041
								t3	54.17	0.000	12.57	0.003	5.72	0.029
T8	550 – 600	6.49	0.012	41.41	0.000	5.81	0.005	A	46.41	0.000	33.50	0.000	29.83	0.000
								t1	1.70	0.211	20.67	0.000	30.33	0.000
								t2	67.96	0.000	52.62	0.000	49.10	0.000
								t3	45.13	0.000	19.74	0.000	13.06	0.002
T9	600 – 650	9.94	0.002	30.76	0.000	7.21	0.001	A	19.92	0.000	29.29	0.000	32.18	0.000
								t1	<1	0.715	7.25	0.016	13.14	0.002
								t2	22.22	0.000	42.70	0.000	46.17	0.000
								t3	28.92	0.000	26.60	0.000	24.79	0.000
T10	650 – 700	8.90	0.003	21.09	0.000	8.64	0.000	A	7.82	0.002	18.78	0.000	27.87	0.000
								t1	1.11	0.307	3.85	0.067	8.83	0.009
								t2	5.92	0.027	21.38	0.000	35.04	0.000
								t3	15.76	0.001	26.03	0.000	28.55	0.000
T11	700 – 750	6.56	0.010	6.17	0.006	3.87	0.020	A	2.67	0.084	5.04	0.013	9.21	0.001
								t1	----	----	<1	0.945	<1	0.979
								t2	----	----	5.45	0.033	9.61	0.007
								t3	----	----	9.48	0.007	15.23	0.001
T12	750 – 800	3.58	0.061	6.00	0.008	3.36	0.034	A	1.79	0.182	5.11	0.012	9.09	0.001
								t1	----	----	<1	0.642	<1	0.910
								t2	----	----	5.85	0.028	8.75	0.009
								t3	----	----	7.91	0.012	16.73	0.001
T13	800 – 850	2.70	0.101	3.03	0.063	2.29	0.104	A	---	---	---	---	---	---
T14	850 – 900	1.75	0.201	3.26	0.051	3.57	0.027	A	<1	0.831	2.51	0.097	7.27	0.002
								t1	----	----	----	----	<1	0.589
								t2	----	----	----	----	10.28	0.006
								t3	----	----	----	----	10.45	0.005

Table 2. Main effects of ELEC (Fz, Cz, Pz), TYPE (antonyms vs. related vs. non-related), ELEC x TYPE, and effects in each of the 3 ELECs (Fz, Cz, Pz) in fourteen successive 50 ms time windows (T1-T14) from 200 to 900 ms post-onset of the critical items in Experiment 2. The main effect for the 3 conditions (ANT = antonyms; REL = related category violations; NON = non-related category violations) in each ELEC is coded as A = ANT x REL x NON. The 3 single comparisons are: t1= REL x NON, t2 = ANT x NON, and t3 = ANT x REL.

2. Experiment 3

	TIME onset in ms	ROI *F* (3,48)	*p*	TYPE *F* (2,32)	*p*	ROI x TYPE *F(6*,69)	*p*		FroL *F* (1,16)	*p*	FroR *F* (1,16)	*p*	PosL *F* (1,16)	*p*	PosR *F* (1,16)	*p*
T1	-200	<1	.457	<1	.459	2.55	.025	A	2.28	.118	2.10	.139	1.09	.347	<1	.470
T2	-150	2.34	.085	1.85	.174	1.31	.259	A	---	---	---	---	---	---	---	---
T3	-100	3.87	.015	<1	.432	<1	.871	A	---	---	---	---	---	---	---	---
T4	-50	1.96	.133	2.69	.083	1.06	.393	A	---	---	---	---	---	---	---	---
T5	0	1.75	.169	<1	.994	2.29	.042	A	1.26	.297	1.19	.318	<1	.517	1.00	.381
T6	50	<1	.941	<1	.972	<1	.600	A	---	---	---	---	---	---	---	---
T7	100	1.17	.332	1.52	.234	<1	.937	A	---	---	---	---	---	---	---	---
T8	150	51.58	.000	<1	.556	<1	.663	A	---	---	---	---	---	---	---	---
T9	200	12.80	.000	1.33	.278	<1	.807	A	---	---	---	---	---	---	---	---
T10	250	4.65	.006	9.47	.001	5.88	.000	A	2.41	.106	10.07	.000	6.31	.005	15.60	.000
								t1	---	---	11.36	.004	2.99	.103	13.96	.002
								t2	---	---	14.70	.001	10.09	.006	21.96	.000
								t3	---	---	<1	.530	5.25	.036	2.57	.129
T11	300	5.42	.003	23.12	.000	9.02	.000	A	9.65	.001	19.11	.000	24.94	.000	29.65	.000
								t1	7.38	.015	16.93	.001	24.15	.000	24.95	.000
								t2	11.07	.004	22.20	.000	28.75	.000	34.50	.000
								t3	8.40	.010	10.74	.005	8.38	.011	19.14	.000
T12	350	4.85	.005	48.04	.000	13.69	.000	A	22.51	.000	23.97	.000	57.75	.000	53.32	.000
								t1	14.65	.001	20.09	.000	61.78	.000	46.61	.000
								t2	31.61	.000	36.88	.000	68.09	.000	64.38	.000
								t3	14.03	.002	9.29	.008	22.99	.000	26.80	.000
T13	400	3.89	.014	25.12	.000	16.52	.000	A	3.98	.029	13.86	.000	28.41	.000	41.04	.000
								t1	<1	.824	<1	.428	29.89	.000	25.20	.000
								t2	4.58	.048	21.95	.000	36.41	.000	72.44	.000
								t3	6.19	.024	14.15	.002	12.21	.003	19.37	.000
T14	450	4.28	.009	3.09	.059	8.14	.000	A	6.48	.004	8.22	.001	2.62	.089	6.40	.005
								t1	10.43	.005	8.10	.012	---	---	2.82	.113
								t2	3.87	.067	<1	.832	---	---	9.50	.007
								t3	3.48	.081	12.42	.003	---	---	5.26	.036
T15	500	3.68	.018	1.55	.227	4.02	.001	A	5.35	.010	3.15	.057	1.25	.301	<1	.669
								t1	9.47	.007	4.97	.040	---	---	---	---
								t2	6.08	.025	2.40	.141	---	---	---	---
								t3	<1	.550	1.33	.266	---	---	---	---
T16	550	12.18	.000	7.73	.002	6.89	.000	A	4.07	.027	2.33	.114	14.66	.000	10.55	.000
								t1	6.97	.018	---	---	9.27	.008	2.49	.134
								t2	5.40	.034	---	---	21.09	.000	22.54	.000
								t3	<1	.755	---	---	9.03	.008	7.36	.015
T17	600	11.99	.000	4.12	.026	5.99	.000	A	1.33	.280	<1	.398	13.39	.000	4.60	.017
								t1	---	---	---	---	7.35	.015	<1	.428
								t2	---	---	---	---	28.69	.000	14.33	.002
								t3	---	---	---	---	5.71	.030	3.68	.073
T18	650	12.23	.000	4.94	.014	7.85	.000	A	2.45	.103	1.52	.233	15.22	.000	5.98	.006
								t1	---	---	---	---	8.66	.010	3.72	.072
								t2	---	---	---	---	29.49	.000	13.38	.002
								t3	---	---	---	---	6.57	.021	2.00	.177
T19	700	10.11	.000	5.39	.010	4.33	.001	A	3.84	.032	4.00	.028	9.53	.001	4.07	.027
								t1	5.40	.034	2.22	.156	12.68	.003	6.11	.025
								t2	<1	.526	1.59	.226	8.80	.009	4.52	.049
								t3	8.65	.010	8.87	.009	1.89	.188	1.20	.289
T20	750	4.56	.007	2.24	.123	3.77	.002	A	<1	.429	3.55	.041	4.04	.027	3.70	.036
								t1	---	---	1.04	.323	5.94	.027	5.78	.029
								t2	---	---	2.63	.124	7.22	.016	5.94	.027
								t3	---	---	7.30	.016	<1	.876	<1	.609
T21	800	4.73	.006	<1	.580	1.96	.079	A	---	---	---	---	---	---	---	---
T22	850	3.71	.018	<1	.457	<1	.763	A	---	---	---	---	---	---	---	---
T23	900	5.32	.003	<1	.696	1.03	.411	A	---	---	---	---	---	---	---	---
T24	950	4.07	.012	2.12	.136	<1	.664	A	---	---	---	---	---	---	---	---

Table 3. Main effects of ROI, TYPE (antonyms vs. related vs. non-related), ROI x TYPE, and effects in each of the 4 ROIs (frontal-left = FroL; frontal-right = FroR; posterior-left = PosL; posterior-right = PosR) in 24 successive 50 ms time windows (T1-T24) from -200 to 1000 ms post-onset of the critical items in Experiment 3. The main effect for the 3 conditions (ANT = antonyms; REL = related category violations; NON = non-related category violations) in each ROI is coded as A = ANT x REL x NON. The 3 single comparisons are: t1= REL x NON, t2 = ANT x NON, and t3 = ANT x REL.

	TIME onset in ms	ELEC *F* (2,32)	*p*	TYPE *F* (2,32)	*p*	ELEC x TYPE *F* (4,64)	*p*		Fz *F* (1,16)	*p*	Cz *F* (1,16)	*p*	Pz *F* (1,16)	*p*
T1	-200	2.55	.094	<1	.912	2.37	.062	A	---	---	---	---	---	---
T2	-150	1.28	.291	<1	.452	<1	.729	A	---	---	---	---	---	---
T3	-100	2.46	.101	<1	.675	<1	.661	A	---	---	---	---	---	---
T4	-50	3.48	.043	3.07	.060	<1	.792	A	---	---	---	---	---	---
T5	0	5.07	.012	<1	.891	1.79	.141	A	---	---	---	---	---	---
T6	50	7.42	.003	<1	.652	<1	.900	A	---	---	---	---	---	---
T7	100	9.49	.001	1.43	.255	<1	.954	A	---	---	---	---	---	---
T8	150	12.04	.000	<1	.762	1.02	.402	A	---	---	---	---	---	---
T9	200	1.26	.297	1.78	.184	1.86	.128	A	---	---	---	---	---	---
T10	250	4.59	.018	13.90	.000	<1	.989	A	13.40	.000	10.50	.000	13.47	.000
								t1	15.75	.001	13.65	.002	13.52	.002
								t2	17.19	.001	13.85	.002	22.89	.000
								t3	1.39	.256	1.02	.327	1.27	.276
T11	300	12.93	.000	26.57	.000	8.82	.000	A	20.44	.000	24.93	.000	30.22	.000
								t1	17.72	.001	24.87	.000	27.47	.000
								t2	24.11	.000	29.43	.000	37.91	.000
								t3	11.84	.003	8.89	.009	8.77	.009
T12	350	9.54	.001	44.39	.000	27.24	.000	A	25.52	.000	42.19	.000	54.72	.000
								t1	12.14	.003	42.52	.000	52.65	.000
								t2	42.60	.000	60.05	.000	74.03	.000
								t3	16.42	.001	14.59	.002	18.13	.001
T13	400	13.51	.000	24.13	.000	25.96	.000	A	7.73	.002	24.72	.000	36.23	.000
								t1	<1	.662	22.31	.000	33.12	.000
								t2	8.47	.010	35.44	.000	53.09	.000
								t3	13.33	.002	12.74	.003	15.42	.001
T14	450	2.57	.092	3.16	.056	19.47	.000	A	11.11	.000	2.59	.091	9.27	.001
								t1	15.44	.001	---	---	11.04	.004
								t2	5.43	.033	---	---	11.40	.004
								t3	8.62	.010	---	---	2.88	.109
T15	500	<1	.694	<1	.668	11.30	.000	A	6.15	.005	<1	.737	1.21	.311
								t1	9.43	.007	---	---	---	---
								t2	6.06	.026	---	---	---	---
								t3	1.65	.218	---	---	---	---
T16	550	10.35	.000	3.82	.033	8.13	.000	A	4.57	.018	2.54	.095	8.35	.001
								t1	6.32	.023	---	---	<1	.643
								t2	4.46	.051	---	---	12.79	.003
								t3	1.82	.196	---	---	9.75	.007
T17	600	6.52	.004	2.03	.147	5.23	.001	A	1.38	.267	1.87	.170	4.83	.015
								t1	---	---	---	---	<1	.700
								t2	---	---	---	---	12.21	.003
								t3	---	---	---	---	4.78	.044
T18	650	4.50	.019	3.86	.031	11.87	.000	A	3.46	.044	3.69	.036	9.89	.000
								t1	4.77	.044	2.40	.141	1.83	.195
								t2	<1	.587	11.92	.003	25.00	.000
								t3	4.36	.053	<1	.380	7.42	.015
T19	700	3.20	.054	3.55	.041	5.78	.000	A	7.35	.002	2.24	.123	2.39	.108
								t1	8.05	.012	---	---	---	---
								t2	<1	.366	---	---	---	---
								t3	12.74	.003	---	---	---	---
T20	750	1.53	.233	<1	.588	8.33	.000	A	4.09	.026	<1	.747	1.57	.224
								t1	5.64	.030	---	---	---	---
								t2	1.26	.279	---	---	---	---
								t3	5.32	.035	---	---	---	---
T21	800	<1	.648	<1	.971	3.56	.011	A	1.90	.167	<1	.938	<1	.835
								t1	---	---	---	---	---	---
								t2	---	---	---	---	---	---
								t3	---	---	---	---	---	---
T22	850	<1	.918	1.06	.358	3.06	.023	A	<1	.936	1.37	.270	2.10	.138
								t1	---	---	---	---	---	---
								t2	---	---	---	---	---	---
								t3	---	---	---	---	---	---
T23	900	<1	.812	<1	.435	1.95	.112	A	---	---	---	---	---	---
T24	950	1.00	.378	2.32	.115	2.03	.100	A	---	---	---	---	---	---

Table 4. Main effects of ELEC (Fz, Cz, Pz), TYPE (antonyms vs. related vs. non-related), ELEC x TYPE, and effects in each of the 3 ELECs (Fz, Cz, Pz) in 24 successive 50 ms time windows (T1-T24) from -200 to 1000 ms post-onset of the critical items in Experiment 3. The main effect for the 3 conditions (ANT = antonyms; REL = related category violations; NON = non-related category violations) in each ELEC is coded as A = ANT x REL x NON. The 3 single comparisons are: t1= REL x NON, t2 = ANT x NON, and t3 = ANT x REL.

3. Experiment 5

	TIME onset in ms	ROI *F* (3,48)	*p*	TYPE *F* (2,32)	*p*	ROI x TYPE *F* (6,96)	*p*		FroL *F* (1,16)	*p*	FroR *F* (1,16)	*p*	PosL *F* (1,16)	*p*	PosR *F* (1,16)	*p*
T1	-200	1.01	.395	<1	.757	<1	.652	A	---	---	---	---	---	---	---	---
T2	-150	3.15	.033	<1	.723	<1	.852	A	---	---	---	---	---	---	---	---
T3	-100	5.71	.002	<1	.768	1.79	.108	A	---	---	---	---	---	---	---	---
T4	-50	3.79	.016	<1	.583	2.18	.052	A	<1	.797	1.26	.296	<1	.530	2.68	.084
T5	0	2.46	.074	<1	.903	<1	.856	A	---	---	---	---	---	---	---	---
T6	50	3.01	.039	<1	.488	<1	.657	A	---	---	---	---	---	---	---	---
T7	100	5.45	.003	<1	.564	<1	.808	A	---	---	---	---	---	---	---	---
T8	150	39.39	.000	<1	.419	1.21	.307	A	---	---	---	---	---	---	---	---
T9	200	16.43	.000	1.46	.247	2.08	.062	A	<1	.626	2.46	.102	1.63	.212	2.36	.110
T10	250	2.81	.050	1.77	.186	1.60	.156	A	---	---	---	---	---	---	---	---
T11	300	3.38	.026	8.47	.001	1.89	.091	A	2.20	.128	4.56	.018	9.42	.001	15.29	.000
								t1	---	---	4.55	.049	6.03	.026	19.29	.000
								t2	---	---	7.67	.014	22.98	.000	22.41	.000
								t3	---	---	1.28	.275	2.93	.106	5.11	.038
T12	350	1.45	.241	24.45	.000	2.09	.062	A	8.36	.001	9.23	.001	46.71	.000	25.83	.000
								t1	2.89	.109	4.57	.048	19.57	.000	25.60	.000
								t2	10.26	.006	12.01	.003	78.79	.000	37.37	.000
								t3	9.56	.007	7.78	.013	35.88	.000	13.24	.002
T13	400	3.61	.020	22.09	.000	4.04	.001	A	5.92	.007	9.60	.001	34.93	.000	30.24	.000
								t1	<1	.528	1.36	.261	27.55	.000	13.49	.002
								t2	8.49	.010	13.40	.002	67.66	.000	56.80	.000
								t3	7.92	.012	17.20	.001	10.93	.004	18.45	.001
T14	450	4.36	.009	15.40	.000	<1	.511	A	7.78	.002	10.98	.000	16.08	.000	10.18	.000
								t1	<1	.914	1.32	.268	6.05	.026	2.66	.122
								t2	8.08	.012	19.01	.000	21.82	.000	14.56	.002
								t3	12.88	.002	10.84	.005	14.83	.001	11.21	.004
T15	500	4.04	.012	4.56	.018	1.89	.091	A	5.11	.012	4.54	.018	4.55	.018	1.24	.302
								t1	<1	.800	1.96	.181	<1	.708	---	---
								t2	5.10	.038	7.95	.012	6.62	.020	---	---
								t3	8.87	.009	2.94	.106	7.39	.015	---	---
T16	550	6.37	.001	<1	.404	2.13	.057	A	<1	.903	<1	.480	2.33	.114	2.07	.143
T17	600	6.84	.001	<1	.874	2.14	.056	A	<1	.780	1.07	.354	<1	.797	1.79	.183
T18	650	5.12	.004	<1	.409	<1	.452	A	---	---	---	---	---	---	---	---
T19	700	4.41	.008	<1	.609	1.63	.147	A	---	---	---	---	---	---	---	---
T20	750	4.73	.006	7.15	.003	2.30	.041	A	2.46	.102	2.72	.081	12.01	.000	8.89	.001
								t1	---	---	---	---	14.58	.002	2.82	.113
								t2	---	---	---	---	28.67	.000	21.25	.000
								t3	---	---	---	---	<1	.385	5.33	.035
T21	800	1.95	.134	2.85	.073	1.78	.112	A	---	---	---	---	---	---	---	---
T22	850	3.81	.016	3.28	.051	1.27	.279	A	<1	.746	1.29	.289	8.65	.001	9.92	.000
								t1	---	---	---	---	4.63	.047	3.26	.090
								t2	---	---	---	---	18.07	.001	14.56	.002
								t3	---	---	---	---	3.77	.070	12.36	.003
T23	900	4.26	.010	<1	.406	<1	.840	A	---	---	---	---	---	---	---	---
T24	950	1.94	.136	<1	.553	<1	.975	A	---	---	---	---	---	---	---	---

Table5. Main effects of ROI, TYPE (antonyms vs. related vs. non-related), ROI x TYPE, and effects in each of the 4 ROIs (frontal-left = FroL; frontal-right = FroR; posterior-left = PosL; posterior-right = PosR) in 24 successive 50 ms time windows (T1-T24) from -200 to 1000 ms post-onset of the critical items in Experiment 5. The main effect for the 3 conditions (ANT = antonyms; REL = related category violations; NON = non-related category violations) in each ROI is coded as A = ANT x REL x NON. The 3 single comparisons are: t1= REL x NON, t2 = ANT x NON, and t3 = ANT x REL.

	TIME in ms	ELEC *F* (2,32)	*p*	TYPE *F* (2,32)	*p*	ELEC x TYPE *F* (4,64)	*p*		Fz *F* (1,16)	*p*	Cz *F* (1,16)	*p*	Pz *F* (1,16)	*p*
T1	-200	4.60	.018	<1	.774	<1	.427	A	---	---	---	---	---	---
T2	-150	<1	.717	<1	.524	<1	.741	A	---	---	---	---	---	---
T3	-100	1.92	.163	<1	.957	1.28	.287	A	---	---	---	---	---	---
T4	-50	2.91	.069	<1	.518	1.44	.233	A	---	---	---	---	---	---
T5	0	3.87	.031	1.00	.380	1.00	.414	A	---	---	---	---	---	---
T6	50	3.91	.030	1.40	.262	<1	.753	A	---	---	---	---	---	---
T7	100	11.34	.000	<1	.528	2.06	.096	A	---	---	---	---	---	---
T8	150	18.58	.000	1.45	.249	1.33	.267	A	---	---	---	---	---	---
T9	200	10.77	.000	1.89	.168	1.94	.114	A	---	---	---	---	---	---
T10	250	3.81	.033	3.57	.040	3.82	.008	A	5.40	.010	3.82	.033	1.38	.267
								t1	6.74	.019	6.40	.022	---	---
								t2	8.84	.009	6.22	.024	---	---
								t3	<1	.536	<1	.758	---	---
T11	300	7.21	.003	8.47	.001	<1	.530	A	5.79	.007	8.27	.001	8.92	.001
								t1	6.41	.022	12.77	.003	15.49	.001
								t2	10.22	.006	13.80	.002	14.16	.002
								t3	1.49	.240	1.68	.213	1.53	.234
T12	350	5.87	.007	29.53	.000	4.47	.003	A	11.85	.000	30.24	.000	39.89	.000
								t1	4.01	.063	12.64	.003	21.13	.000
								t2	13.43	.002	36.27	.000	51.61	.000
								t3	14.38	.002	34.91	.000	34.40	.000
T13	400	2.87	.071	22.64	.000	3.94	.006	A	12.14	.000	19.46	.000	26.40	.000
								t1	1.88	.189	9.25	.008	20.42	.000
								t2	16.51	.001	36.10	.000	40.22	.000
								t3	16.83	.001	11.18	.004	11.14	.004
T14	450	3.35	.048	19.00	.000	1.43	.234	A	10.28	.000	20.32	.000	18.40	.000
								t1	1.46	.244	5.55	.032	8.33	.011
								t2	15.61	.001	34.38	.000	27.37	.000
								t3	10.59	.005	15.76	.001	15.28	.001
T15	500	1.62	.214	3.94	.029	<1	.579	A	3.69	.036	4.01	.028	2.69	.083
								t1	<1	.589	<1	.968	---	---
								t2	5.98	.026	7.30	.016	---	---
								t3	4.00	.063	5.77	.029	---	---
T16	550	7.40	.002	1.18	.320	2.76	.035	A	<1	.674	<1	.417	3.09	.059
T17	600	6.69	.004	<1	.994	1.03	.401	A	---	---	---	---	---	---
T18	650	6.29	.005	1.65	.208	1.00	.415	A	---	---	---	---	---	---
T19	700	7.79	.002	1.08	.350	<1	.874	A	---	---	---	---	---	---
T20	750	6.41	.005	8.32	.001	2.01	.103	A	4.38	.021	8.50	.001	9.68	.001
								t1	<1	.460	6.64	.020	5.92	.027
								t2	8.02	.012	25.78	.000	32.99	.000
								t3	4.35	.053	1.51	.237	2.53	.131
T21	800	6.23	.005	3.18	.055	2.49	.052	A	3.36	.047	3.38	.047	2.39	.108
								t1	<1	.844	2.11	.165	---	---
								t2	5.12	.038	9.03	.008	---	---
								t3	6.92	.018	<1	.391	---	---
T22	850	9.04	.001	5.83	.007	1.33	.270	A	1.74	.192	5.72	.008	11.54	.000
								t1	---	---	4.81	.043	6.96	.018
								t2	---	---	7.84	.013	20.87	.000
								t3	---	---	1.49	.240	4.85	.043
T23	900	7.19	.003	1.60	.218	<1	.567	A	---	---	---	---	---	---
T24	950	2.65	.086	1.22	.309	<1	.533	A	---	---	---	---	---	---

Table 6. Main effects of ELEC (Fz, Cz, Pz), TYPE (antonyms vs. related vs. non-related), ELEC x TYPE, and effects in each of the 3 ELECs (Fz, Cz, Pz) in 24 successive 50 ms time windows (T1-T24) from -200 to 1000 ms post-onset of the critical items in Experiment 5. The main effect for the 3 conditions (ANT = antonyms; REL = related category violations; NON = non-related category violations) in each ELEC is coded as A = ANT x REL x NON. The 3 single comparisons are: t1= REL x NON, t2 = ANT x NON, and t3 = ANT x REL.

A	TIME in ms	ROI *F* (3,48)	*p*	STIM$_A$ *F* (1,16)	*p*	ROI x STIM$_A$ *F* (3,48)	*p*		FroL *F* (1,16)	*p*	FroR *F* (1,16)	*p*	PosL *F* (1,16)	*p*	PosR *F* (1,16)	*p*
T1	-200	1.37	.263	<1	.985	<1	.806	A	---	---	---	---	---	---	---	---
T2	-150	4.65	.006	<1	.606	1.58	.206	A	---	---	---	---	---	---	---	---
T3	-100	7.93	.000	<1	.874	<1	.822	A	---	---	---	---	---	---	---	---
T4	-50	3.24	.030	<1	.593	1.12	.348	A	---	---	---	---	---	---	---	---
T5	0	4.34	.009	<1	.590	<1	.515	A	---	---	---	---	---	---	---	---
T6	50	3.17	.033	<1	.681	<1	.721	A	---	---	---	---	---	---	---	---
T7	100	4.56	.007	1.63	.220	<1	.453	A	---	---	---	---	---	---	---	---
T8	150	34.83	.000	<1	.369	<1	.867	A	---	---	---	---	---	---	---	---
T9	200	15.42	.000	3.48	.081	<1	.939	A	---	---	---	---	---	---	---	---
T10	250	5.36	.003	5.34	.034	1.01	.398	A	<1	.621	1.39	.256	5.70	.030	6.79	.019
T11	300	3.68	.018	25.44	.000	4.18	.010	A	6.99	.018	7.98	.012	23.86	.000	28.99	.000
T12	350	3.30	.028	38.24	.000	<1	.609	A	13.81	.002	26.20	.000	46.05	.000	48.32	.000
T13	400	6.71	.001	17.22	.001	<1	.555	A	10.97	.004	8.12	.012	29.46	.000	9.17	.008
T14	450	4.46	.008	3.80	.069	<1	.676	A	2.33	.147	5.15	.037	3.92	.065	1.09	.311
T15	500	2.39	.080	<1	.512	1.17	.330	A	---	---	---	---	---	---	---	---
T16	550	7.10	.000	5.83	.028	2.99	.040	A	6.25	.024	1.66	.215	4.60	.048	7.09	.017
T17	600	9.80	.000	12.85	.002	7.88	.000	A	9.85	.006	2.64	.124	12.69	.003	16.96	.001
T18	650	14.33	.000	17.52	.001	6.60	.001	A	10.04	.006	3.12	.097	18.22	.001	16.77	.001
T19	700	12.24	.000	21.73	.000	10.20	.000	A	4.49	.050	8.19	.011	28.68	.000	29.54	.000
T20	750	7.56	.000	30.21	.000	7.60	.000	A	5.78	.029	14.61	.001	40.79	.000	22.28	.000
T21	800	4.43	.008	14.33	.002	5.67	.002	A	2.02	.175	5.15	.037	33.04	.000	10.33	.005
T22	850	4.09	.011	8.36	.011	1.93	.137	A	1.18	.294	1.60	.225	18.79	.001	12.56	.003
T23	900	2.20	.101	<1	.682	<1	.613	A	---	---	---	---	---	---	---	---
T24	950	3.47	.023	<1	.874	<1	.454	A	---	---	---	---	---	---	---	---

Table 7. Main effects of ROI, STIM$_A$ (antonyms vs.pseudowords), ROI x STIM$_A$, and effects in each of the 4 ROIs (frontal-left = FroL; frontal-right = FroR; posterior-left = PosL; posterior-right = PosR) in 24 successive 50 ms time windows (T1-T24) from -200 to 1000 ms post-onset of the critical items in Experiment 5. The effects for the 2 conditions (ANT = antonyms; PSW = pseudoword in 2nd position) in each ROI are coded as A = ANT x PSW.

A	TIME in ms	ELEC *F*(2,32)	*p*	STIM$_A$ *F* (1,16)	*p*	ELEC x STIM$_A$ *F* (2,32)	*p*		Fz *F* (1,16)	*p*	Cz *F* (1,16)	*p*	Pz *F* (1,16)	*p*
T1	-200	2.67	.085	<1	.693	<1	.766	A	---	---	---	---	---	---
T2	-150	1.08	.352	1.47	.242	<1	.697	A	---	---	---	---	---	---
T3	-100	3.53	.041	1.50	.238	<1	.476	A	---	---	---	---	---	---
T4	-50	3.45	.044	<1	.378	2.12	.136	A	---	---	---	---	---	---
T5	0	7.35	.002	<1	.856	<1	.873	A	---	---	---	---	---	---
T6	50	4.29	.022	<1	.806	<1	.928	A	---	---	---	---	---	---
T7	100	8.99	.001	<1	.373	5.53	.009	A	<1	.696	1.91	.186	3.39	.084
T8	150	15.20	.000	<1	.638	<1	.937	A	---	---	---	---	---	---
T9	200	9.62	.001	3.08	.098	<1	.777	A	---	---	---	---	---	---
T10	250	5.75	.007	4.89	.042	<1	.754	A	1.84	.193	5.99	.026	3.25	.090
T11	300	10.75	.000	20.74	.000	5.45	.009	A	9.65	.007	21.68	.000	22.46	.000
T12	350	8.73	.001	38.57	.000	6.81	.003	A	12.30	.003	50.17	.000	49.73	.000
T13	400	2.73	.080	11.06	.004	3.37	.047	A	4.07	.061	13.40	.002	12.61	.003
T14	450	2.89	.070	1.22	.286	<1	.466	A	---	---	---	---	---	---
T15	500	1.72	.196	<1	.349	<1	.857	A	---	---	---	---	---	---
T16	550	8.34	.001	6.73	.020	2.14	.134	A	6.22	.024	8.06	.012	5.07	.039
T17	600	12.00	.000	12.38	.003	11.87	.000	A	7.31	.016	14.38	.002	13.02	.002
T18	650	17.57	.000	14.51	.002	8.28	.001	A	5.66	.030	16.78	.001	13.92	.002
T19	700	19.09	.000	15.79	.001	9.00	.001	A	5.23	.036	15.72	.001	23.95	.000
T20	750	11.89	.000	17.39	.001	5.27	.011	A	6.09	.025	15.49	.001	20.33	.000
T21	800	10.13	.000	6.24	.024	4.15	.025	A	1.41	.252	7.12	.017	8.54	.010
T22	850	8.67	.001	3.33	.087	1.27	.296	A	---	---	---	---	---	---
T23	900	4.67	.017	<1	.690	<1	.580	A	---	---	---	---	---	---
T24	950	5.84	.007	<1	.773	1.48	.242	A	---	---	---	---	---	---

Table 8. Main effects of ELEC (Fz, Cz, Pz), STIM$_A$ (antonyms vs. pseudowords), ELEC x STIM$_A$, and effects in each of the 3 ELECs (Fz, Cz, Pz) in 24 successive 50 ms time windows (T1-T24) from -200 to 1000 ms post-onset of the critical items in Experiment 5. The effects for the 2 conditions (ANT = antonyms; PSW = pseudowords in 2nd position) in each ELEC is coded as A = ANT x PSW.

B	TIME in ms	ROI *F* (3,48)	*p*	STIM$_B$ *F* (1,16)	*p*	ROI x STIM$_B$ *F* (3,48)	*p*		FroL *F* (1,16)	*p*	FroR *F* (1,16)	*p*	PosL *F* (1,16)	*p*	PosR *F* (1,16)	*p*
T1	-200	1.16	.335	<1	.537	<1	.826	B	---	---	---	---	---	---		
T2	-150	4.28	.009	<1	.693	<1	.453	B	---	---	---	---	---	---		
T3	-100	6.74	.001	<1	.755	2.65	.060	B	---	---	---	---	---	---		
T4	-50	5.15	.004	<1	.955	<1	.857	B	---	---	---	---	---	---		
T5	0	2.71	.056	<1	.387	2.98	.040	B	<1	.930	<1	.478	1.68	.213	4.80	.044
T6	50	2.54	.068	1.67	.214	<1	.927	B	---	---	---	---	---	---		
T7	100	4.10	.011	3.24	.091	<1	.667	B	---	---	---	---	---	---		
T8	150	37.76	.000	3.00	.103	<1	.523	B	---	---	---	---	---	---		
T9	200	15.11	.000	2.10	.166	1.48	.233	B	---	---	---	---	---	---		
T10	250	3.34	.027	1.09	.312	4.72	.006	B	<1	.651	1.37	.259	5.37	.034	4.02	.062
T11	300	1.86	.149	1.63	.220	1.22	.314	B	---	---	---	---	---	---		
T12	350	<1	.444	1.15	.299	1.33	.276	B	---	---	---	---	---	---		
T13	400	2.64	.060	<1	.350	3.01	.039	B	<1	.455	<1	.528	1.55	.230	2.98	.104
T14	450	3.64	.019	3.75	.071	<1	.665	B	1.85	.192	2.30	.149	2.81	.113	5.53	.032
T15	500	2.24	.095	7.59	.014	<1	.752	B	7.63	.014	7.27	.016	4.98	.040	6.33	.023
T16	550	8.33	.000	8.27	.011	<1	.562	B	12.04	.003	6.26	.024	4.33	.054	8.10	.012
T17	600	12.96	.000	19.05	.000	2.92	.043	B	19.54	.000	10.84	.005	15.26	.001	18.35	.001
T18	650	12.95	.000	29.28	.000	5.47	.003	B	15.72	.001	7.03	.017	24.73	.000	24.00	.000
T19	700	10.78	.000	19.44	.000	8.39	.000	B	8.59	.010	5.19	.037	36.60	.000	20.58	.000
T20	750	8.14	.000	7.56	.014	4.83	.005	B	<1	.388	3.27	.090	14.44	.002	7.37	.015
T21	800	4.69	.006	4.76	.044	4.81	.005	B	<1	.920	1.49	.240	12.71	.003	4.04	.062
T22	850	5.00	.004	2.19	.158	1.15	.340	B	---	---	---	---	---	---		
T23	900	2.91	.044	<1	.463	<1	.673	B	---	---	---	---	---	---		
T24	950	2.63	.061	<1	.474	<1	.463	B	---	---	---	---	---	---		

Table 9. Main effects of ROI, STIM$_B$ (non-related vs. pseudowords), ROI x STIM$_B$, and effects in each of the 4 ROIs (frontal-left = FroL; frontal-right = FroR; posterior-left = PosL; posterior-right = PosR) in 24 successive 50 ms time windows (T1-T24) from -200 to 1000 ms post-onset of the critical items in Experiment 5. The effects for the 2 conditions (NON = non-related; PSW = pseudoword in 2nd position) in each ROI are coded as B = NON x PSW.

B	TIME in ms	ELEC *F*(2,32)	*p*	STIM$_B$ *F* (1,16)	*p*	ELEC x STIM$_B$ *F* (2,32)	*p*		Fz *F* (1,16)	*p*	Cz *F* (1,16)	*p*	Pz *F* (1,16)	*p*
T1	-200	3.87	.031	<1	.502	<1	.881	B	---	---	---	---	---	---
T2	-150	<1	.390	<1	.980	<1	.560	B	---	---	---	---	---	---
T3	-100	2.22	.125	<1	.619	3.10	.059	B	---	---	---	---	---	---
T4	-50	5.41	.009	<1	.659	<1	.490	B	---	---	---	---	---	---
T5	0	5.29	.010	1.00	.332	1.36	.270	B	---	---	---	---	---	---
T6	50	3.66	.037	1.43	.250	<1	.855	B	---	---	---	---	---	---
T7	100	9.03	.001	2.93	.106	3.20	.054	B	<1	.612	4.01	.062	6.82	.019
T8	150	16.85	.000	4.01	.062	1.82	.178	B	<1	.555	6.57	.021	5.79	.029
T9	200	7.74	.002	<1	.431	<1	.566	B	---	---	---	---	---	---
T10	250	4.20	.024	<1	.871	3.67	.037	B	3.20	.092	<1	.921	1.60	.225
T11	300	10.74	.000	<1	.643	1.37	.268	B	---	---	---	---	---	---
T12	350	9.41	.001	<1	.485	<1	.727	B	---	---	---	---	---	---
T13	400	3.29	.050	5.00	.040	<1	.922	B	4.65	.047	3.76	.070	4.30	.055
T14	450	2.37	.109	4.63	.047	<1	.645	B	4.08	.061	4.37	.053	4.15	.058
T15	500	1.46	.247	8.04	.012	<1	.512	B	10.25	.006	8.80	.009	4.91	.041
T16	550	9.05	.001	9.85	.006	<1	.409	B	11.20	.004	11.55	.004	5.70	.030
T17	600	12.79	.000	17.51	.001	6.35	.005	B	10.17	.006	22.84	.000	16.05	.001
T18	650	14.98	.00	18.69	.001	9.18	.001	B	5.30	.035	20.72	.000	21.81	.000
T19	700	13.24	.000	11.41	.004	15.65	.000	B	3.04	.101	10.72	.005	22.58	.000
T20	750	9.51	.001	2.86	.110	4.84	.015	B	<1	.654	2.91	.107	5.34	.034
T21	800	8.60	.001	<1	.483	6.14	.006	B	<1	.415	1.09	.311	2.46	.136
T22	850	10.39	.000	<1	.437	<1	.967	B	---	---	---	---	---	---
T23	900	6.37	.005	3.90	.066	<1	.395	B	---	---	---	---	---	---
T24	950	5.12	.142	2.39	.142	<1	.572	B	---	---	---	---	---	---

Table 10. Main effects of ELEC (Fz, Cz, Pz), STIM$_B$ (non-related vs. pseudowords), ELEC x STIM$_B$, and effects in each of the 3 ELECs (Fz, Cz, Pz) in 24 successive 50 ms time windows (T1-T24) from -200 to 1000 ms post-onset of the critical items in Experiment 5. The effects for the 2 conditions (NON = non-related; PSW = pseudowords in 2nd position) in each ELEC is coded as B = NON x PSW.

4. Experiment 6

	TIME in ms	OR *F* (1,15)	*p*	ROI x OR *F* (5,75)	*p*	FroL *F* (1,15)	*p*	FroR *F* (1,15)	*p*	PosL *F* (1,15)	*p*	PosR *F* (1,15)	*p*	CeAnt *F* (1,15)	*p*	CePos *F* (1,15)	*p*
T1	-200	1.29	.273	4.49	.001	<1	.678	<1	.741	2.29	.151	6.59	.021	<1	.927	5.63	.032
T2	-150	<1	.730	<1	.433	---	---	---	---	---	---	---	---	---	---	---	---
T3	-100	1.85	.194	1.36	.248	---	---	---	---	---	---	---	---	---	---	---	---
T4	-50	<1	.680	<1	.762	---	---	---	---	---	---	---	---	---	---	---	---
T5	0	<1	.911	1.09	.372	---	---	---	---	---	---	---	---	---	---	---	---
T6	50	<1	.644	1.15	.342	---	---	---	---	---	---	---	---	---	---	---	---
T7	100	3.16	.096	1.06	.387	---	---	---	---	---	---	---	---	---	---	---	---
T8	150	<1	.359	1.02	.412	---	---	---	---	---	---	---	---	---	---	---	---
T9	200	<1	.577	1.26	.288	---	---	---	---	---	---	---	---	---	---	---	---
T10	250	1.02	.329	2.67	.028	3.72	.073	<1	.342	1.00	.333	<1	.792	4.67	.047	<1	.987
T11	300	<1	.617	<1	.491	---	---	---	---	---	---	---	---	---	---	---	---
T12	350	<1	.490	1.97	.092	---	---	---	---	---	---	---	---	---	---	---	---
T13	400	2.55	.131	1.05	.392	---	---	---	---	---	---	---	---	---	---	---	---
T14	450	18.49	.001	3.81	.004	1.50	.239	6.45	.023	19.04	.001	26.91	.000	13.12	.003	20.22	.000
T15	500	24.81	.000	3.43	.008	2.04	.174	4.49	.051	14.14	.002	18.89	.001	13.46	.002	21.17	.000
T16	550	9.97	.007	5.64	.000	<1	.867	2.68	.122	12.39	.003	21.91	.000	2.30	.150	21.19	.000
T17	600	<1	.436	8.04	.000	1.26	.279	<1	.666	2.33	.148	6.89	.019	<1	.974	5.89	.028
T18	650	3.28	.090	1.85	.114	---	---	---	---	---	---	---	---	---	---	---	---
T19	700	2.21	.158	<1	.755	---	---	---	---	---	---	---	---	---	---	---	---
T20	750	<1	.967	<1	.603	---	---	---	---	---	---	---	---	---	---	---	---
T21	800	<1	.540	2.43	.043	1.45	.247	1.84	.195	<1	.903	<1	.820	1.88	.190	<1	.631
T22	850	<1	.904	<1	.517	---	---	---	---	---	---	---	---	---	---	---	---
T23	900	<1	.741	<1	.798	---	---	---	---	---	---	---	---	---	---	---	---
T24	950	1.04	.324	<1	.841	---	---	---	---	---	---	---	---	---	---	---	---

Table 11. Main effects of ORDER (*subject-object* vs. *object-subject*) and ROI x ORDER, and effects in each of the 6 ROIs (frontal-left = FroL; frontal-right = FroR; posterior-left = PosL; posterior-right = PosR; central-anterior = CeAnt; central-posterior = CePos) in 24 successive 50 ms time windows (T1-T24) from -200 to 1000 ms post-onset of the critical items in Experiment 6.

Appendix D

Supplementary Time-frequency Plots

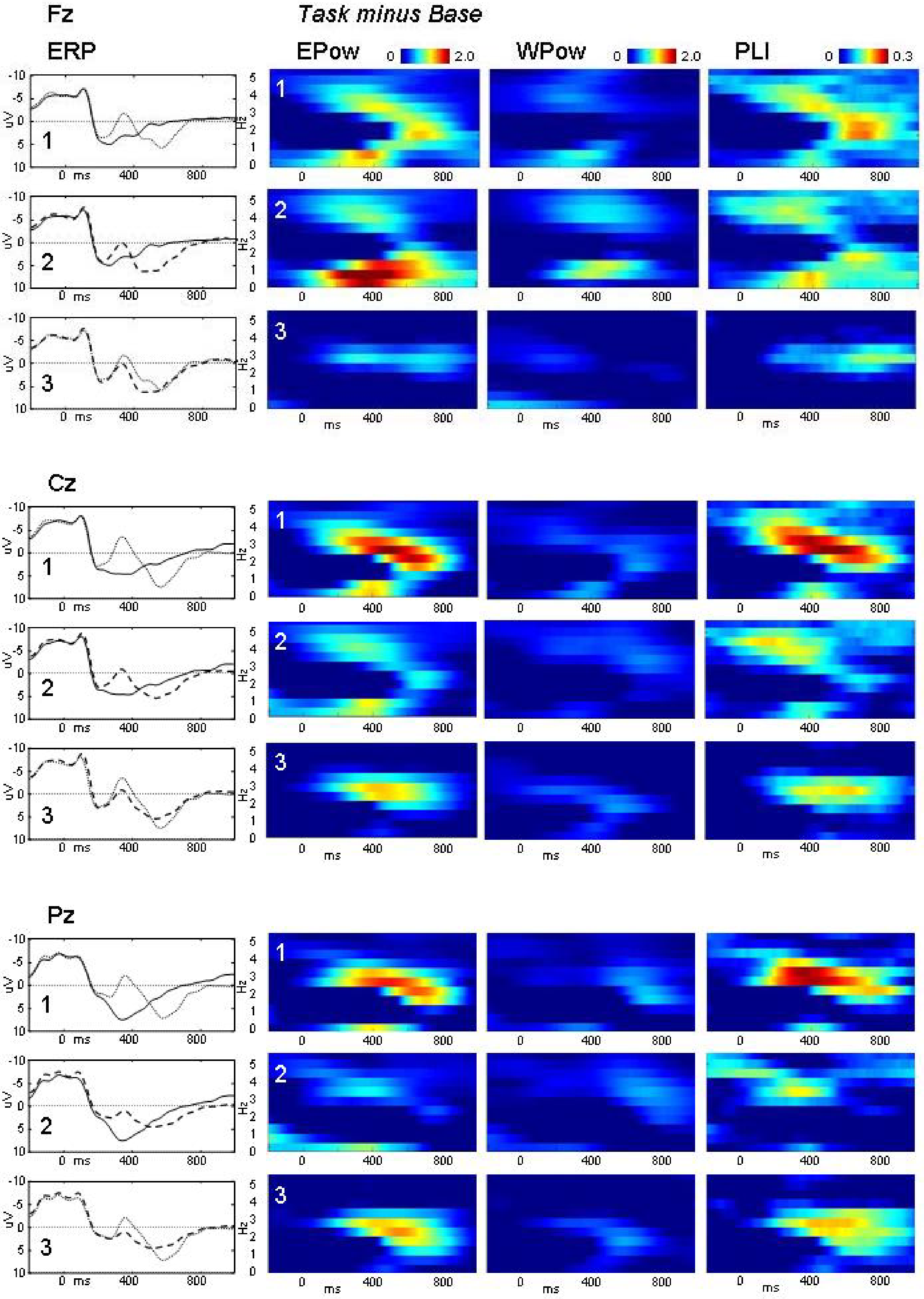

Figure D1-1. Experiment 2: Grand average ERPs and Gabor wavelet-based time-frequency difference plots for the non-related category (1) and related category violations (2) in comparison to the antonym control condition at electrodes Fz, Cz, and Pz (N=17). The antonym control condition is subtracted from the two critical conditions. In (3) the related category is subtracted from the non-related category violation.

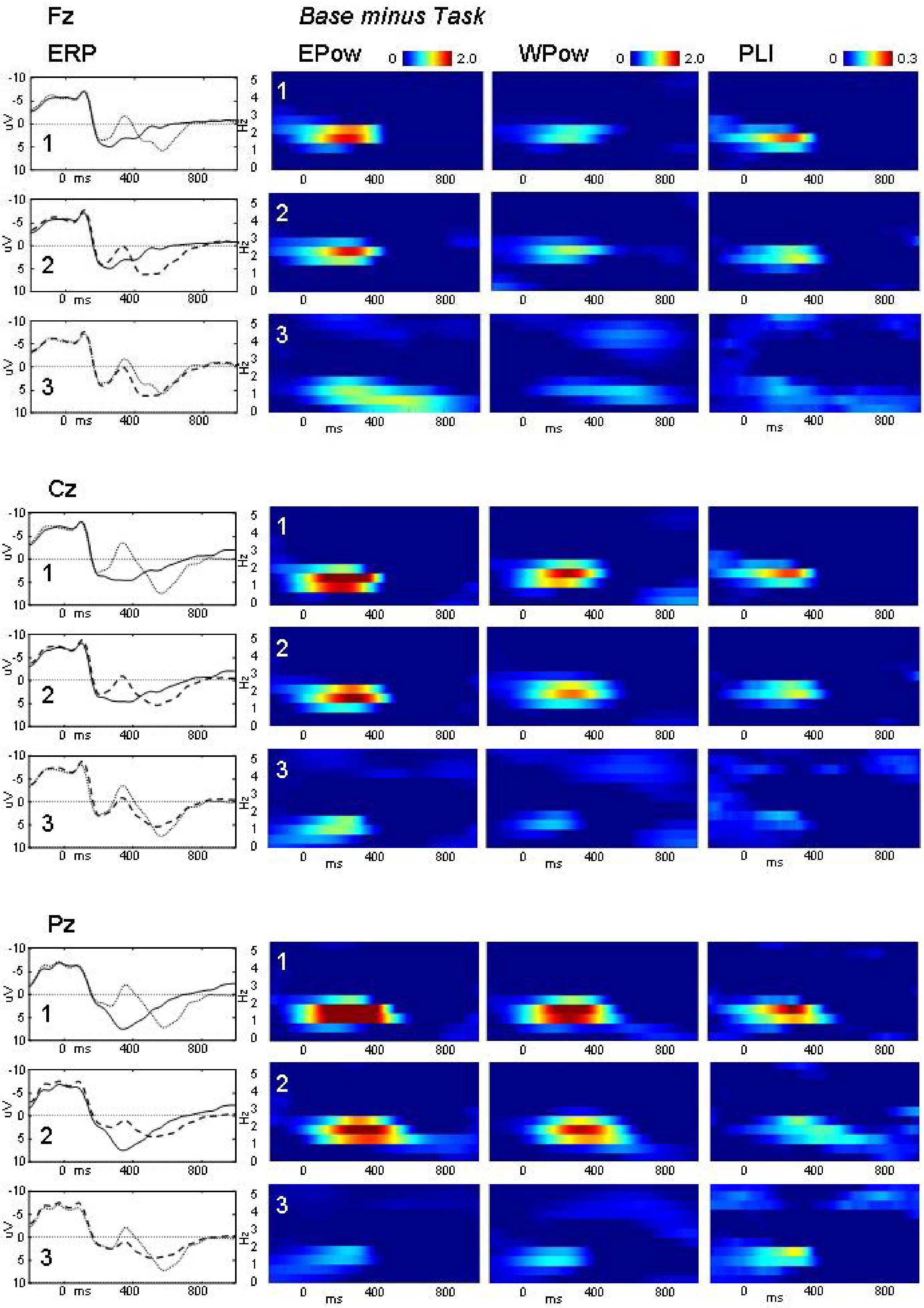

Figure D1-2. Experiment 2: Grand average ERPs and Gabor wavelet-based time-frequency difference plots for the antonym control condition in comparison to the non-related category (1) and related category violations (2) at electrodes Fz, Cz, and Pz (N=17). The two critical conditions are subtracted from the antonym control condition. In (3) the non-related category is subtracted from the related category violation.

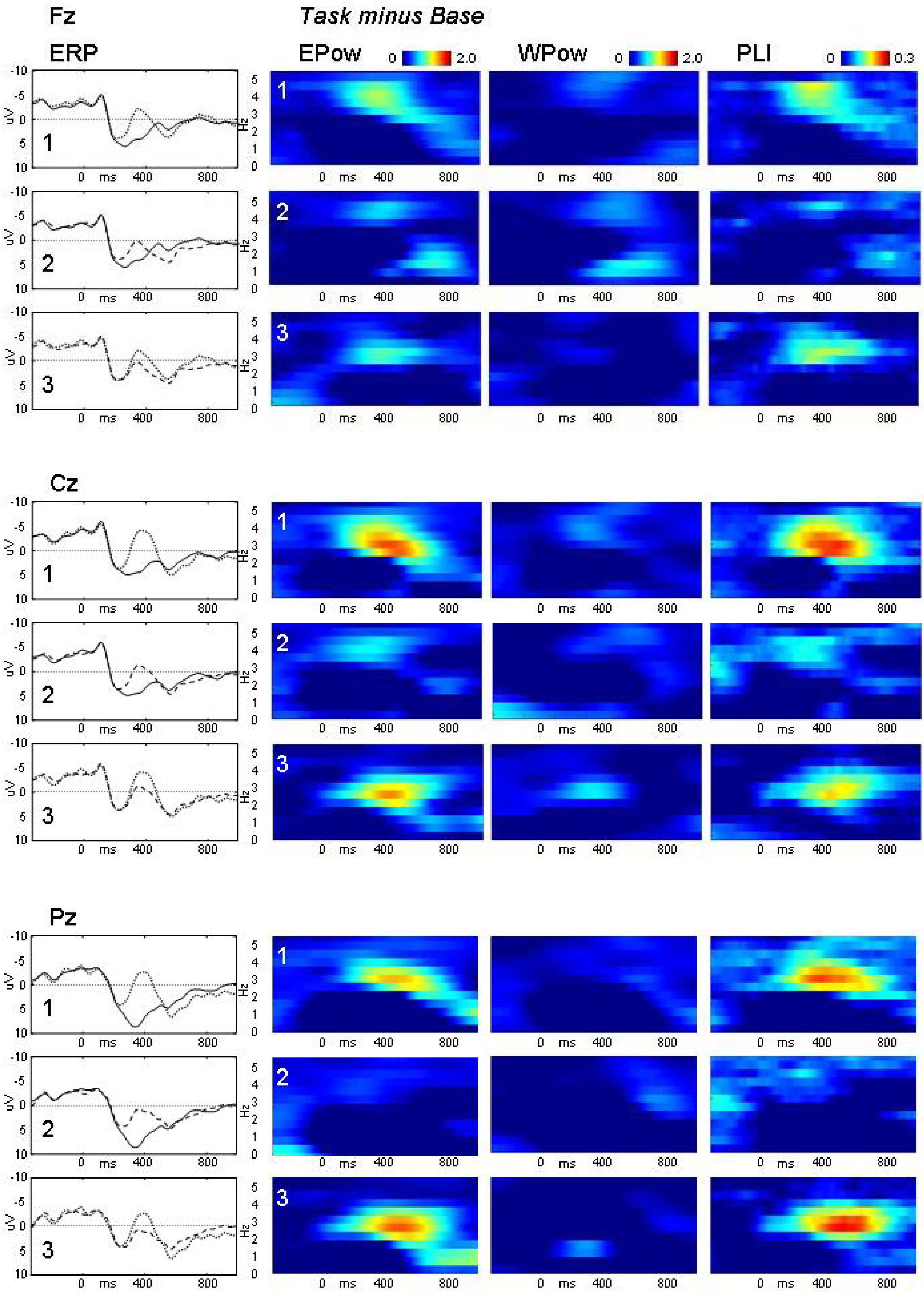

Figure D2-1. Experiment 3: Grand average ERPs and Gabor wavelet-based time-frequency difference plots for the non-related category (1) and related category conditions (2) in comparison to the antonym control condition at electrodes Fz, Cz, and Pz (N=17). The antonym control condition is subtracted from the two critical conditions. In (3) the related category is subtracted from the non-related category condition.

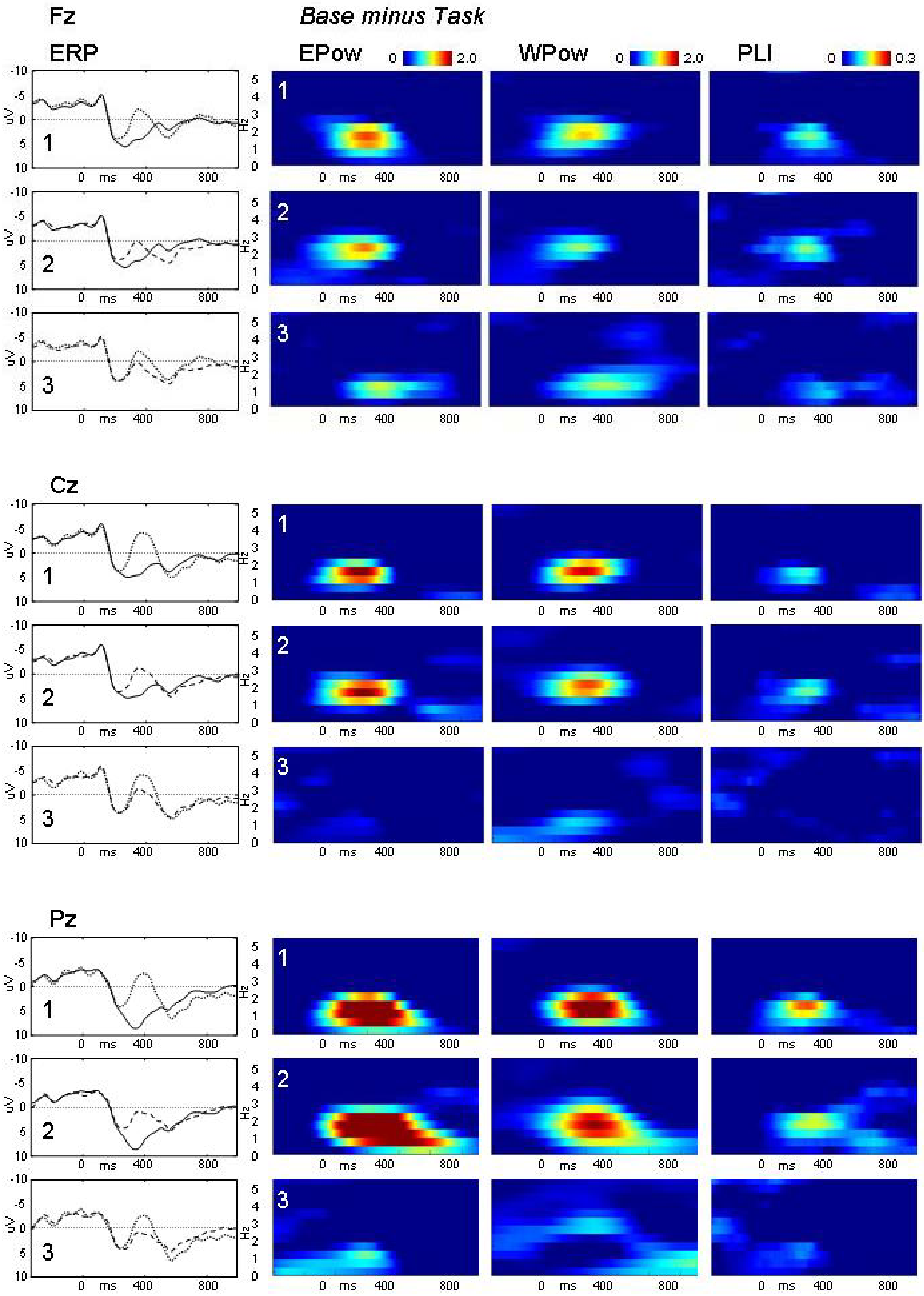

Figure D2-2. Experiment 3: Grand average ERPs and Gabor wavelet-based time-frequency difference plots for the antonym control condition in comparison to the non-related category (1) and related category conditions (2) at electrodes Fz, Cz, and Pz (N=17). The two critical conditions are subtracted from the antonym control condition. In (3) the non-related category is subtracted from the related category condition.

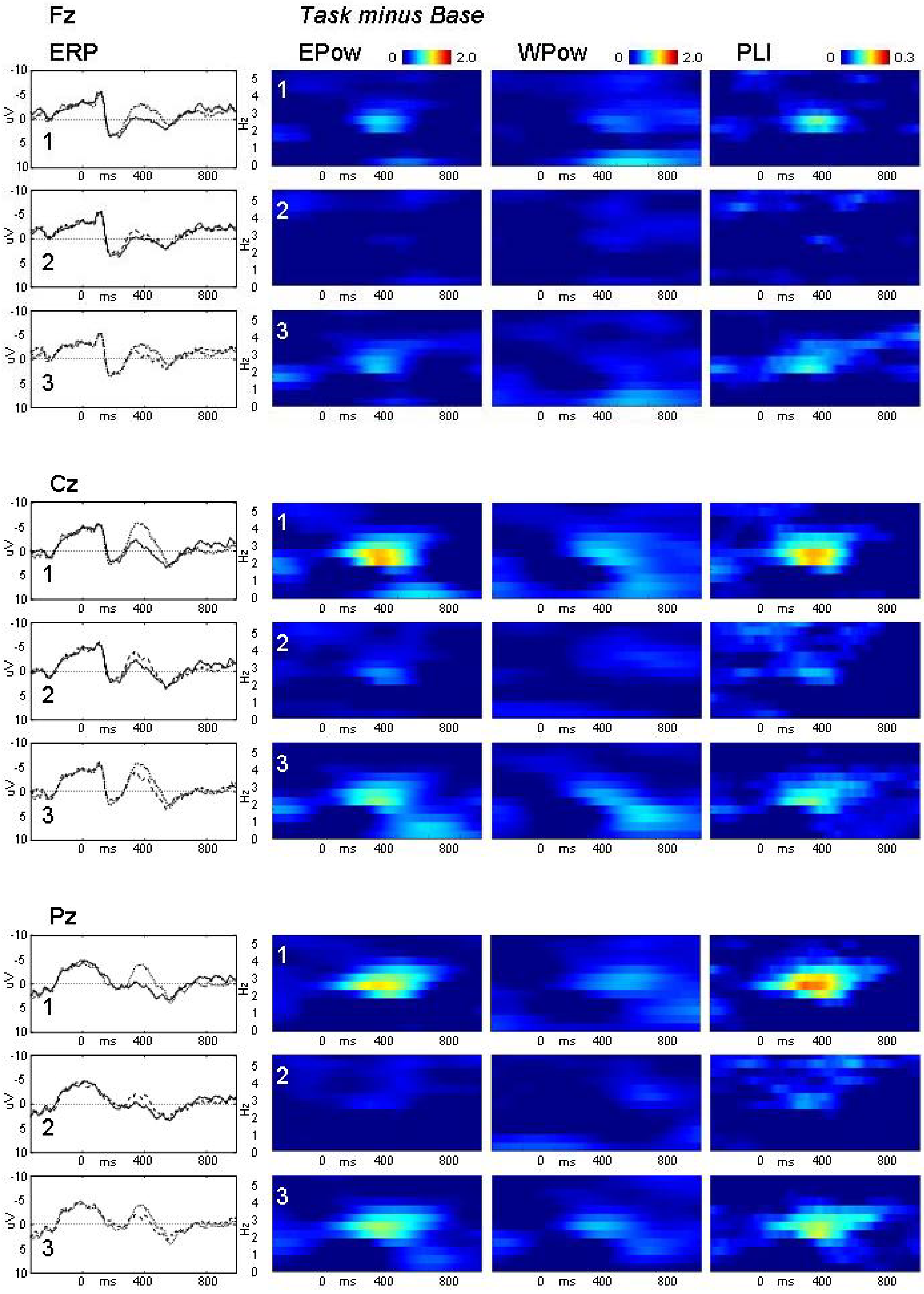

Figure D3-1. Experiment 5: Grand average ERPs and Gabor wavelet-based time-frequency difference plots for the non-related category (1) and related category conditions (2) in comparison to the antonym control condition at electrodes Fz, Cz, and Pz (N=17). The antonym control condition is subtracted from the two critical conditions. In (3) the related category is subtracted from the non-related category condition.

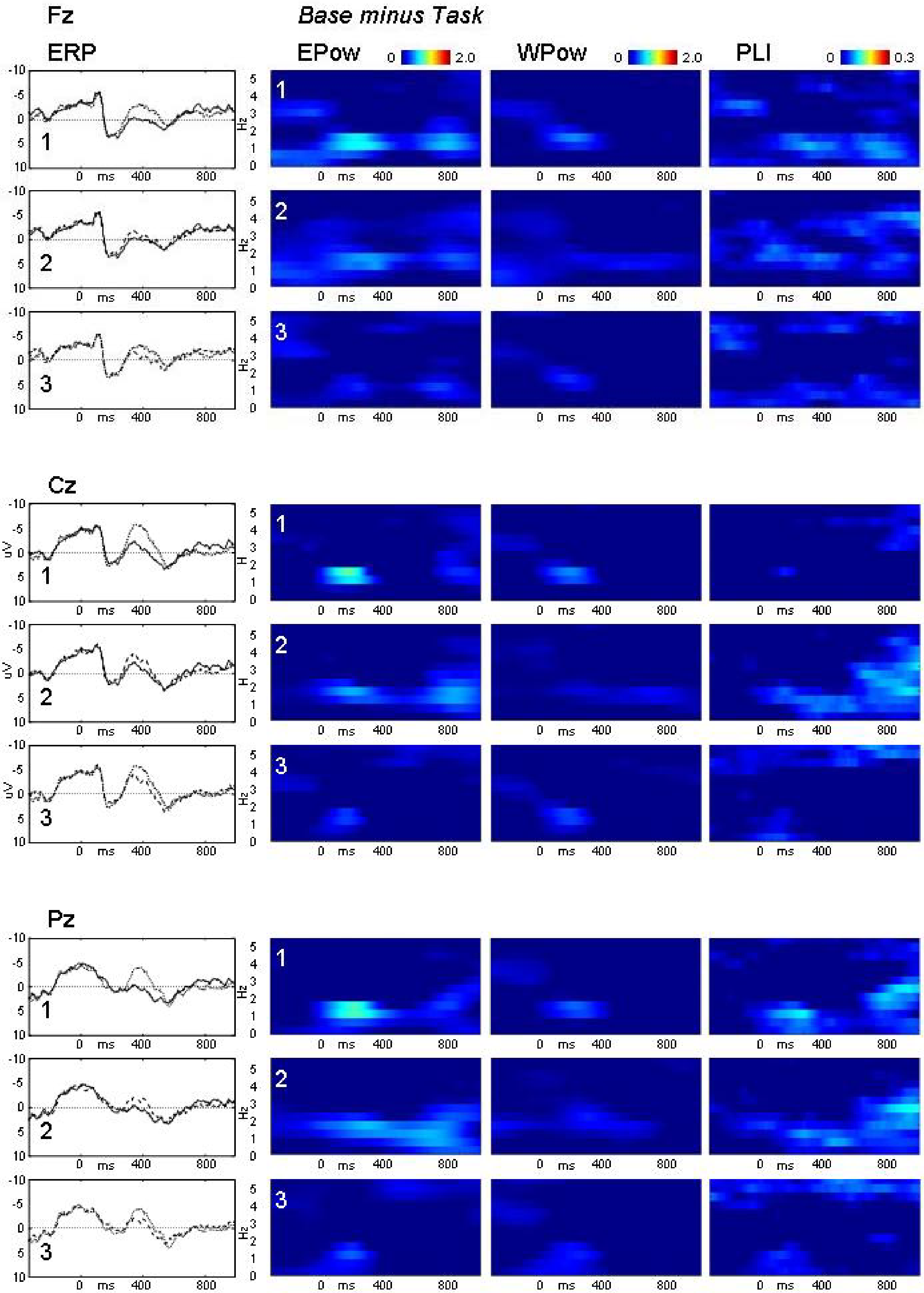

Figure D3-2. Experiment 5: Grand average ERPs and Gabor wavelet-based time-frequency difference plots for the antonym control condition in comparison to the non-related category (1) and the related category conditions (2) at electrodes Fz, Cz, and Pz (N=17). The two critical conditions are subtracted from the antonym control condition. In (3) the non-related category is subtracted from the related category condition.

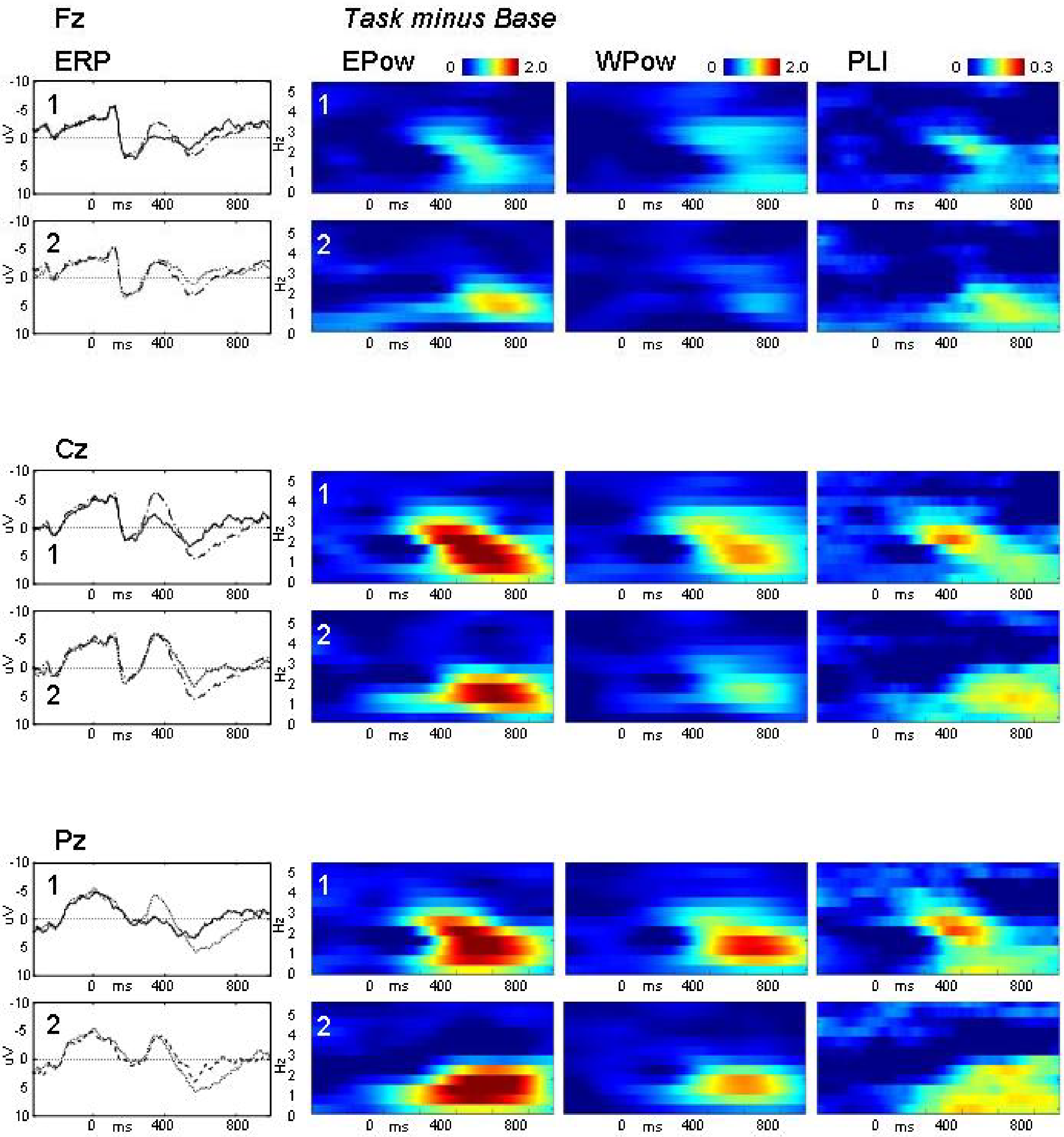

Figure D3-3. Experiment 5: Grand average ERPs and Gabor wavelet-based time-frequency difference plots for pseudowords in comparison to the antonym (1) and the non-related category conditions (2) at electrodes Fz, Cz, and Pz (N=17). The antonym and the non-related category conditions are subtracted from the pseudoword condition. The colour scale depicts the magnitude of the wavelet coefficient differences for EPow and WPow and the PLI value difference for PLI.

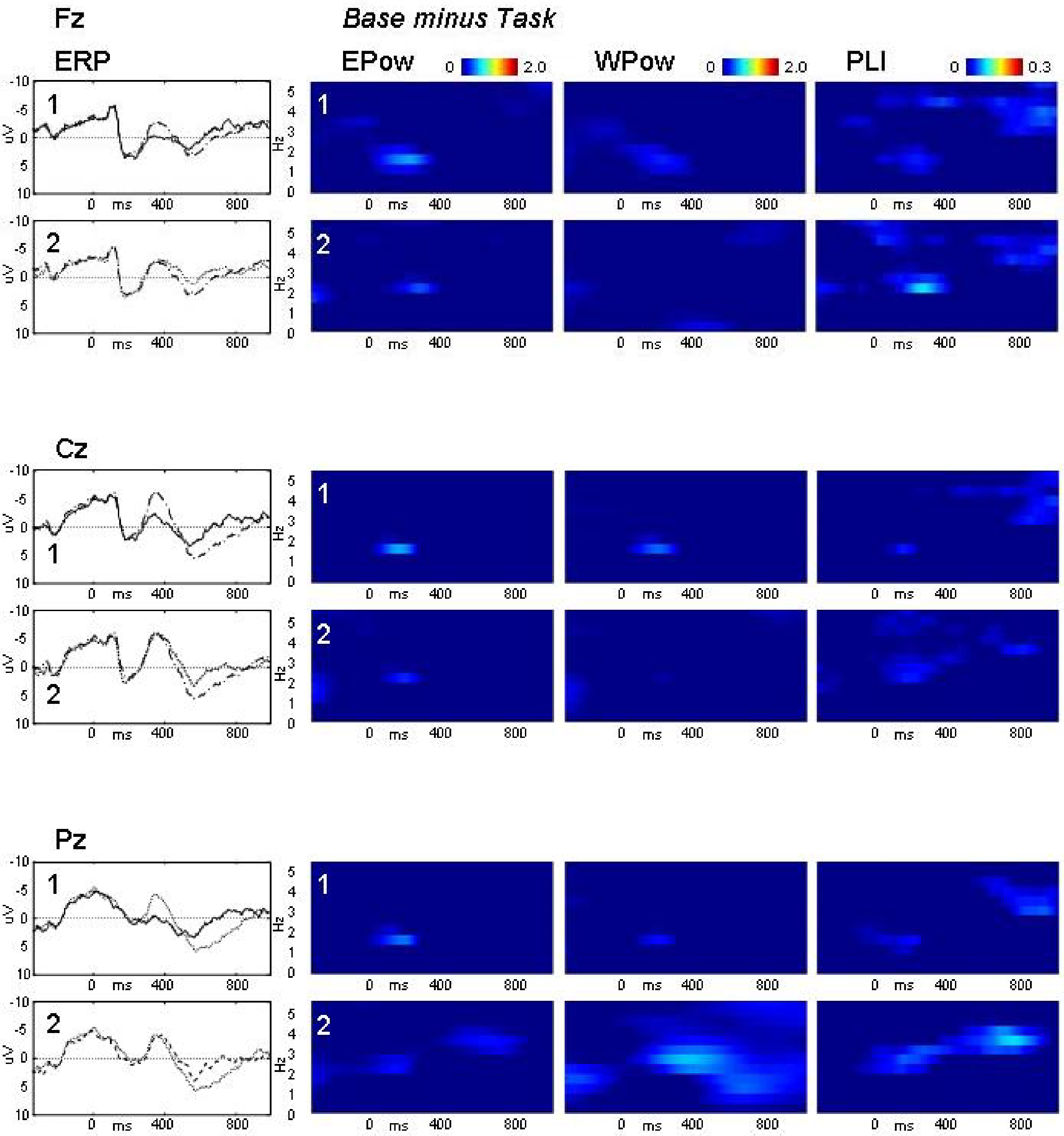

Figure D3-4. Experiment 5: Grand average ERPs and Gabor wavelet-based time-frequency difference plots for the antonym (1) and non-related category conditions (2) in comparison to pseudowords at electrodes Fz, Cz, and Pz (N=17). The pseudoword condition is subtracted from the antonym and the non-related category conditions. The colour scale depicts the magnitude of the wavelet coefficient differences for EPow and WPow and the PLI value difference for PLI.

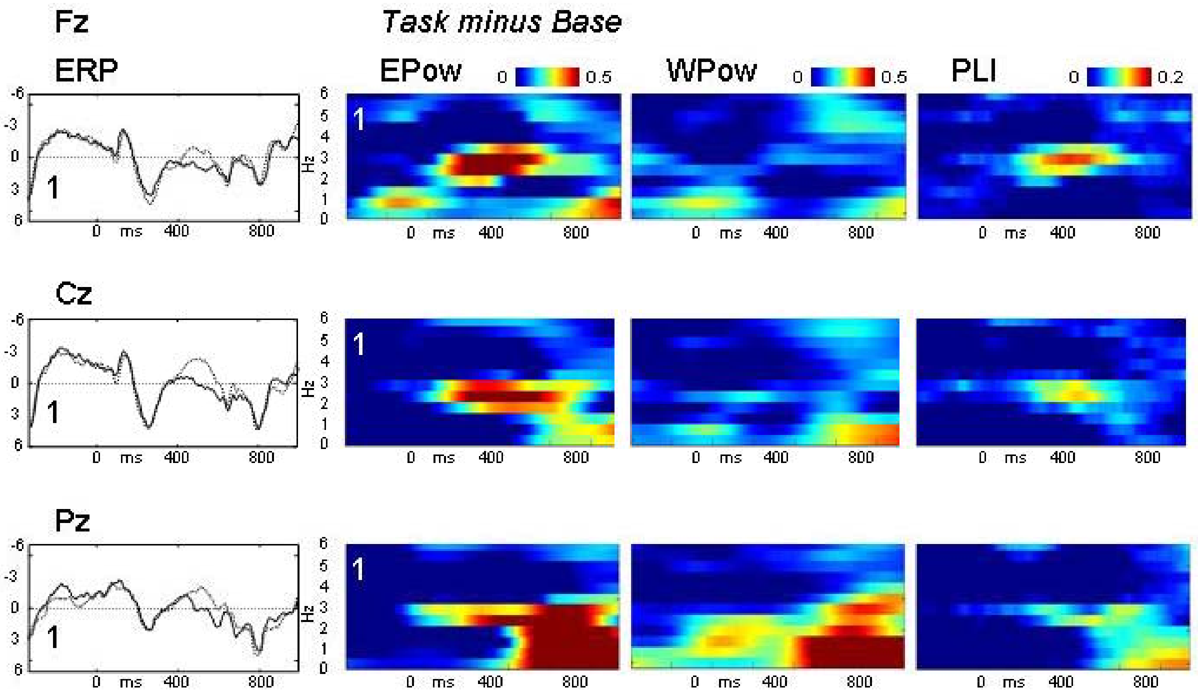

Figure D4-1. Experiment 6: Grand average ERPs and Gabor wavelet-based time-frequency difference plots for object-initial sentences in comparison to subject-initial sentences at electrodes Fz, Cz, and Pz (N=16). The subject-initial sentences are subtracted from the object-initial sentences. The colour scale depicts the magnitude of the wavelet coefficient differences for EPow and WPow and the PLI value difference for PLI.

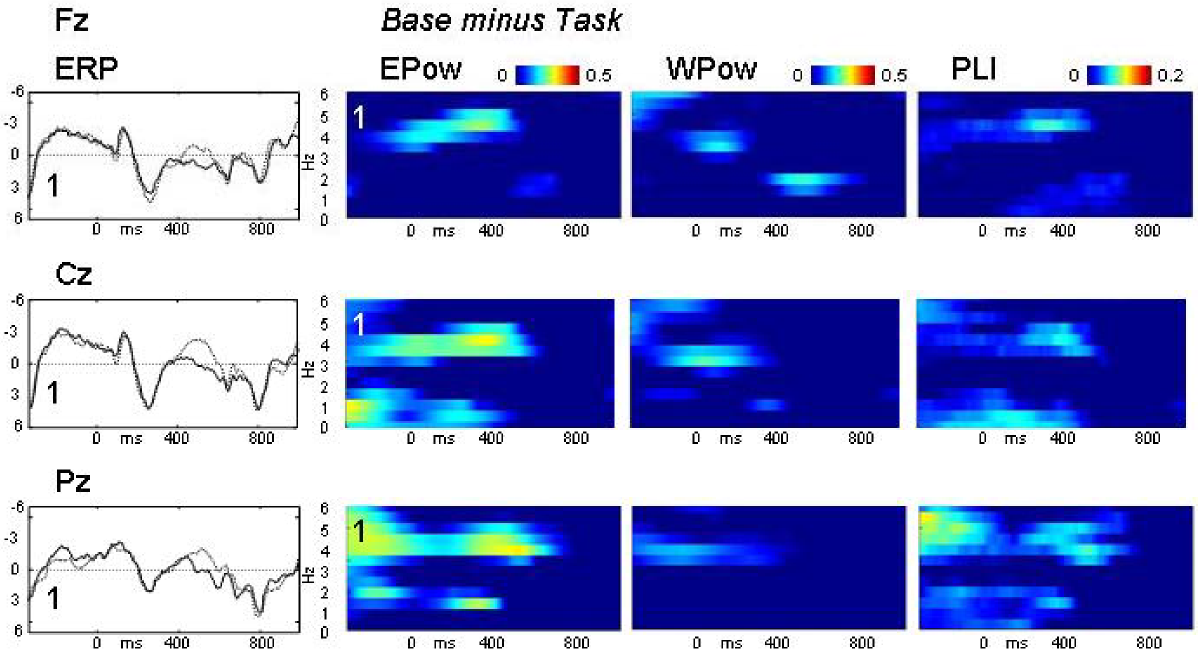

Figure D4-2. Experiment 6: Grand average ERPs and Gabor wavelet-based time-frequency difference plots for subject-initial sentences in comparison to object-initial sentences at electrodes Fz, Cz, and Pz (N=16). The object-initial sentences are subtracted from the subject-initial sentences. The colour scale depicts the magnitude of the wavelet coefficient differences for EPow and WPow and the PLI value difference for PLI.

Appendix E

Statistical Overviews of the TF-Findings

E1. Experiment 2

EPow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	21.68	.000	33.46	.000	27.64	.000	35.38	.000	35.48	.000
NON x ANT	25.29	.000	37.61	.000	29.14	.000	35.70	.000	40.63	.000
REL x ANT	32.65	.000	60.05	.000	51.53	.000	69.75	.000	59.37	.000
NON x REL	1.05	.322	3.38	.085	1.85	.193	<1	.760	1.14	.302

WPow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	13.53	.000	12.51	.000	3.96	.029	9.77	.000	6.78	.004
NON x ANT	16.31	.001	14.26	.002	5.27	.036	7.94	.012	7.07	.017
REL x ANT	19.62	.000	25.84	.000	5.71	.030	29.14	.000	15.00	.001
NON x REL	<1	.651	<1	.639	<1	.563	<1	.411	<1	.733

PLI	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	16.52	.000	33.32	.000	38.70	.000	33.65	.000	39.67	.000
NON x ANT	20.72	.000	41.30	.000	41.29	.000	36.36	.000	46.86	.000
REL x ANT	20.22	.000	45.86	.000	55.07	.000	44.12	.000	47.89	.000
NON x REL	<1	.862	1.31	.270	2.29	.150	<1	.462	3.23	.091

Table E1.1. Main effects of TYPE and pairwise comparisons for the electrodes Fz, Cz, Pz, P3 and P4 with regard to the three measures applied for the delta frequency band in Experiment 2 (time window: 100-400 ms; averaged frequency bins: 1.10-2.75 Hz; main effect = *F* (2,32); single comparisons = *F* (1,16)).

EPow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	12.75	.000	20.43	.000	14.02	.000	3.89	.031	6.93	.003
NON x ANT	21.36	.000	32.56	.000	22.68	.000	4.95	.041	9.56	.007
REL x ANT	6.63	.020	<1	.493	3.55	.078	<1	.537	<1	.815
NON x REL	7.66	.014	35.06	.000	17.83	.001	9.71	.007	13.46	.002

WPow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	4.09	.026	3.09	.059	1.87	.170	<1	.724	<1	.854
NON x ANT	6.64	.020	<1	.461	4.51	.050	---	---	---	---
REL x ANT	4.52	.049	2.34	.146	1.83	.195	---	---	---	---
NON x REL	<1	.900	6.13	.025	<1	.633	---	---	---	---

PLI	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	12.40	.000	21.02	.000	21.77	.000	5.04	.012	8.98	.001
NON x ANT	21.51	.000	35.19	.000	35.89	.000	6.62	.020	12.14	.003
REL x ANT	6.53	.021	2.46	.136	8.98	.009	1.52	.236	<1	.639
NON x REL	7.23	.016	34.13	.000	18.03	.001	7.02	.017	15.25	.001

Table E1.2. Main effects of TYPE and pairwise comparisons for the electrodes Fz, Cz, Pz, P3 and P4 with regard to the three measures applied for the lower theta frequency band in Experiment 2 (time window: 200-600 ms; averaged frequency bins: 3.30-4.95 Hz; main effect = *F* (2,32); single comparisons = *F* (1,16)).

EPow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	13.92	.000	10.08	.000	11.70	.000	16.62	.000	15.34	.000
NON x ANT	28.67	.000	13.39	.002	12.34	.003	18.06	.001	16.68	.001
REL x ANT	5.97	.027	4.46	.051	<1	.578	<1	.377	<1	.459
NON x REL	8.18	.011	9.74	.007	38.17	.000	32.97	.000	32.29	.000

Wpow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	<1	.595	3.15	.056	7.58	.002	7.22	.003	6.55	.004
NON x ANT	---	---	7.27	.016	14.62	.001	13.36	.002	12.15	.003
REL x ANT	---	---	1.59	.225	10.28	.005	8.78	.009	10.08	.006
NON x REL	---	---	1.37	.260	<1	.345	<1	.340	<1	.570

PLI	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	24.54	.000	8.72	.001	12.82	.000	16.54	.000	16.69	.000
NON x ANT	56.96	.000	12.58	.003	13.21	.002	17.01	.001	18.99	.000
REL x ANT	9.06	.008	2.73	.118	<1	.845	<1	.876	<1	.972
NON x REL	14.40	.002	9.25	.008	62.58	.000	40.54	.000	42.68	.000

Table E1.3. Main effects of TYPE and pairwise comparisons for the electrodes Fz, Cz, Pz, P3 and P4 with regard to the three measures applied for the upper delta frequency band in Experiment 2 (time window: 600-800 ms; averaged frequency bins: 1.65-3.30 Hz; main effect = *F* (2,32); single comparisons = *F* (1,16)).

E2. Experiment 3

EPow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	8.85	.001	6.43	.004	20.10	.000	15.80	.000	22.18	.000
NON x ANT	10.82	.005	5.62	.031	24.29	.000	16.70	.001	23.28	.000
REL x ANT	9.77	.007	12.30	.003	21.92	.000	21.74	.000	25.77	.000
NON x REL	1.50	.238	<1	.660	1.46	.244	<1	.810	<1	.352

WPow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	10.91	.000	7.81	.002	20.01	.000	16.68	.000	24.67	.000
NON x ANT	15.31	.001	10.99	.004	23.77	.000	20.13	.000	29.98	.000
REL x ANT	5.79	.029	7.42	.015	24.70	.000	19.48	.000	31.40	.000
NON x REL	8.07	.012	1.73	.207	<1	.425	<1	.531	<1	.673

PLI	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	6.74	.004	3.66	.037	10.56	.000	8.72	.001	10.34	.000
NON x ANT	8.99	.009	2.39	.142	14.74	.001	10.79	.005	10.57	.005
REL x ANT	8.82	.009	8.79	.009	13.02	.002	14.29	.002	16.28	.001
NON x REL	<1	.577	<1	.387	<1	.479	<1	.957	<1	.920

Table E2.1. Main effects of TYPE and pairwise comparisons for the electrodes Fz, Cz, Pz, P3 and P4 with regard to the three measures applied for the delta frequency band in Experiment 3 (time window: 100-500 ms; averaged frequency bins: 1.0-3.0 Hz; main effect = *F* (2,32); single comparisons = *F* (1,16)).

EPow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	9.39	.001	8.67	.001	4.22	.024	13.50	.000	6.07	.006
NON x ANT	7.94	.012	9.88	.006	6.71	.020	14.03	.002	4.46	.049
REL x ANT	<1	.710	<1	.448	<1	.421	<1	.985	<1	.469
NON x REL	33.12	.000	19.27	.000	7.70	.014	39.30	.000	23.75	.000

WPow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	2.68	.084	2.21	.127	1.68	.203	4.09	.026	<1	.566
NON x ANT	<1	.598	1.01	.330	<1	.459	3.19	.093	---	---
REL x ANT	2.93	.106	<1	.349	2.04	.173	1.42	.251	---	---
NON x REL	5.24	.036	6.06	.026	<1	.650	6.27	.023	---	---

PLI	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	18.30	.000	17.93	.000	6.05	.006	15.82	.000	8.97	.001
NON x ANT	19.23	.000	27.11	.000	8.40	.010	21.80	.000	7.47	.015
REL x ANT	<1	.948	2.67	.122	<1	.923	<1	.698	<1	.502
NON x REL	46.58	.000	22.97	.000	10.85	.005	30.22	.000	33.24	.000

Table E2.2. Main effects of TYPE and pairwise comparisons for the electrodes Fz, Cz, Pz, P3 and P4 with regard to the three measures applied for the lower theta frequency band in Experiment 3 (time window: 300-600 ms; averaged frequency bins: 3.0-4.5 Hz; main effect = *F* (2,32); single comparisons = *F* (1,16)).

EPow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	2.83	.074	4.86	.014	8.89	.166	9.29	.001	7.95	.002
NON x ANT	5.17	.037	7.97	.012	9.53	.007	8.61	.010	8.59	.010
REL x ANT	1.42	.250	<1	.405	<1	.660	<1	.406	<1	.575
NON x REL	1.55	.232	4.99	.040	14.33	.002	16.46	.001	12.60	.003

WPow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	2.49	.099	<1	.426	1.90	.166	1.09	.348	2.49	.099
NON x ANT	<1	.859	---	---	2.14	.163	1.57	.228	2.00	.177
REL x ANT	3.22	.091	---	---	3.68	.073	<1	.411	5.61	.031
NON x REL	3.73	.071	---	---	<1	.877	<1	.436	<1	.545

PLI	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	3.09	.059	6.47	.004	14.09	.000	14.51	.000	11.32	.000
NON x ANT	4.83	.043	10.22	.006	18.34	.001	18.40	.001	11.94	.003
REL x ANT	<1	.363	1.33	.266	<1	.482	<1	.405	<1	.575
NON x REL	2.45	.137	5.99	.026	20.00	.000	20.26	.000	16.18	.001

Table E2.3. Main effects of TYPE and pairwise comparisons for the electrodes Fz, Cz, Pz, P3 and P4 with regard to the three measures applied for the upper delta frequency band in Experiment 3 (time window: 600-800 ms; averaged frequency bins: 2.0-3.5 Hz; main effect = *F* (2,32); single comparisons = *F* (1,16)).

E3. Experiment 5

EPow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	3.73	.035	11.31	.000	25.79	.000	24.19	.000	32.77	.000
NON x ANT	4.50	.050	17.19	.001	44.80	.000	39.07	.000	58.75	.000
REL x ANT	<1	.922	4.02	.062	2.20	.158	1.61	.223	<1	.342
NON x REL	6.17	.024	8.86	.009	26.78	.000	25.29	.000	40.69	.000

ANT x PSW	6.21	.024	26.14	.000	32.21	.000	33.36	.000	32.23	.000
PSW x NON	<1	.356	1.55	.232	<1	.783	<1	.791	<1	.611

Wpow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	4.26	.023	13.19	.000	16.29	.000	15.45	.000	13.13	.000
NON x ANT	7.10	.017	19.38	.000	25.83	.000	20.33	.000	19.26	.000
REL x ANT	2.02	.175	3.42	.083	<1	.888	<1	.459	<1	.656
NON x REL	2.71	.120	11.55	.004	21.24	.000	23.04	.000	17.79	.001

ANT x PSW	20.84	.000	70.19	.000	60.21	.000	33.29	.000	48.11	.000
PSW x NON	6.36	.023	9.41	.007	5.38	.034	3.92	.065	8.12	.012

PLI	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	3.08	.060	8.96	.001	17.25	.000	15.57	.000	19.58	.000
NON x ANT	3.30	.088	13.81	.002	32.69	.000	27.14	.000	31.57	.000
REL x ANT	<1	.825	3.62	.075	3.30	.088	2.14	.163	<1	.344
NON x REL	5.39	.034	6.81	.019	15.40	.001	15.95	.001	25.03	.000

ANT x PSW	3.96	.064	19.84	.000	19.46	.000	24.84	.000	20.22	.000
PSW x NON	<1	.936	<1	.754	<1	.529	<1	.702	<1	.410

Table E3.1. Main effects of TYPE and pairwise comparisons for the electrodes Fz, Cz, Pz, P3 and P4 with regard to the three measures applied for the lower theta band in Experiment 5 (time window: 200-500 ms; averaged frequency bins: 3.0-4.5 Hz; main effect = *F* (2,32); single comparisons = *F* (1,16)).

EPow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
ANT x PSW	6.65	.020	20.45	.000	16.61	.001	14.52	.002	12.67	.003

Wpow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
ANT x PSW	3.82	.068	20.95	.000	25.26	.000	22.57	.000	26.63	.000

PLI	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
ANT x PSW	10.04	.006	16.02	.001	9.76	.007	9.57	.007	9.66	.007

Table E3.2. Main effects of TYPE and pairwise comparisons for the electrodes Fz, Cz, Pz, P3 and P4 with regard to the three measures applied for the delta frequency band in Experiment 5 (time window: 400-800 ms; averaged frequency bins: 1.0-2.5 Hz; main effect = *F* (2,32); single comparisons = *F* (1,16)).

EPow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	2.40	.107	<1	.397	4.54	.018	5.81	.007	4.22	.024
NON x ANT	2.71	.119	---	---	5.48	.033	6.82	.019	6.34	.023
REL x ANT	5.48	.033	---	---	6.14	.025	10.52	.005	5.64	.030
NON x REL	<1	.538	---	---	1.01	.329	<1	.491	<1	.591

Wpow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	<1	.558	<1	.570	1.80	.182	3.31	.057	<1	.538
NON x ANT	---	---	---	---	2.22	.156	4.17	.058	---	---
REL x ANT	---	---	---	---	<1	.577	3.18	.094	---	---
NON x REL	---	---	---	---	3.18	.093	1.33	.265	---	---

PLI	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
TYPE	2.08	.141	1.52	.235	3.44	.044	4.44	.020	1.64	.209
NON x ANT	2.49	.134	1.75	.205	4.51	.050	4.79	.044	2.88	.109
REL x ANT	2.47	.136	5.99	.026	8.33	.011	10.46	.005	2.35	.145
NON x REL	<1	.338	<1	.886	<1	.842	<1	.912	<1	.753

Table E3.3. Main effects of TYPE and pairwise comparisons for the electrodes Fz, Cz, Pz, P3 and P4 with regard to the three measures applied for the delta frequency band in Experiment 5 (time window: 200-400 ms; averaged frequency bins: 1.0-1.5 Hz; main effect = *F* (2,32); single comparisons = *F* (1,16)).

E4. Experiment 6

EPow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
SO x *OS*	8.54	.010	5.87	.029	3.98	.065	<1	.342	5.66	.031

Wpow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
SO x *OS*	<1	.479	<1	.558	1.96	.182	<1	.783	3.04	.102

PLI	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
SO x *OS*	12.44	.003	7.76	.014	3.95	.065	<1	.411	4.29	.056

Table E4.1. Main effects of ORDER for the electrodes Fz, Cz, Pz, P3 and P4 with regard to the three measures applied for the upper delta frequency band in Experiment 6 (time window: 300-600 ms; averaged frequency bins: 2.0-3.0 Hz; main effect = *F* (1,15)).

EPow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
SO x *OS*	4.00	.064	7.29	.016	10.55	.005	<1	.747	6.22	.025

Wpow	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
SO x *OS*	<1	.740	<1	.996	<1	.933	<1	.974	<1	.759

PLI	Fz		Cz		Pz		P3		P4	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
SO x *OS*	9.60	.007	5.74	.030	5.92	.028	<1	.646	4.10	.061

Table E4.2. Main effects of ORDER for the electrodes Fz, Cz, Pz, P3 and P4 with regard to the three measures applied for the theta frequency band in Experiment 6 (time window: 200-500 ms; averaged frequency bins: 4.0-5.0 Hz; main effect = *F* (1,15)).

Curriculum vitae

Name	Dietmar Roehm
Geburtsdatum	10. November 1964
Geburtsort	Backnang, Deutschland
Nationalität	deutsch

Ausbildung

1986 – 1992	Schweizerische Ballettberufsschule Zürich, Hochschule für Musik und Darstellende Kunst Mannheim-Heidelberg, Hogeschool voor Muziek en Dans Rotterdam (Klassischer und Moderner Tanz)
1992	Diplom für Tanz und Bühnenpraxis & Tanzpädagogik, Hogeschool voor Muziek en Dans Rotterdam
1993 – 1997	Universität Stuttgart (Magisterstudiengang Linguistik, Philosophie)
1997 – 1999	Universität Salzburg (Linguistik, Psychologie, Philosophie)
12/1999	Mag.phil., Allgemeine Sprachwissenschaft (magna cum laude), *EEG und Sprache: Elektrophysiologische Korrelate der Sprachverarbeitung.*
11/2004	Dr.phil., Germanistische Sprachwissenschaft (summa cum laude)

Beruflicher Werdegang

01/1998 – 01/2000	Forschungsassistent im FWF-Projekt „Funktionelle Korrelate oszillatorischer Prozesse im EEG“ am Institut für Psychologie, Universität Salzburg
02/2000 – 01/2002	Forschungsassistent im FWF-Projekt: "EEG-oscillations during sentence processing" am Institut für Sprachwissenschaft, Universität Salzburg
06/2002 – 12/2002	Forschungsassistent im „BMBF-Forschungsprojekt SmartKom“ am Institut für Maschinelle Sprachverarbeitung, Universität Stuttgart
01/2003 – 06/2003	Forschungsassistent am Institut für Maschinelle Sprachverarbeitung, Universität Stuttgart
Seit 09/2002	Wissenschaftlicher Mitarbeiter in der Nachwuchsgruppe Neurolinguistik am Institut für Germanistische Sprachwissenschaft, Philipps-Universität Marburg
Seit 07/2003	Forschungsassistent im FWF-Projekt: “Arten der Konfliktresolution und ihre EEG-Korrelate: frequenz-analytische Differenzierung” am Institut für Sprachwissenschaft, Universität Salzburg

Abstract

Successful language comprehension depends not only on the involvement of different domain-specific linguistic processes, but also on their respective time-courses. Both aspects of the comprehension process can be examined by means of event-related brain potentials (ERPs), which not only provide a direct reflection of human brain activity within the millisecond range, but also allow for a qualitative dissociation between different language-related processing domains. However, recent ERP findings indicate that the desired one-to-one mapping between ERP components and linguistic processes cannot be upheld, thus leading to an interpretative uncertainty.

This thesis presents a fundamentally new analysis technique for language-based ERP components, which aims to address the ambiguity associated with traditional language-related ERP effects. It is argued that this new method, which supplements ERP measures with corresponding frequency-based analyses, not only allows for a differentiation of ERP components on the basis of activity in distinct frequency bands and underlying dynamic behaviour (in terms of power changes and/or phase locking), but also provides further insights into the functional organisation of the language comprehension system and its inherent complexity.

On the basis of 5 EEG experiments, I show (1) that it is possible to dissociate two superficially indistinguishable language-related ERP components on the basis of their respective underlying frequency characteristics (Experiment 1), thereby resolving the vagueness of interpretation inherent to the ERP components themselves; (2) that the processing nature of the ‘classical’ semantic N400 effect can be unambiguously specified in terms of its underlying frequency characteristics, i.e. in terms of (evoked and whole) power and phase-locking differences in specific frequency bands, thereby allowing for a first interpretative categorisation of the N400 effect with respect to its underlying neuronal processing dynamics; and (3) that frequency-based analyses may be employed to distinguish the semantic N400 effect from N400-like effects that appear in contexts which cannot readily be characterised as semantic-interpretative processes. Experiments 2 – 5 investigated the processing of antonym relations under different task conditions. Whereas in Experiment 2, the processing of antonym pairs (black – white) was compared to that of related (black – yellow) and non-related (black – nice) word pairs in a sentence context, Experiments 3 to 5 presented

isolated word pairs. The frequency-based analysis showed that the observed N400 effects were not uniform in nature, but rather resulted from the superposition of functionally different frequency components. Task-relevant targets elicited a specific frequency modulation, which showed up as a P300-like positivity in terms of ERP measures. In addition, lexical-semantic processing elicited a pronounced increase in a different frequency range that was independent of the experimental context. For antonyms (Experiments 2 and 3), the task-related positive component appeared almost simultaneously to the N400 deflection for non-related words, thereby giving rise to a substantial N400 effect. In contrast, for pseudowords (Experiment 5), this positivity appeared in temporal succession to the N400.

In sum, in the present results provide converging evidence that N400 effects should not be regarded as functionally uniform. Depending on the respective task and stimulus manipulations, the N400 effect appears as a result of the superposition of functionally different activities, which can be clearly distinguished in terms of their underlying frequency characteristics. In this way, the proposed frequency-based methods directly bear upon the interpretation of language-related ERP effects and thus have straightforward consequences for psycholinguistic theory. In view of the phenomenon that language-related processes have, in a number of cases, been directly attributed to the lexical-semantic processing domain on account of the observation of an N400, these results not only call for a reinterpretation of previous findings but also for a reinterpretation of their theoretical consequences.

Zusammenfassung

Die erfolgreiche Verarbeitung von Sprache ist nicht nur abhängig von der effektiven Zusammenarbeit unterschiedlicher domänenspezifischer linguistischer Prozesse, sondern in wesentlichem Maße auch von deren jeweiligen zeitlichen Verlauf. Die Erfassung der elektrischen Gehirnaktivität beim Menschen mittels ereigniskorrelierter Potentiale (EKPs) als Korrelat sprachlicher Verarbeitungsprozesse erlaubt eine millisekundengenaue Differenzierung und Zuordnung unterschiedlicher sprachlicher Verarbeitungsdomänen. Neuere Befunde aus EKP-Experimenten zeigen jedoch, dass die erhoffte eins-zu-eins Korrelation zwischen EKP-Komponenten und linguistischen Prozessen nicht mehr aufrecht zu erhalten ist und daher eine interpretatorische Unschärfe ensteht.

Die in meiner Dissertation vorgeschlagene Methodik einer frequenzanalytischen Untersuchung von EKP-Komponenten hat das Ziel, diese interpretatorische Unschärfe zu beheben. Zu diesem Zweck wird eine für die elektroenzephalographische (EEG) Untersuchung von Sprachverstehensprozessen neue Analysetechnik vorgestellt, die die klassischen EKP-Maße mit korrespondierenden frequenzbasierten Analysen ergänzt. Die Ergebnisse liefern Evidenz dafür, dass eine frequenzanalytische Dissoziation von EKP-Komponenten mittels der eingeführten Methode möglich ist. Darüber hinaus gestattet eine Beschreibung der den EKPs zugrundeliegenden Frequenzeigenschaften (Power vs. Phasenkopplung) weiterführende Einsichten bezüglich der funktionalen Organisation unseres Sprachverstehenssystems und seiner inhärenten Komplexität.

Die Durchführung und Auswertung von insgesamt 5 EEG Experimenten führte zu folgenden Ergebnissen: (1) Sprachliche EKP-Komponenten, die aus einer Oberflächenperspektive nicht voneinander zu unterscheiden sind (Experiment 1), lassen sich auf der Basis der ihnen zugrundeliegenden Frequenzeigenschaften (Frequenzband, Power, Phasenkopplung) voneinander dissoziieren. Damit kann die interpretatorische Vagheit von EKP Komponenten aufgelöst werden. (2) Der klassische lexikalisch-semantische N400-Effekt lässt sich anhand seiner Frequenzeigenschaften eindeutig beschreiben und spezifischen Frequenzkorrelaten zuordnen lässt, so dass eine erste interpretatorische Zuordnung des N400-Effekts im Hinblick auf die ihm zugrundeliegende neuronale Prozess-Dynamik möglich erscheint. (3) Lexikalisch-semantische N400-Effekte unterscheiden sich von N400-ähnlichen Effekten, die nicht der Domäne semantisch-interpretativer Prozesse zugeordnet werden können, auf der Basis ihrer

jeweiligen Frequenzeigenschaften voneinander. In den Experimenten 2 bis 5 wurde die Verarbeitung von Antonym-Relationen untersucht. Während in Experiment 2 Antonym-Wortpaare (schwarz - weiß) im Vergleich zu relatierten (schwarz - gelb) und nicht-relatierten (schwarz - nett) Wortpaaren in einem Satzkontext präsentiert wurden, wurden in den Experimenten 3 bis 5 dieselben Stimuli als isolierte Wortpaare dargeboten. Die frequenzanalytische Auswertung der Experimente ergab, dass die erzielten lexikalisch-semantischen N400-Effekte bezüglich der ihnen inhärenten Frequenzeigenschaften keine monolithischen Effekte darstellen, sondern sich durch eine Überlagerung funktional unterschiedlicher Frequenzkomponenten manifestieren. Ein aufgabenbezogener Effekt spiegelte sich in einer spezifischen Frequenzbandmodulation wider, die im EKP zu einer P300-ähnliche Positivierung führte. Hingegen korrelierten lexikalisch-semantische Verarbeitungsprozesse unabhängig von den experimentellen Randbedingungen mit einer Erhöhung in einem anderen Frequenzband. In Experiment 2 und 3 trat der aufgabenrelatierte Positivierungs-Effekt im Zeitbereich der N400 auf, so dass es zu einer zeitlich-räumlichen Überlagerung der beiden Komponenten kam. Im Gegensatz dazu trat in Experiment 5 eine aufgabenrelatierte Positivierung lediglich bei der Verarbeitung von Pseudowörtern und in Abhängigkeit einer zeitlich vorangegangenen N400 auf.

Zusammengefasst sprechen die Ergebnisse dafür, dass N400-Effekte nicht als monolithische Effekte angesehen werden sollten. In Abhängigkeit von externen und stimulusbedingten Faktoren erscheint der N400-Effekt als das Resultat einer Überlagerung von mehreren funktional unterschiedlichen Aktivierungsprozessen, die jedoch anhand der ihnen zugrunde liegenden Frequenzeigenschaften voneinander dissoziiert sind. In diesem Sinne haben die hier vorgestellten frequenzbasierten Verfahren einen direkten sprachwissenschaftlichen Bezug mit unmittelbaren Konsequenzen für die psycholinguistische Theoriebildung. Unter der Annahme, dass in etlichen experimentellen Befunden sprachliche Verarbeitungsprozesse aufgrund des bloßen Auftretens einer N400 sogleich der lexikalisch-semantischen Verarbeitungsdomäne zugeschrieben wurden, erfordern diese Ergebnisse sowohl eine Reinterpretation der Datenlage als auch der sprachtheoretischen Interpretation.