

Anna Sophie Hasting: Syntax in a Blink: Early and Automatic Processing of Syntactic Rules as Revealed by Event-Related Brain Potential. Leipzig: Max Planck Institute for Human Cognitive and Brain Sciences, 2008 (MPI Series in Human Cognitive and Brain Sciences; 97)

Syntax in a blink: Early and automatic processing of syntactic rules as revealed by event-related brain potentials

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

D I S S E R T A T I O N

zur Erlangung des akademischen Grades
doctor rerum naturalium
Dr. rer. nat.

vorgelegt von
Dipl. psych. Anna Sophie Hasting
geboren am 26. Februar 1978 in Bremen

Dekanin: Prof. Dr. Annette Beck-Sickinger

Gutachter: PD Dr. Sonja A. Kotz
Prof. Dr. Erich Schröger
Prof. Dr. István Winkler

Tag der Verteidigung: 06.03.2008

Acknowledgements

The present dissertation is the result of my time as a PhD student at the Max Planck Institute for Human Cognitive and Brain Sciences in Leipzig, Germany. During this time, I enjoyed the support of many people who contributed in many different ways to the fact that the dissertation materialized into the product at hand. In particular, I would like to thank:

Angela Friederici for providing the financial and scientific opportunity to conduct the reported experiments in her Department of Neuropsychology, and for critical input and discussions along the way,

Sonja Kotz for supervising the entire process from the first ideas to the final print, as a mentor who was never short of expert advice, motivating words and personal support,

Burkhard Maess for a both pleasant and vital collaboration during the entire (ad-)venture of obtaining and making sense of the MEG data, and Thomas Knösche for his technical expertise concerning the computation of the BSCD results,

István Winkler for the fruitful discussions on the use of the MMN in language research that inspired the Excursus experiment,

many amicable MPI colleagues for professional advice and valuable discussions during different stages of this work, in particular Juliane Hofmann, Dirk Köster, Korinna Eckstein, Amelie Mahlstedt, Jutta Müller, Jörg Bahlmann, Maren Grigutsch and Thom Gunter,

Heike Böthel, Cornelia Schmidt, Ina Koch, Andreas Winzer and Yvonne Wolf for their help during data acquisition,

Kerstin Flake for her support during the preparation of the illustrations,

the three referees for agreeing to assess this dissertation,

and last but not least, Lela, Akele, Philipp and Johan for their backup and understanding not only during the final spurt of writing.

Thank you!

Contents

Preface	1
I Theoretical and Empirical Background	3
1 Syntax and syntactic processing: An introduction	5
1.1 What is syntax?	5
1.2 Assumed properties of the human syntax processor	8
2 Syntax in the brain: Methods of investigation	13
2.1 Methods in cognitive neuroscience	14
2.1.1 Electroencephalography and event-related brain potentials	14
2.1.2 Magnetoencephalography and event-related fields	20
2.1.3 Neuroimaging techniques	21
2.2 Experimental paradigms for studying syntax in the brain	22
2.2.1 Common rationale	22
2.2.2 Violation paradigms	22
2.2.3 The syntactic MMN paradigm	24
3 Neuroscientific evidence on syntax processing	27
3.1 Evidence from ERP data	27
3.2 Evidence from neuroimaging data	31
4 In need of clarification: Open questions and ways to address them	33
4.1 The question of timing	33
4.2 The question of automaticity	35

4.3	The question of spatial differentiation	36
4.4	Aims and experiments of the present study	37
II	Experiments	39
5	General methods	41
5.1	Selection and preparation of the stimulus material	41
5.2	ERP data acquisition and analysis	44
6	Experiment 1: Different types of syntactic Mismatch Negativities	49
6.1	Experiment 1A: The agreement MMN	50
6.1.1	Methods	50
6.1.2	Results	53
6.1.3	Discussion	57
6.2	Experiment 1B: The phrase structure MMN	60
6.2.1	Methods	60
6.2.2	Results	62
6.2.3	Discussion	66
6.3	Summary and conclusions	69
7	Excursus: Is there a word category MMN?	73
7.1	Methods	74
7.2	Results	77
7.3	Discussion	82
7.4	Summary and Conclusions	84
8	Experiment 2: Localization of the syntactic MMNs using MEG	87
8.1	Methods	89
8.2	Results	93
8.3	Discussion	99
8.4	Summary and Conclusions	102

9 Experiment 3: A little less repetition ...	105
9.1 Experiment 3A: Passive processing of agreement	107
9.1.1 Methods	107
9.1.2 Results	108
9.2 Experiment 3B: Passive processing of phrase structure	111
9.2.1 Methods	111
9.2.2 Results	111
9.3 Discussion	115
9.4 Summary and Conclusions	118
10 Experiment 4: ... a little more action!	119
10.1 Experiment 4A: Attentional processing of agreement	121
10.1.1 Methods	121
10.1.2 Results	122
10.2 Experiment 4B: Attentional processing of phrase structure	125
10.2.1 Methods	125
10.2.2 Results	125
10.3 Discussion	130
10.4 Summary and Conclusions	133
III General Discussion	135
11 Conclusions: Syntactic timing and automaticity revised	137
11.1 Summary of the study and its main findings	137
11.2 On the modularity of syntactic subprocesses	140
11.3 Implications for serial models of parsing	140
11.4 Possible brain mechanisms underlying the early syntactic negativities	141
12 Perspectives for further research	143
12.1 Shortcomings of the present study	143
12.2 Outlook: Future experiments and clinical applications	144
Bibliography	147

List of Figures	165
List of Tables	167
List of Items	169
List of Abbreviations	171

Preface

The ability to analyze and understand language is clearly one of the most fascinating features of the human brain. Although spoken language input has a highly complex structure, occurs at an enormous speed and is often disguised by dialects, speech errors and background noise, we are usually able to understand a conveyed message without apparent effort. Sometimes, we even overhear a message that appears somewhere in acoustic space without having focused our attention on it. These observations evoke the impression that the human language processor must be a very fast and highly automatic device that manages speech input literally in a blink.

Drawing upon the assumption that cognitive operations are best described in a modular fashion (Fodor, 1983), the present dissertation is concerned with one important component of this language processing device, namely the structural or *syntactic* analysis of the speech input. In how far does the human syntax processor contribute to the fast and seemingly automatic nature of auditory language comprehension? What is the precise timing of the different subprocesses involved in syntactic analysis? Which aspects of syntax can be analyzed automatically, and which necessitate the involvement of attentional resources? And finally, by means of which neuronal mechanisms does the brain capture the complex structure of language? These questions have been in the focus of psycholinguistic as well as neurolinguistic research for many years. Early accounts of the implicit nature of syntax processing have been provided by behavioral studies measuring the impact of syntactic context on reaction times during word recognition. As more direct measures of neuronal activity, electrophysiological recordings have led to important insights into the relative timing and automaticity of different steps in syntactic analysis, and studies using neuroimaging techniques have identified several brain areas that appear to be dealing with syntactic operations. Considering the vast amount of studies already published in this area of research, one may ask whether further investigations on the topic will add any value to what is already known. The problem, as in any area of empir-

ical research, is, however, not the amount of available data, but the lack of consistency among them. The use of different methods and paradigms have made comparisons between different studies difficult and precluded a comprehensive synthesis concerning the above questions to date.

The aim of the present dissertation is to bridge one of these methodological gaps in order to explain previously controversial findings on the relative timing and automaticity of certain syntactic subprocesses. After a short introduction into the topic of syntax (Chapter 1), an overview over neurocognitive methods and a review of the neurolinguistic literature on syntax processing are given (Chapters 2 and 3). On this basis, some of the methodological factors that may have led to inconsistent findings in the past are identified, and the aims for the present investigation are defined with respect to a control of these factors (Chapter 4). In the experimental part of the thesis, the relative timing and automaticity of two different syntactic subprocesses and their underlying brain mechanisms are re-investigated in a set of interrelated studies that control for the previously identified methodological factors. An outline of the conducted experiments and the applied methods is provided in Chapter 5. The focus on temporal characteristics suggested the use of event-related brain potentials (ERPs) as the method of choice, as it guarantees a real-time correlate of syntactic processing. The automaticity of the respective subprocesses was investigated by a stepwise variation of the task demands, ranging from visual distraction in an oddball paradigm (Chapter 6) to active violation detection in variable utterances (Chapter 10). One experiment complements the ERP method by a measurement of the magnetic counterpart of the electric brain activity that contains additional spatial information about the brain regions activated by the investigated syntactic subprocesses (Chapter 8). Finally, the obtained data are evaluated conjointly with respect to the questions raised above (Chapter 11), and shortcomings as well as future extensions of the presented experiments are discussed (Chapter 12). Thus, the present dissertation will contribute to a more integrated understanding of the syntactic processing abilities of the human brain.

Part I

Theoretical and Empirical Background

Chapter 1

Syntax and syntactic processing: An introduction

The topic of the present dissertation is at the interface between linguistics and cognitive neuroscience. The cutting-edge state of this area of research is demonstrated by the recent emergence of an independent new field termed *neurolinguistics* that bridges the gap between the two disciplines. However, any interdisciplinary area of research implicates the need for a careful definition of its concepts. In the case of neurolinguistics it is of critical importance that relevant linguistic, psychological, and neuroscientific terms are used and understood in a unified way. The first chapter of this thesis is therefore concerned with a definition of its central concepts. It starts with a brief introduction of syntax as a linguistic term and continues with some critical assumptions and aspects concerning its procedural implementation in the human brain.

1.1 What is syntax?

The process of auditory language comprehension ranges from the perception of acoustic signals to the derivation of meaning. Along this process, the listener has to decompose the continuous stream of speech sounds (phonemes) into meaningful units (words), access their meaning and combine these into larger chunks (phrases and sentences) that convey the message of an utterance. For example, if we listen to someone pronouncing the sentence

(1) The dog chases the cat.

we immediately understand that the speaker refers to a barking animal that runs after a meowing animal. Likewise, it is very clear that the utterance

(2) The cat chases the dog.

refers to the opposite scenario. However, we have to acknowledge the fact that although the speech input comes about in a serial fashion, the correct meaning of a sentence cannot always be inferred by a serial stringing of the words included in it. This becomes obvious if we try to understand the meaning of the sentence

(3) The dog is chased by the cat.

Instead, we have to understand the *structure* of the sentence in order to comprehend that although the order of the words changed, the meaning of (2) and (3) is identical. The necessity of such structural analysis of speech input is even more evident in the following sentence:

(4) The dog the boy likes chases the cat.

Here, we additionally receive the information that a child is fond of the barking animal that runs after the meowing animal, if we correctly assign the embedded phrase "the boy likes" to the subject noun phrase "the dog". Thus, we have to build up a mental representation of the hierarchical structure of the sentence in order to understand its meaning.

Generally speaking, the combination of words into sentences does not occur in a random fashion, but adheres to a fixed set of grammatical rules. The term *Syntax*¹ refers to the structure of a sentence that is determined by these rules. The examples listed above show that it is not sufficient to process the order and meaning of the elements occurring in a sentence. Instead, we have to analyze the underlying syntactic structure in order to determine the relations between these elements. Only then can we arrive at a correct interpretation of a sentence's meaning. This process of syntactic analysis, also called *parsing*, involves the consideration of various types of grammatical cues. Two of these cues, namely word category information and inflectional information, are particularly relevant for the present thesis and shall therefore be described in greater detail.

First and foremost, the words that occur in a sentence belong to different categories, e.g. nouns, verbs, or adjectives. The identification of a word's category allows the listener to build a primary representation of the structure of a sentence based on the implicit knowledge on what kind of elements must be combined to form a grammatically coherent sentence. This implicit

¹ Ancient Greek: *syntaxis* = "arrangement"

knowledge is formally described in so-called *phrase structure rules*. On the basis of such rules, we can decide that the famous example given by the influential linguist Noam Chomsky,

(5) Colorless green ideas sleep furiously.

is a grammatical sentence of English despite the fact that it is completely meaningless, whereas

(6) Furiously sleep ideas green colorless.

is clearly ungrammatical (Chomsky, 1957). This example has been used to point out the fact that the syntactic structure of a sentence exists independently of the sentence's meaning, and to show that it cannot be captured by probabilistic models of grammar based on the argument that the word strings in both (5) and (6) are equally unlikely to occur in any English conversation (see, however, Pereira, 2000).

A second important cue is provided by inflectional information, which helps the listener to determine the *syntactic relations* between the elements of a sentence again based on certain rules. For example, in English and German (and several other languages), a verb has to agree in number and person with the subject noun phrase to which it belongs. This *subject-verb agreement* is signalled by the matching inflection of the verb. The value of agreement information for comprehension becomes evident when comparing the two sentences

(7) The dogs of the boy who chase the cat bark loudly.

and

(8) The dogs of the boy who chases the cat bark loudly.

In (7), the cat is being chased by several barking dogs, whereas in (8), it is the boy who chases the cat. This difference in meaning is procured solely by the singular versus plural inflection of the verb. In other cases, verb inflections provide exclusive information about the voice (i. e. active vs. passive) and the tense in which a sentence is formulated.

Another type of grammatical cue that plays an important role during syntactic analysis but is less relevant for the present work is case information. Case is particularly prominent in German and other languages with a relatively free word order. Furthermore, verb transitivity, indicating how many objects a verb requires, helps to decode the argument structure of a sentence.

For many decades, psycholinguistic research has been concerned with the question how the human syntax processor accomplishes the complex task to consider all these types of information in the seemingly instantaneous formation of a syntactic structure for spoken as well

as written language input. During this quest, much thought has been given to the cognitive architecture and mechanisms of this computational device (e.g. Forster, 1979; Frazier, 1987; Crocker, 1994; Pickering, Clifton, & Crocker, 2000). The resulting assumptions about the nature of the human syntax processor that are most relevant for the present work shall be outlined in the following section.

1.2 Assumed properties of the human syntax processor

Modularity A fundamental principle underlying many models that have been developed to describe the human syntax processor is the assumed *modularity* of cognitive processes. According to this notion, each cognitive process can be divided into a number of subcomponents, or *modules*, that work independently of each other and subserve different functional purposes. In his influential monograph on *The Modularity of Mind*, Fodor (1983) defines several criteria for modules - or *input systems*, as he calls them - that are often encountered in theories on syntax processing. For example, a module is supposed to be domain-specific in that it is specialized to process a certain input type, and informationally encapsulated in that it operates independently of information provided by other modules. Furthermore, it is assumed to operate at a fast speed and in a mandatory fashion with little influence of central resources such as attention. Last but not least, each module is associated with a fixed neural architecture.

Likewise, syntactic processing is mostly described as displaying high degrees of autonomy, speed and automaticity (e.g. Forster, 1979; Flores d'Arcais, 1988). This speaks in favor of an independent module of syntax. However, the assumption of modularity does not stop at this level: As models of language comprehension become more sophisticated they usually undertake a further division of the syntax processor into several subcomponents. These are assumed to reflect linguistically defined subprocesses such as the phrase structure building and syntactic-relational processes introduced in the previous section (e.g. Frazier, 1987; Friederici, 1995, 1999). Thus, the modularity principle appears to be a fruitful approach to capture the nature of the human syntax processor.

Before the modular properties of the syntax processor and its subcomponents are examined in greater detail, it should be noted that the modularity of cognitive processing in general is far from being without controversy. Some theories rather postulate domain-general processing, in which complex cognitive functions cannot be decomposed into independent units. By

assuming complex patterns of distributed and interactive neuronal activity to be involved in each cognition, this view is particularly incompatible with the attempt to localize cognitive processes in the brain (see Uttal, 2001). For the purpose of the present thesis, the modularity principle shall nevertheless be adopted for its heuristic value. Even if the reality of the modular organization of cognitive processes is theoretically debatable, the break-down of complex cognitive functions such as syntax processing into subcomponents is indispensable to make the issue accessible to experimental investigation in the first place.

Seriality It appears intuitively evident that the syntax processor as such should be a rather fast device. This intuition is founded in the obvious necessity to measure up to the enormous speed at which speech input is delivered. In how far though does the assumption of immediate processing hold for each of the syntactic subcomponents that are assumed to constitute the syntax processor? In fact, several modular models of sentence processing propose a serial rather than a parallel organization of such subcomponents (e.g. Frazier, 1987; Friederici, 1995, 2002; Bornkessel & Schlesewsky, 2006). This is based on the assumption that local phrase structure building (drawing upon word category information, as described in the previous section) temporally precedes all other syntactic or semantic processing steps (Frazier, 1987; Gorrell, 1995). Empirical evidence in support of this view will be presented in Chapter 3, and the relative timing of phrase structure building and syntactic-relational processing will be thoroughly tested in the experimental section of this thesis (Chapters 6 to 10). For the time being, it shall be sufficient to note that different syntactic subcomponents do not appear to be as uniformly fast as one may predict for parallel processing modules in terms of Fodor (1983).

Automaticity Other characteristics of modular processes according to Fodor (1983) are their mandatory nature and their independence of central resources such as attention. Generally speaking, they could be described as *automatic*. Indeed, syntactic processing is often assumed to be automatic (e.g. Flores d'Arcais, 1988). This is quite plausible given that we do not appear to spend any particular effort to parse a sentence. In fact, we usually cannot even keep ourselves from performing this action. This suggests a truly mandatory, involuntary, obligatory, and therefore automatic underlying process. However, similar to the issue of timing, the degree of automaticity appears to vary for different syntactic subcomponents, as will be shown in Chapter 3. As this circumstance is one of the central objects of investigation of the

current thesis, it appears appropriate to extend the intuitive understanding of automaticity and automatic processing by conceptual definitions from the literature.

One of these is provided by Posner and Snyder (1975), who state that a process is regarded as automatic (as opposed to controlled) if it occurs "without intention, without giving rise to any conscious awareness, and without producing interference with other ongoing mental activity" (p. 56). They further imply that automatic processes are "strategy independent", to the extent that "subjects cannot choose to avoid processing aspects of an input item that they desire to ignore" (p. 56). Similarly, Schneider, Dumais, and Shiffrin (1984) describe automatic processing as "a fast, parallel, fairly effortless process that is not limited by short-term memory (STM) capacity, is not under direct subject control, and is responsible for the performance of well-developed skilled behaviors" (p. 1). Importantly, they further point out that even rather complex tasks can become automatic after extensive, consistent training (see also Schneider & Shiffrin, 1977). In this sense, automatic processing can be equated with well-practiced memory retrieval. According to Logan (1992), this aspect substantiates the important distinction of automatic and so-called *preattentive* processes that in his view cannot be learned and are restricted to the processing of elementary physical stimulus features. As preattentive processes are not only independent of but also temporally prior to attention (hence the term *pre-attentive*), they are automatic per definition. In contrast, not all automatic processes fulfill the criteria of preattentiveness. Therefore, the two terms should not be treated as synonyms.

Further confinements of the concept of automaticity are provided by Kahnemann and Treisman (1984), who propose three different levels of automatic processing. In their terms, "(1) An act of perceptual processing is *strongly automatic* if it is neither facilitated by focusing attention on a stimulus, nor impaired by diverting attention from it. (2) It is *partially automatic* if it is normally completed even when attention is diverted from the stimulus, but can be speeded or facilitated by attention. (3) A perceptual process is *occasionally automatic* if it generally requires attention but can sometimes be completed without it." (p. 42). However, they acknowledge the problem that these different levels of automaticity are difficult to distinguish experimentally.

In view of this variety of aspects involved in the concept of automaticity, it appears most reasonable to fall back on the least common denominator to define how the term is used in the context of the present thesis. This seems to be the independence of attentional resources.

Accordingly, a process will be regarded as automatic if it occurs irrespectively of whether attention is focussed on the input or not (as suggested by Pulvermüller & Shtyrov, 2006). This definition is admittedly weak in the sense that it accommodates cases in which attention has a modulating influence on the outcome of the process (and that therefore merely qualify as being *partially* automatic in terms of Kahnemann and Treisman). However, it has the advantage of providing a relatively clear experimental operationalization for testing the respective automaticity of the targeted syntactic subcomponents.

Neuroanatomical representation A final aspect of the modular approach to syntax processing that is of relevance in the present thesis concerns the assumed fixed neural architecture of the syntactic subcomponents, or in other words, their localization in the human brain. The basic assumption underlying this relatively recent undertaking of neurolinguistic research is best described by the term "syntacto-topic conjecture" coined by Grodzinsky (2006). This notion implies that the subcomponents of human syntactic knowledge are neurologically distinguishable and localizable in an aspired "brain map for syntax" (see also Grodzinsky & Friederici, 2006). Until recently, most localization approaches focused on the neuroanatomical differentiation of rather superordinate systems (e.g. language comprehension vs. language production, or syntactic vs. semantic processing). However, with advanced localization methods, there is an increasing number of studies that attempt to identify representational differences between subprocesses of syntactic analysis. A review of the current state of evidence concerning this point will be given in Chapter 3. Although the neuroanatomical representation of the investigated syntactic subprocesses is rather a side issue in the present work, the assumption that syntactic subprocesses could be subserved by different brain areas should be kept in mind, because it is clearly relevant to the interpretation of the presented data.

Chapter 2

Syntax in the brain: Methods of investigation

For a long time experimental psycholinguistic research on cognitive processes during language comprehension was based on overt behavioral responses. While much has been learned about the psychological reality of linguistic concepts by this approach, it remains restricted to the evaluation of the final outcome of the complex processes underlying language comprehension. Such "offline measures" have therefore provided little insight into the exact time course of syntactic analysis and the neuronal mechanisms subserving it.

In the last two decades the advent and increased accessibility of advanced neurocognitive techniques has allowed to identify and to investigate more direct correlates of brain activity during language comprehension. In particular, the understanding of the time course of language comprehension has gained extensively from the use of event-related brain potentials (ERPs), and their magnetic counterparts. Neuroimaging techniques such as functional magnetic resonance imaging (fMRI) or positron emission tomography (PET) have contributed to our knowledge about the localization of language-related processes in the brain. In addition, the availability of enhanced computing resources and improved presentation techniques has increased the portion of studies investigating language comprehension in the auditory modality.

The first part of the current chapter will describe different neurocognitive methods that have been used to study the representations of syntax and syntactic subprocesses in the brain. In view of the experiments that will be presented later on, the focus will be on the time-sensitive method of ERPs. The second part of the chapter will introduce specific syntax-related experimental

designs and paradigms. These provide the basis for the empirical findings that motivated the present investigation.

2.1 Methods in cognitive neuroscience

2.1.1 Electroencephalography and event-related brain potentials

Physiological basis Communication between neurons is effected via the movement of charged ions across cell membranes. Neuronal activity is thus primarily characterized by changes in electric current flow. The synchronous activity of large neuronal assemblies including 10000 or more cortical pyramidal cells produces open field potentials that are strong enough to be measured noninvasively by means of electrodes placed on the scalp surface. Provided that suitable signal amplification techniques are used, these signals can be recorded without any delay as voltage variations over time. Such recording is referred to as an electroencephalogram (EEG), a label coined by Hans Berger in 1929. Berger was also one of the first scientists who associated changes in the characteristics of the EEG signal with specific cognitive states and functions. In the following years, this idea advanced the notion that the occurrence of a given stimulus affects the EEG in a characteristic fashion, and that such stimulus-evoked or *event-related* brain activity reflects cognitive processing of that stimulus. It is commonly assumed that ERPs are elicited by the conjoined activation of large neuronal populations that are in charge of a given cognitive operation¹.

Methodological principles of ERP extraction When measured from the scalp ERPs constitute only a fraction of the overall EEG signal, and are therefore invisible in the continuous recording. Thus, the signal-to-noise ratio (SNR) is not sufficient to evaluate ERPs on a single trial basis. Based on the idea by Dawson (1954) that brain responses related to the processing of a stimulus would be nonrandom and repeat over trials, whereas simultaneously occurring "random" brain responses would cancel each other out, this problem is usually addressed by a statistical averaging procedure. Thus, the extraction of ERPs from continuous EEG recordings involves the repeated presentation of physically (or at least conceptually) identical stimuli, the epoching of the signal with respect to the onset of the stimuli, and the averaging of the resulting

¹An alternative to this assumption is the view that ERPs reflect stimulus-related phase resetting of ongoing EEG oscillations (for a recent discussion, see Shah et al., 2004)

epochs. To compensate for slow fluctuations of the EEG signal over time, the ERP average is usually calculated in relation to a baseline interval (typically covering the 100 - 200 ms preceding stimulus onset), for which activity is equated with zero. Under the assumption that the targeted event-related brain activity is time-locked to the averaging trigger and invariant over trials, the SNR improves as a function of the square root of the number of averaged epochs (Cooper, Osselson, & Shaw, 1984)². Figure 2.1 illustrates the averaging procedure for ERP extraction.

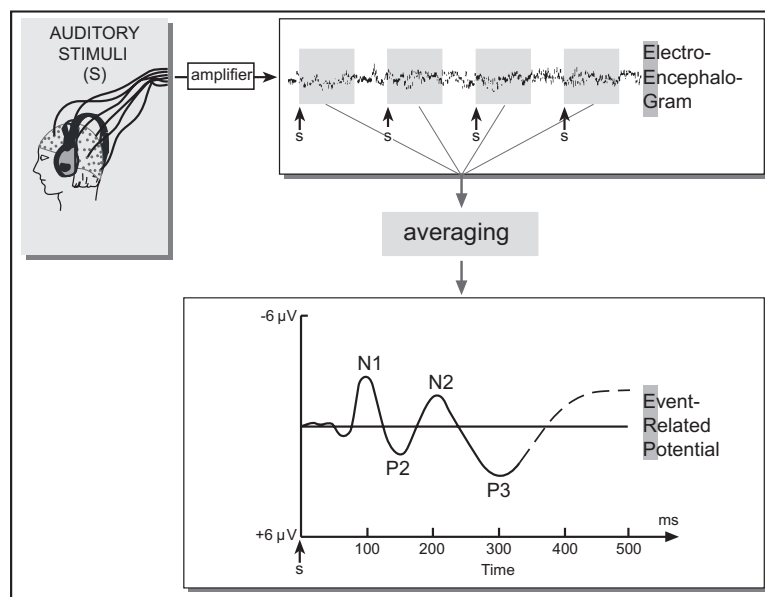


Figure 2.1: From EEG to ERP. Averaging procedure resulting in a typical auditory ERP waveform, including the N1/P2 complex as well as the endogenous components N2 and P3. Negativity is plotted upwards by convention.

ERP component definition and interpretation The waveform displayed in Figure 2.1 represents an auditory ERP as it would typically occur in response to the presentation of short tones. The waveform shows several positive and negative deflections that are referred to as *components*. These are characterized by their polarity (i.e. negative vs. positive), their latency in milliseconds (ms) relative to stimulus onset, and their topographical distribution across the

²It should be noted that the assumption of signal invariance over trials is rather problematic. In view of stimulus repetition effects such as habituation, it is rather likely that the SNR actually decreases if a certain optimum number of averaged epochs is exceeded (e.g. Elbert, 1998; McGee et al., 2001).

scalp. ERP components are divided into two major classes. Components occurring within about 80 ms after stimulus onset are regarded as "exogenous" or stimulus-driven, as they reflect obligatory brain responses to a stimulus, and are considered to be independent of changing psychological states. In contrast, later components are termed "endogenous", and are believed to be elicited or at least modulated by "higher" cognitive operations related to the stimulus as they are clearly influenced by task demands, attentional set, or expectancies of the participant. These components are of major interest in any ERP investigation of cognitive processes.

There is considerable disaccord in the literature as to whether ERP components should be defined based on their physiological or functional characteristics (see detailed information in Rugg & Coles, 1995; Handy, 2005). The present investigation will follow the functional approach. In this most common approach in psychological and psycholinguistic research, ERP component definition is mainly based on comparisons between ERP waveforms in response to two or more experimental conditions. Differences in the waveforms are then interpreted as reflecting differences in the cognitive operations involved in the processing of the respective conditions. This approach shall be demonstrated in the following by introducing some classic ERP components (most of which are displayed in Figure 2.1) along with their prevalent functional interpretation.

N1 / P2 The occurrence of any auditory or visual stimulus elicits an ERP pattern known as the N1-P2 complex, consisting of a negative deflection around 100 ms and a following positive deflection around 200 ms. These components are associated with activity in primary sensory cortices, and are thus taken as the primary indicators of cortical stimulus processing. Although strongly correlated with the physical properties of a stimulus, they are the earliest to demonstrate variations depending on cognitive variables such as selective attention. The amplitude enhancement that is observed when comparing the N1 in response to attended stimuli to the N1 in response to unattended stimuli is taken to reflect attention-related cognitive activity facilitating stimulus detection (Hillyard, Hink, Schwent, & Picton, 1973; Näätänen & Picton, 1987; Hackley, Woldorff, & Hillyard, 1990).

N2/MMN A second negative deflection in the ERP response that is associated with cognitive processing is the N2 component occurring at around 200 ms after stimulus onset. In contrast to the obligatory N1, the elicitation of the N2 depends on the detection of a stimulus that

deviates from the preceding context (Coles & Rugg, 1995). The N2 can be divided into the two subcomponents N2a and N2b based on different topographical distributions and functional characteristics (Näätänen, Simpson, & Loveless, 1982). Whereas the N2b is only elicited if the deviant stimulus is task relevant and is thus associated with processes of conscious deviance detection, the occurrence of the N2a is independent of attention. The latter subcomponent is equivalent to the functionally labelled *mismatch negativity* (MMN) first described by Näätänen and colleagues in 1978. The MMN is assumed to reflect an "automatic, preconscious change detection mechanism" (Näätänen, Paavilainen, Tiitinen, Jiang, & Alho, 1993, p. 437)³. The fact that the MMN is elicited reliably even in the absence of focused attention has made it a favorable object of investigation in the study of automatic cognitive processes. It thus seems ideally suited for the purposes of the present study and shall therefore be described in greater detail in the following.

The classic MMN is elicited in auditory oddball paradigms⁴ in which participants are presented with a sound sequence consisting of a frequently repeated standard sound (i.e. the *standard* stimulus) that is occasionally replaced by a sound that deviates in one or several features from the standard (i.e. the *deviant* stimulus). To avoid a component overlap with the N2b and other attention-related components, participants are usually distracted from the auditory stimulation by means of stimulus irrelevant tasks such as reading a book or watching a silent movie. The MMN is commonly displayed by subtracting the ERP to the standards from the ERP to the deviants. In the resulting difference waveform it appears as a negative peak between 100 and 250 ms after the onset of the acoustic change. This component is maximal over fronto-central scalp sites and inverts polarity at the mastoids (e.g. Näätänen, Tervaniemi, Sussman,

³The view that the MMN is "automatic" or even "preattentive" is just as prevalent as controversial. As a detailed discussion of the expanding literature on this issue would go beyond the scope of the present work, the interested reader is referred to the overview given in Picton, Alain, Otten, Ritter, and Achim (2000). For the present purpose, the assumption that the MMN reflects automatic processing is adopted based on the definition of automaticity given earlier, according to which "a process will be regarded as automatic if it occurs irrespectively of whether attention is focussed on the input or not" (page 11). This definition accommodates both the fact that "no study has shown that the withdrawal of attention could totally abolish the MMN" (Näätänen & Alho, 1997, p. 342) and reports of attentional and other top-down modulations of the MMN amplitude (e.g. Sussman, Ritter, & Vaughan, 1998; Sussman, Winkler, Huotilainen, Ritter, & Näätänen, 2002).

⁴For a review on attempts to identify an equivalent to the MMN in the visual modality, see Pazo-Alvarez, Cadaveira, and Amenedo (2003).

Paavilainen, & Winkler, 2001). Its primary neuronal generators have been localized within the auditory cortices of both hemispheres (Giard, Perrin, Pernier, & Bouchet, 1990; Alho, 1995; Opitz, Mecklinger, von Cramon, & Kruggel, 1999; Opitz, Rinne, Mecklinger, von Cramon, & Schröger, 2002). In the course of MMN research, the MMN amplitude and latency have been shown to vary as a function of the magnitude of deviation (e.g. Sams, Paavilainen, Alho, & Näätänen, 1985; Tiitinen, May, Reinikainen, & Näätänen, 1994) and the number of deviating stimulus features (Schröger, 1995; Wolff & Schröger, 2001; Paavilainen, Valppu, & Näätänen, 2001). Furthermore, it became apparent that the repetitive presentation of the same standard is not a necessary precondition for MMN elicitation. Rather, the MMN is elicited whenever an established auditory pattern or *regularity* is interrupted by the deviant, even if this regularity arises from a rather abstract rule (e.g. Tervaniemi, Maury, & Näätänen, 1994; Paavilainen, Simola, Jaramillo, Näätänen, & Winkler, 2001). Functionally, the MMN has been interpreted as reflecting a neural mechanism that detects changes in the auditory environment based on the comparison of an incoming stimulus against a preattentively established memory trace of repetitive or regular aspects of the auditory scene (e.g. Näätänen, 1992; Winkler, Karmos, & Näätänen, 1996). As such, it has been discussed to play the initiating role in the involuntary allocation of attentional resources to previously unattended sounds, thus reflecting a vital sub-process of the auditory orienting response (e.g. Näätänen, 1992; Schröger, 1996; Schröger & Wolff, 1998a).

Importantly, the MMN has been shown to be influenced not only by memory traces concerning the immediate auditory past, but also by experience dependent long-term or *permanent* memory traces that serve as recognition patterns during auditory scene analysis (Näätänen, 1995; Näätänen et al., 2001). This observation extended the use of the MMN to the investigation of language-related phenomena including syntax processing (for a recent review, see Pulvermüller & Shtyrov, 2006), an approach that will be motivated further in Section 2.2 of the present chapter.

P300 A further ERP component that is elicited in the context of oddball paradigms is the P300 (or P3) wave, a prominent positive-going ERP deflection that typically peaks about 300 ms after stimulus onset (as displayed in Figure 2.1). First discovered by Sutton and colleagues in 1965, it is probably the most extensively studied and most reliably elicited ERP component (for reviews, see Donchin, 1981; Hruby & Marsalek, 2003). Like the N2b, its occurrence is

bound to the conscious detection of an unexpected stimulus. It can be observed in response to deviant stimuli that were either a priori defined as targets (e.g. by means of a deviance detection task) or salient enough to trigger an involuntary attention switch. The occurrence of the P300 can therefore be taken as an indicator of the conscious classification of a stimulus as "being different". Conversely, the absence of a P300 in response to a deviant stimulus is usually taken as a sign that the deviance escaped conscious awareness (e.g. Schröger, 1996; Schröger & Wolff, 1998b, 1998a).

Further ERP components that are relevant for the present investigation due to their association to syntax processing will be introduced in the following chapter.

General theories of ERPs In addition to the one-to-one mapping between single components and cognitive functions described in the above, some theories attempt to arrive at a more general understanding of what is reflected in ERPs. In his *Theory of cortical responses*, Friston (2005) suggests that ERPs can be understood in terms of a model of inference and learning that is based on empirical Bayes. In his view, the brain attempts to minimize the free energy (i.e. "surprise") induced by a given stimulus by means of predictive coding, and sensory ERP components represent the prediction error that occurs during this process and its subsequent suppression by top-down modulatory processes. Along similar lines, Kotchoubey (2006) proposes that negative ERP deflections may reflect the formulation of perceptual expectancies or hypotheses, whereas positive ERP deflections may reflect the comparison of these with the actual sensory input and the confirmation or revision of the previous hypotheses. Such general theories of ERPs are certainly preliminary in that they focus on sensory ERPs and thus may not explain every single observation in ERP research. By explicitly considering principles of brain organization and neuronal activation patterns, these theories nevertheless constitute an important link between the electrophysiological phenomena measured outside the head and the neuronal processes they reflect.

Benefits and limitations of the ERP method In sum, it can be noted that the measurement of ERPs represents an ideal method to study the temporal sequence of cognitive events. It provides a real-time correlate of cognitive processes, even when these processes are relatively short-lived. Furthermore, ERPs represent a *direct* measure of neuronal activity as opposed to

methods that rely on changes in blood flow or metabolism (see below). It is thus ideally suited for the present enterprise to look into the relative timing of different syntactic subprocesses.

In spite of these advantages, there are several limitations of the ERP method that should be considered when conclusions about underlying neuronal mechanisms are being drawn. First and foremost, not all of the functionally relevant brain activity associated with a cognitive process is reflected in scalp-recorded ERP responses. Anatomically, ERPs are blind to activity in structures that produce closed fields, as well as to subcortical activity and cortical responses that do not involve sufficiently large samples of neurons. Methodologically, they are restricted to activity that is time-locked to the critical stimulus, although it is a fact that cognitive processes also induce signal changes that occur at varying latencies following stimulus presentation (Tallon-Baudry, 2003; Kaiser & Lutzenberger, 2003). This selectivity of ERPs means that they may not be regarded as an exhaustive reflection of the neuronal activity associated with specific cognitive processes.

A related issue concerns the spatial resolution of the ERP method. A scalp-recorded ERP component shows *that* and precisely *when* a certain process has taken place, but it conveys relatively little information about *where* in the brain the measured signal originates. This *inverse problem* denotes the fact that the location of electrical sources cannot be determined based on the topographical distribution of the scalp potentials alone, because theoretically there is an infinite number of possible source constellations that could lead to the same scalp distribution (e.g. Nunez, 1981, 1990; Otten & Rugg, 2005). Although there are highly advanced methods of source modelling that take anatomical constraints and a priori assumptions about possibly activated areas into account (e.g. Scherg & Picton, 1991; Scherg & Ebersole, 1993; Schroeder et al., 1995), the localization of generators underlying scalp-recorded ERPs remains an estimation and can by no means be regarded as exhaustive. It is therefore important to keep in mind that topographically similar ERP components do not justify the assumption of identical underlying neuronal processes.

2.1.2 Magnetoencephalography and event-related fields

A way to combine high temporal resolution with a reasonable spatial resolution is offered by the measurement of event-related magnetic fields (ERFs) by means of magnetoencephalography (MEG). This method is closely related to EEG / ERPs as it comprises the recording of

the magnetic fields induced by the brain's electrical activity. It is thus equally time-sensitive. The recording device consists of a number of sensors that rest in a so-called Dewar that is shaped such that the sensors can be placed above the scalp. Similar to EEG, MEG has several limitations with respect to the recordable brain activity. It is equally selective to open fields and additionally selective to fields that are oriented tangentially to the brain's surface. MEG-recorded signals therefore reflect mainly activity in the sulci rather than in the gyri. Furthermore, MEG is less sensitive to cortical sources located far away from the scalp. However, MEG has several advantages over EEG when it comes to spatial resolution. The volume current reflected in EEG signals gets considerably distorted on its way from the source to the electrode because conductivity varies greatly for brain tissue, cerebro-spinal fluid, skull, and scalp. In contrast, magnetic fields reach the sensors undistortedly. Furthermore, MEG-recorded signals carry some spatial information about the location of their underlying electric generators. For example, the magnetic field is zero directly above the source and of opposite orientation to the sides of it, and the distance between the sensors that register the strongest activations reveals information about the depth of a source (Elbert, 1998). It is for these reasons that the MEG is regarded as "perhaps the best combination of spatial and temporal resolution of noninvasive methods in common use" (Kutas, Van Petten, & Kluender, 2006, p. 663).

2.1.3 Neuroimaging techniques

When the precise localization of neuronal activity in the brain takes center stage in an investigation and temporal resolution is less important, there are methods of functional neuroimaging that are to be preferred over source modelling approaches based on EEG or even MEG data. The most prevalent neuroimaging techniques in the literature on syntax processing are positron emission tomography (PET) and functional magnetic resonance imaging (fMRI). Both of these methods make use of the fact that neuronal activity in a region of the brain induces regional cerebral blood flow (rCBF) to this region due to increased metabolism. They thus provide an indirect measure of neuronal activity and, as increases in rCBF are gradual rather than instantaneous, a temporal resolution that ranges in the order of seconds (fMRI) and minutes (PET). In exchange, their spatial resolution is as precise as a few millimeters⁵. The consideration of

⁵A more comprehensive description of these methods is provided by Orrison, Lewine, and Sanders (1995).

neuroimaging data is thus imperative for any investigation that aims at the identification of brain areas involved in syntax processing.

2.2 Experimental paradigms for studying syntax in the brain

2.2.1 Common rationale

The above neuroscientific techniques have been employed in a number of different experimental approaches to investigate syntax processing in the brain. The common rationale of all of these is to contrast two or more conditions that differ only with respect to the process of interest, and to interpret differences in the respective dependent measures as reflections of this process. Although the assumptions inherent to this logic of "cognitive subtraction" are not unproblematic (see Friston et al., 1996), it offers the opportunity to study syntax along several dimensions. In order to trigger syntactic processing mechanisms and to isolate them from other processes during online language comprehension, experiments have compared scrambled word lists to sentences (e.g. Schriefers, Friederici, & Rose, 1998), sentences with different syntactic complexity (e.g. Friederici, Hahne, & Saddy, 2002), ambiguous to non-ambiguous sentences (e.g. Frisch, Schlesewsky, Saddy, & Alpermann, 2002; Kaan & Swaab, 2003), so-called 'Jabberwocky' sentences, in which all content words have been replaced by phonologically legal pseudowords, to ordinary sentences (e.g. Hahne & Jescheniak, 2001), as well as correct sentences to sentences containing syntactic violations (e.g. Neville, Nicol, Barss, Forster, & Garrett, 1991; Friederici, Pfeifer, & Hahne, 1993; Friederici, Hahne, & Mecklinger, 1996).

2.2.2 Violation paradigms

While all of these experimental manipulations allow for a distinction between syntactic and other processes during online sentence comprehension, the violation paradigm appears to be suited best for the differentiation of subprocesses *within* syntactic analysis. The idea behind this is that a given syntactic violation will disrupt ongoing steps in syntactic analysis at its level of occurrence, and that this disruption will have specific effects on the respective dependent variable. Accordingly, employing different syntactic violations allows for a direct comparison between different syntactic processing stages. This procedure has produced reliable results in numerous ERP and neuroimaging studies. A further important advantage of the violation

paradigm is that the correct and incorrect conditions can be constructed to be identical up to the violation point. This makes it comparatively easy to define adequate control conditions. These features render the violation paradigm an ideal candidate for the purposes of the present investigation⁶.

Within the violation paradigm, there are several experimental parameters that need to be considered as they may restrict the comparability between experiments. One important parameter is the modality of presentation, i.e., whether the language stimuli are conveyed visually or auditorily. Using written language input is of advantage because stimuli are easy to prepare and to present, and the physical stimulus features are readily controlled for. On the other hand, auditory stimulation approximates the natural language environment more closely. As differences between the visual and auditory modality are rarely addressed directly (see, however, Hahne, 1997; Hagoort & Brown, 2000), it is questionable whether processes triggered during reading are identical to those evoked during spoken language comprehension. After all, our brains are able to process (and produce) spoken language long before they are even confronted with written language input. It appears unreasonable to assume that this fact should not result in quantitatively or even qualitatively different processing mechanisms, in particular when the processing speed or the degree of automatization are concerned.

A second important experimental parameter is the task the participants are asked to perform during testing. A broad range of tasks has been applied in violation paradigms, including correctness judgements (e.g. Neville et al., 1991), probe verifications (e.g. Friederici et al., 1993), reading or listening for comprehension (e.g. Kutas & Hillyard, 1983), or active and passive distraction (Pulvermüller, Shtyrov, Hasting, & Carlyon, 2008). The task is often enlisted to test whether a given process is influenced by the participant's strategic control or independent of it. It is thus an important tool in the investigation of the automaticity of syntactic processing.

And third, violation paradigms differ according to the proportion of correct and incorrect stimuli presented during an experiment. Similarly to task demands, the violation probability has been used to test the automaticity of the investigated processes. The rationale behind this is that controlled processes will adapt to violations that are presented at high probability, whereas

⁶It should, however, be kept in mind that despite the many methodological advantages, investigating syntax by means of violations entails the use of stimuli that rarely occur during natural language processing. This may pose a problem for the external validity of the results, as pointed out previously by Frisch, Hahne, and Friederici (2004) and Kutas et al. (2006).

truly automatic processes will remain unaffected by variations of violation probability (e.g. Gunter, Stowe, & Mulder, 1997; Coulson, King, & Kutas, 1998; Hahne & Friederici, 1999).

2.2.3 The syntactic MMN paradigm

As indicated earlier in this chapter, the MMN paradigm has also been used to investigate syntax processing in the auditory modality. Aiming at statements on the automaticity of such processing, it may be regarded as an extreme form of task and violation probability manipulations. Syntactic MMN studies (e.g. Pulvermüller & Shtyrov, 2003; Shtyrov, Pulvermüller, Näätänen, & Ilmoniemi, 2003; Menning et al., 2005; Pulvermüller et al., 2008) typically employ pairs of short utterances as standard and deviant stimuli in oddball sequences with less than 20 percent deviations. The stimulus pairs differ only in one phoneme (in most cases the final suffix) that determines their grammaticality. Thus, the acoustic change between standard and deviant stimulus coincides with a change in grammatical correctness. The sequences are constructed in pairs according to the principle that each of two sequences must contain the identical acoustic change between standard and deviant stimuli, whereas the grammaticality of the stimuli (correct vs. incorrect utterance) is switched. This is achieved by changing the syntactic context in which the deviating phonemes are presented. Amplitude modulations between the MMNs from a pair of sequences can then be unequivocally attributed to the syntactic processing of the stimuli.

The most prominent difference between syntactic MMN studies and the standard violation paradigms described in the previous section consists in the repetitiveness of the stimulus material. While standard violation paradigms employ numerous different stimuli that are averaged within conditions, the syntactic MMN paradigm usually comprises the repetitive presentation of the same pair of standard and deviant. On the one hand, this repetitiveness poses a problem for the generalization of results from syntactic MMN studies, because it may promote processing mechanisms that are different from those in use for natural non-repetitive language input. On the other hand, it offers the possibility to study the brains responses to individual linguistic items. This is of advantage because it is never clear whether effects are representative or driven by outliers when assessing averaged brain responses in response to groups of different stimuli. Furthermore, averaging across different stimuli brings along the danger that small effects are missed due to physical or linguistic stimulus variance (Pulvermüller, 1999; Penolazzi, Hauk, &

Pulvermüller, 2007). Other advantages of the syntactic MMN paradigm are the provable task independence of the MMN component and a thorough control of the effect of physical stimulus features that is comparatively difficult to achieve for large groups of different stimuli.

The present study will combine the advantages of the syntactic MMN paradigm and standard violation paradigms to test for the relative timing and automaticity of the syntactic subcomponents of phrase structure building and syntactic-relational processing. This approach will be motivated in the following two chapters that present both insights and inconsistencies that have been obtained by means of the introduced methods and paradigms.

Chapter 3

Neuroscientific evidence on syntax processing

The current chapter presents an overview over the empirical findings that motivated the current investigation. These stem mainly from ERP studies utilizing violation paradigms, including the syntactic MMN paradigm. A review of the relevant ERP findings will be given in the first part of this chapter. The second part briefly summarizes the current state of research concerning the mapping of syntactic processes to specific brain areas by means of neuroimaging techniques.

3.1 Evidence from ERP data

While ERPs in neurolinguistics were initially used to differentiate between syntactic and semantic subcomponents of language processing (e.g. Kutas & Hillyard, 1983; Münte, Heinze, & Mangun, 1993; Gunter et al., 1997; Hagoort, Wassenaar, & Brown, 2003), their use was soon extended to the investigation of syntactic subprocesses, mainly by means of standard violation paradigms. To date, this research has yielded several distinctive ERP components that exhibit different temporal and attentional properties.

First, standard violation paradigms reveal an early left anterior negativity (ELAN) in response to words that violate the word category predicted on the basis of the previously encountered phrase structure. This effect was first shown by Neville et al. (1991) in response to English phrase structure violations that were created by inverting the order of prepositions and

head nouns, e.g.,

- (1) The man admired Don's **of** sketch the landscape.

and later replicated in numerous studies using German sentences (e.g. Friederici et al., 1993, 1996; Hahne, 1997; Hahne & Friederici, 1999) in which a noun was replaced by a past participle, e.g.,

- (2) Das Eis wurde im **gegessen** (*The icecream was in-the eaten*)¹.

The ELAN usually peaks around 150 ms after the point at which the violation becomes obvious (i.e. the word category decision point). Because of the particularly early onset of this component and its functional precedence over semantic (Hahne & Friederici, 2002; Friederici, Gunter, Hahne, & Mauth, 2004) and syntactic-relational processes (Rossi, Gugler, Hahne, & Friederici, 2005), it has been interpreted as an index of parsing disruption at the initial level of phrase structure building (Friederici, 1995, 2002). This syntactic subprocess is believed to be based on word category information that has been suggested to precede the processing of other syntactic information types (Frazier, 1987; Gorrell, 1995). As such, it is considered to be universal across languages (Friederici & Weissenborn, 2007). A recent study by Lau, Stroud, Plesch, and Phillips (2006) showed that the degree of distinctiveness of the ELAN depends on the strength of the word category predictions based on the context. However, the ELAN was attenuated, but never absent, even if contextual restrictions were not as tight as in (1) and (2). Demonstrations that the ELAN is unaffected by variations in violation probability (Hahne & Friederici, 1999) and task demands (Hahne & Friederici, 2002) further corroborate the view that the syntactic subprocess underlying this component is of a highly automatic nature.

An even larger amount of studies employed violations that leave the syntactic structure intact but affect tense, number, gender or case agreement or other morphological cues. Most of these report an ERP component that is topographically similar, but temporally shifted as compared to the ELAN. This left anterior negativity (LAN) usually occurs in a time range between 300 and 500 ms (Kutas & Hillyard, 1983; Friederici et al., 1993; Osterhout & Mobley, 1995; Gunter, Friederici, & Schriefers, 2000; Hagoort & Brown, 2000). It has been observed in numerous languages including English, Dutch, Italian, Spanish and German, but seems to depend on the degree to which a language uses morphological cues to establish syntactic relations (for a review, see Friederici & Weissenborn, 2007). It has therefore been interpreted

¹Translations of examples are word-by-word in order to demonstrate the syntactic features. Critical words are in bold.

as an index of syntactic-relational processing subserving thematic role assignment (Friederici, 2002). An alternative interpretation refers to the fact that the LAN is not only elicited by syntactic-relational violations, but also by grammatically correct constructions that impose a particular load on working memory (e.g. Kluender & Kutas, 1993; Rösler, Pechmann, Streb, Röder, & Hennighausen, 1998). According to this view, the function underlying the LAN is best described in terms of a more general working memory-related mechanism that attempts to align current unexpected syntactic information with information occurring elsewhere in the sentence ("look forward" or "look back" functions; see Kutas et al., 2006, p. 692). Similar to the ELAN, the LAN has been shown to be unaffected by variations in violation probability (Gunter et al., 1997; Coulson et al., 1998). This attests to a certain independence of attention and strategic control. On the other hand, data showing that the LAN is influenced by task demands (Gunter & Friederici, 1999; Osterhout & Mobley, 1995), and constrained by working memory capacity (Vos, Gunter, Kolk, & Mulder, 2001) suggest underlying processes that are to a lesser degree automatic than those reflected in the ELAN.

A third ERP component that has been related to syntactic processing is the P600 (Osterhout & Holcomb, 1992) or "syntactic positive shift" (Hagoort, Brown, & Groothusen, 1993). This centro-parietal positivity occurs at a latency of about 600 ms following different types of syntactic violations, as well as instances of syntactic complexity (Kaan, Harris, Gibson, & Holcomb, 2000) and ambiguity (Frisch et al., 2002). Studies showing that the P600 is susceptible to variations in violation probability (Gunter et al., 1997; Coulson et al., 1998; Hahne & Friederici, 1999) have raised the question whether this component is a domain-general member of the P300 family reflecting the detection of rare events rather than syntactic processing difficulties. However, evidence from patients with brain lesions demonstrating a double dissociation between the P600 and the P300 dispelled this ambiguity (Frisch, Kotz, von Cramon, & Friederici, 2003; Wassenaar, Brown, & Hagoort, 2004). The P600 is thus most commonly seen as an index of syntactic revision and repair (Friederici, 2002). In contrast to earlier syntactic processing steps, these processes are considered to depend on the participants' strategic control and the attentive processing of syntactic stimulus features. This is demonstrated by the finding that the P600 is reduced when the violation probability is high (Gunter et al., 1997; Coulson et al., 1998; Hahne & Friederici, 1999), and when it is tested under physical or semantic processing demands (Gunter & Friederici, 1999; Hahne & Friederici, 2002).

With their different temporal and attentional characteristics, the three syntactic ERP components are in favour of the modular approach and serial models of parsing. For example, Friederici (1995, 2002) calls on the above findings in her comprehensive *Neurocognitive Model of Auditory Sentence Comprehension*, which assumes that following the primary acoustic and phonological analysis of the speech input, syntactic analysis proceeds in three hierarchically organized and temporally consecutive processing phases. In the initial phase, word category information is used to build up a local phrase structure. This first-pass parse occurs very early, i.e., within the first 200 ms after the word category of a word can be determined, as demonstrated by the ELAN. The second phase between 300 and 500 ms entails the establishment of syntactic relations as indicated by the LAN. And finally, processes of syntactic integration and - if necessary - reanalysis and repair are assigned to the ensuing third phase around 600 ms, as reflected in the P600. With respect to the degree of automaticity of the different syntactic subprocesses, it further appears that each subsequent phase requires more attention for its successful completion, turning from highly automatic (ELAN) to controlled processing (P600).

However, recent years have put forth several findings that are not easily integrated within this framework. First and foremost, studies employing the syntactic MMN paradigm (see Section 2.2.3) demonstrated that the MMN and its magnetic counterpart (MMNm) are modulated by different types of agreement violations. In these studies, the MMN in response to grammatically incorrect deviant stimuli is consistently reported to be enhanced as compared to that elicited by correct deviant stimuli. The syntactic MMN effect has been shown for agreement violations in English (Pulvermüller & Shtyrov, 2003; Pulvermüller et al., 2008), Finnish (Shtyrov et al., 2003) and German (Menning et al., 2005; Pulvermüller & Assadollahi, 2007) and therefore appears universal across languages. It challenges the above view of serial processing of phrase structure and agreement in two aspects. First, it occurs in the time range between 100 and 200 ms that, according to previous findings, would be reserved for phrase structure building. Second, based on the assumed automatic nature of the MMN component (see page 16), it also suggests that syntactic relations can be processed just as automatically as a sentence's phrase structure. In addition to the syntactic MMN, there are several instances in which conspicuously early brain responses to non-phrase structure violations were obtained by means of the standard violation paradigm. For example, an effect in the time range of the ELAN was demonstrated following visually presented gender agreement violations in Hebrew (Deutsch

& Bentin, 2001). Furthermore, an equally early magnetic component (termed SF-M150) was observed in response to within-category violations in English (e.g., I believe him **is** a spy; Kubota, Ferrari, & Roberts, 2003, 2004). It thus seems that the relative timing and automaticity of ERP components in response to phrase structure versus syntactic-relational manipulations is not satisfactorily explained by the assumption of temporally fixed processing phases. This point will be elaborated in the following chapter.

3.2 Evidence from neuroimaging data

Attempts to identify brain areas that are concerned with syntax processing in healthy participants have taken two different approaches, namely the localization of generators underlying the above ERP effects (mainly by means of MEG) and the application of hemodynamic measures (i.e., PET and fMRI).

The first approach has identified bilateral regions in superior temporal and inferior frontal areas as the main sources of the ELAN (Gross et al., 1998; Knösche, Maess, & Friederici, 1999; Friederici, Wang, Herrmann, Maess, & Oertel, 2000). In concordance with the left anterior focus of this component, two of these studies report stronger sources in the left hemisphere (Gross et al., 1998; Friederici et al., 2000). Similarly, Kubota et al. (2003, 2004) report the sources of their SF-M150 to be located in superior temporal regions bilaterally, with an additional source in the superior temporal region of the left hemisphere in the earlier of the two related studies (Kubota et al., 2003). Localizations of the syntactic MMN effect have indicated distributed activations in left superior temporal cortex (Shtyrov et al., 2003), left inferior frontal cortex (Pulvermüller & Shtyrov, 2003) and bilateral activations of superior temporal cortices with a lateralization to the left hemisphere (Pulvermüller & Assadollahi, 2007).

Although being largely consistent in suggesting left-lateralized temporo-frontal networks to be involved in syntax processing in general, these findings do not allow for conclusions about possible spatial differentiations between syntactic subprocesses. Due to their enhanced spatial resolution, neuroimaging data have been more revealing with regard to this point. A review of all the manifold PET and fMRI investigations concerning syntax processing would go beyond the scope of the present work². The general picture that emerges from these investigations is

²Recent comprehensive reviews on the matter can be obtained from Kaan and Swaab (2002), Friederici and Kotz (2003) or Grodzinsky and Friederici (2006).

that early processes of phrase structure building mainly engage the anterior portion of the left superior temporal gyrus as well as selective areas in left inferior frontal gyrus (i.e. Brodmann Area BA 44 and the deep frontal operculum), whereas late processes of revision and repair appear to be subserved by the left posterior superior temporal gyrus (Friederici, Rüschemeyer, Hahne, & Fiebach, 2003; Friederici & Kotz, 2003; Grodzinsky & Friederici, 2006). The intermediate phase of syntactic-relational processing is being associated with activations in Broca's area situated in the inferior frontal gyrus of the left hemisphere (BA 44/45; Friederici, 2002; Friederici & Kotz, 2003). The latter aspect is mainly deduced from studies that employed variations in syntactic complexity rather than different violation types (Stromswold, Caplan, Alpert, & Rauch, 1996; Ben-Shachar, Hendler, Kahn, Ben-Bashat, & Grodzinsky, 2003; Friederici, Fiebach, Schlesewsky, Bornkessel, & von Cramon, 2006). Several neuroimaging studies that tested agreement violations along with other syntactic anomalies (Meyer, Friederici, & von Cramon, 2000; Moro et al., 2001; Kuperberg et al., 2003) failed to report differential activations according to violation type.

A possible explanation for the apparent difficulty to demonstrate such effects is given by Friederici (2004), who suggests that the distinction of subregions of left inferior frontal cortex according to syntactic functions may depend on whether the structure to be processed is governed by local transition probabilities or long-distance syntactic hierarchies. The validity of this idea was shown impressively by recent investigations of artificial grammar processing (Friederici, Bahlmann, Heim, Schubotz, & Anwender, 2006; Bahlmann, 2007). Cortical activations in response to violations of a finite state grammar (FSG) that is fully determined by transitional probabilities were compared to activations elicited by violations of a phrase structure grammar (PSG) that includes hierarchical structure and long distance dependencies. While both grammar types engaged the left frontal operculum, only PSG violations additionally activated Broca's area (BA 44/45). It thus seems that the processing of local syntactic errors is supported by the left frontal operculum independently of the specific syntactic structure to be analyzed, presumably by means of a comparison between incoming and predicted speech elements, and that additional brain areas are only recruited when it comes to the analysis of syntactically more complex sentence hierarchies. However, it remains to be shown whether this dependency holds for natural language processing before conclusions about representational differences between syntactic subprocesses can be drawn.

Chapter 4

In need of clarification: Open questions and ways to address them

The previous chapter showed that the use of neuroscientific methods led to important advances concerning the question of how the human brain accomplishes syntax processing. The conjoined evaluation of time-sensitive ERP data and spatially revealing neuroimaging data suggests a left-lateralized perisylvian neuronal network that executes different syntactic subprocesses in temporally consecutive processing phases. In spite of these proceedings, there are several inconsistencies in the data that require further explanations. These open questions shall be elaborated in the following three sections. The final section of this chapter will present the ensuing aims of the current investigation and give a brief outline of the experiments that were conducted in their pursuit.

4.1 The question of timing

The first question that arises from the reviewed data is whether the assignment of phrase structure building and syntactic-relational processing to temporally fixed, consecutive processing phases as assumed by Friederici (2002) is justified in view of the contradicting syntactic MMN data showing early effects of agreement. Unfortunately, a true comparison of the diverging findings regarding this point is hampered by methodological differences between the studies.

A first important methodological issue that could easily affect the timing of syntactic ERP effects concerns the precision of time-locking with respect to the violation point of the stim-

uli. It has been noted earlier that the timing of the ERP effects in response to phrase structure manipulations depends on the point at which the word category information becomes available (cf. Friederici & Meyer, 2004). An early onset of the effect (ELAN, 150 - 200 ms) is observed when the word category information is encoded in the prefix of the critical word (Friederici et al., 1993; Hahne & Friederici, 1999), whereas the effect is delayed (but still early with respect to the word category recognition point) when the word category is marked in the suffix (Friederici et al., 1996; Hagoort et al., 2003; Friederici et al., 2004). In contrast, this confound has not been explicitly considered for the timing of syntactic-relational ERP effects. This is particularly problematic in the case of auditorily presented agreement violations induced by verb inflection errors, as these cannot be detected prior to the suffix of the critical verb (e.g. Rossi et al., 2005). ERP responses to such violations unequivocally sustain an artificial delay if they are time-locked to word onset. Additionally, the common procedure to average ERP responses across conceptually identical but acoustically different stimuli induces a considerable latency jitter depending on the length of the critical words that may cancel out early ERP effects, or at least obscure their exact onset latency (see also Pulvermüller & Shtyrov, 2006; Penolazzi et al., 2007). Perhaps unsurprisingly, all of the studies that reported early syntactic-relational ERP effects either used violations that were detectable in the first syllable of the critical word (Deutsch & Bentin, 2001; Kubota et al., 2003, 2004; Menning et al., 2005; Pulvermüller & Assadollahi, 2007) or time-locked the ERP responses directly to the critical suffix (Pulvermüller & Shtyrov, 2003; Shtyrov et al., 2003; Pulvermüller et al., 2008).

Another aspect of these studies that is remarkable in the context of timing is the invariably local nature of the tested violations. Whereas phrase structure violations are local per definition and can therefore be captured by a fast-working mechanism based on syntactic predictions¹, the syntactic relations affected by agreement violations can persist over longer distances requiring enhanced working memory capacity to be processed (e.g. Vos et al., 2001). Under the assumption that an involvement of working memory processes will complicate syntactic processing to a degree that impedes such predictions, latency differences observed between ERP effects to local phrase structure violations and non-local syntactic-relational violations (e.g. Rossi et al., 2005) may be due to differences in violation locality rather than type.

¹For a theoretical elaboration of this concept, see Gibson's *Syntactic Prediction Locality Theory* (SPLT; Gibson, 1998) that assumes syntactic integration costs to be "proportional to the distance between the elements being integrated" (p. 11).

A third and final methodological difference that constrains the comparison of results from syntactic MMN and standard violation paradigms concerns the repetitiveness of the stimulus material. As already pointed out in Section 2.2.3, the syntactic MMN paradigm involves a highly repetitive presentation of short utterances. It is conceivable that this presentation mode accelerates syntactic processing independently of the syntactic structure presented, and thus overrides temporal processing differences observed under none-repetitive circumstances with a larger sentence context. On the other hand, the syntactic MMN paradigm promotes the detection of early ERP effects, because all physical and linguistic stimulus properties are extremely well controlled for. This is of advantage because simple factors like word length and frequency influence the ERP (Hauk & Pulvermüller, 2004) and thus add to the variance in the data, which in turn may obscure early effects. Furthermore, it was recently shown that suprasegmental acoustic information exerts an early influence on syntactic processing (Eckstein & Friederici, 2006). Subtle differences in prosodic parameters such as duration, pitch, or intensity may therefore convey the word category of a given word prior to the actual violation point, resulting in a selective temporal advantage for word category as compared to agreement manipulations when these are defined by the suffix. Other evidence indicating that the input conditions may influence the latency of syntactic ERP effects results from studies using visual stimulus presentation. Here, the latency of the phrase structure effect has been shown to be delayed to 300 - 500 ms when the visual contrast is low (Gunter, Friederici, & Hahne, 1999), or when the sentences are presented word-by-word at a slow rate (Münte et al., 1993).

In sum, it appears that the detection of early syntactic ERP effects depends on certain optimal input conditions. The latency of negative ERP deflections in response to syntactic violations seems to be affected by experimental factors such as the precision of time-locking, the locality of the employed violation, the repetitiveness of the stimulus material and the control of physical and linguistic stimulus parameters just as much as by the violation type itself. It is therefore essential to take these factors into account when investigating the relative latency of phrase structure and syntactic-relational processing by means of ERPs.

4.2 The question of automaticity

While the findings reviewed in the previous chapter are relatively clear-cut concerning the automaticity of phrase structure building as reflected in the ELAN versus the controlled nature

of syntactic revision and repair as reflected in the P600, the case appears to be less clear for syntactic-relational processing. It is tempting to assume a gradual increase of attentional involvement as syntactic analysis advances, and therefore a moderate degree of automaticity for this intermediate processing phase. Although some studies have suggested that phrase structure information is processed more automatically than inflectional information (e.g. Gunter & Friederici, 1999), others have demonstrated high automaticity for the processing of agreement (e.g. Pulvermüller & Shtyrov, 2003). This lack of clarity may be due to the same methodological points that were presented in the previous section. In particular, the locality of the manipulated syntactic dependency as well as the repetitiveness of the stimulus material are likely to affect the automaticity of syntactic processing. The two issues of timing and automaticity are in fact closely intertwined. The earlier a process takes place, the more automatic it is generally assumed to be. Conversely, it is common sense that automatic processing is faster than conscious, controlled processing. Therefore, controlling the abovementioned experimental factors is crucial in order to clarify both the timing and the automaticity of the syntactic subprocesses in question.

4.3 The question of spatial differentiation

According to the modularity principle and Grodzinskys aligned syntacto-topic conjecture, one would expect distinct brain loci to be activated for each linguistically relevant syntactic subprocess. Consequently, the processing of phrase structure violations and agreement violations should result in at least partially different activation patterns. However, neuroimaging studies using natural language processing have so far failed to demonstrate this dissociation. The recent artificial grammar data by Friederici, Bahlmann, et al. (2006) suggest once more that the locality of the violations may play an important role in this shortcoming: As long as a syntactic violation can be detected by local predictions, the left frontal operculum appears to be sufficient for this task (see also Section 3.2). In spite of this confinement, the idea of a differential anatomical manifestation of phrase structure building as compared to agreement processing still awaits clarification by means of data on natural language processing.

4.4 Aims and experiments of the present study

The above sections demonstrate the crucial role of specific experimental factors in the empirical differentiation of phrase structure and syntactic-relational processing. As a result, it becomes clear that the determinants of syntactic ERP effects are still not sufficiently defined. The aim of the present study is therefore to systematically control those experimental factors that may influence the temporal characteristics as well as the attentional prerequisites of such effects, in order to provide truly unbiased conditions for the comparison between phrase structure building and syntactic-relational processing.

To this end the effects of word category violations and subject-verb agreement violations on the ERP were investigated in a set of interrelated experiments, as these violation types disrupt phrase structure building and syntactic-relational processing, respectively. All experiments utilized the same stimulus material that was developed specifically for the current purposes. To address the issue of timing (Section 4.1), acoustic stimulus features were strictly controlled and violation points were kept identical across conditions. Possible influences of the locality of the respective syntactic relation on the ERP responses were ruled out by realizing both syntactic violation types in two-word utterances at the very local level, thus reducing possible involvements of working memory to a minimum. Finally, influences of stimulus repetitions on the timing of syntactic ERP effects were investigated by employing the same stimuli both within the repetitive MMN protocol and in a non-repetitive standard violation paradigm. The question concerning the relative automaticity of the investigated syntactic subprocesses (Section 4.2) was tackled by applying different paradigms and tasks and comparing the characteristics of the emerging ERP effects. The order in which the experiments are presented follows the gradually increasing amount of attention directed to the stimuli by this manipulation.

Experiment 1 (Chapter 6) compares phrase structure and syntactic-relational processing in the absence of attention by replicating the syntactic MMN effect in response to subject-verb agreement violations as reported by Pulvermüller and Shtyrov (2003), Shtyrov et al. (2003) and Pulvermüller et al. (2008), and extending it to word category violations. The side issue concerning the spatial differentiation of the two syntactic subprocesses (Section 4.3) was addressed in Experiment 2 (Chapter 8) that aims at the localization of the syntactic MMN effects observed in Experiment 1 by means of MEG. The amount of attention directed to the speech stimuli was increased in two steps, first by presenting variable stimuli in a non-oddball setting

under visual distraction (Experiment 3; Chapter 9), and second by explicitly directing the participants' attention towards the variable speech stimuli by means of a correctness judgement task (Experiment 4; Chapter 10).

By increasing the variability of the stimulus material in Experiments 3 and 4 while preserving the stimulus characteristics of Experiments 1 and 2, the present study builds a bridge between the restrictive and highly repetitive syntactic MMN protocols and studies investigating syntax processing in variable sentences of greater complexity. Furthermore, the strict control of the stimulus material guarantees that any difference observed between the two violation types can be unequivocally attributed to processing differences between the underlying syntactic subprocesses. This approach will show whether the correspondence of linguistically defined syntactic subprocesses and specific brain responses can be retained at the level of highly controlled two-word utterances. By shedding light on possible causes for the conflictive findings presented above, it will hopefully contribute to a more integrated understanding of how the brain processes syntax.

Part II

Experiments

Chapter 5

General methods

The EEG experiments presented in the following chapters were designed and evaluated by means of largely identical methods. These will be explicated in the current chapter to avoid unnecessary repetitions during the actual description of the experiments. Section 5.1 describes the selection and preparation of the stimulus material that was used in all of the experiments and is of great importance to the purpose of the present study. Section 5.2 provides detailed information on the applied ERP recording and analysis techniques. Occasional deviations from these general methods will be indicated in the methods sections of the respective experiments. The latter pertains to Experiment 2 in particular, as it was conducted in the MEG and therefore required a different analysis procedure.

5.1 Selection and preparation of the stimulus material

Stimulus sets Stimuli consisted of German two-word utterances that were constructed to compare the effects of syntactic-relational and phrase structure processing on the ERP. Two sets of stimuli were created that realized two syntactic violation types and their respective control conditions. In the AGREEMENT set, two inflected forms of bisyllabic regular verbs were each combined with two personal pronouns (2nd or 3rd person singular) that either syntactically matched the inflected verbform or violated subject-verb agreement. In this stimulus set, the phrase structure of all word pairs remained constant [subject NP + verb]. The combination of both pronouns with both suffixes allowed for the assessment of syntax effects without confounding them with the occurrence of a particular phoneme. Example 1 shows one item from

the AGREEMENT set in the four experimental conditions, with English literal translations given in parentheses. In this and all following stimulus examples grammatically incorrect word pairs are marked with an asterisk (*).

1. (a) er kegelt (*he bowls*)
 (b) *er kegelst (**he bowl*)
 (c) du kegelst (*you bowl*)
 (d) *du kegelt (**you bowls*)

The PHRASE STRUCTURE set was constructed according to the same principle. For each item, the word stem of the second word was the same as in the AGREEMENT set. However, the suffix of this word was exchanged so that either the 3rd person inflected verbform or a noun was generated. The two words were combined with either the 3rd person singular pronoun or with the indefinite article 'ein'. This resulted in four word pairs with different phrase structures:

2. (a) er kegelt (*he bowls*)
 (b) *er Kegel (**he cone*)
 (c) ein Kegel (*a cone*)
 (d) *ein kegelt (**a bowls*)

The correct word pairs either comprised a [subject NP + verb] or a [determiner + noun] combination (2a and 2c). One incorrect word pair (2d) was a syntactically illegal [determiner + verb] combination. The other incorrect word pair (2b) was a [subject NP + NP] combination. This is not entirely illegal with respect to German syntax, as two NPs can occur in succession given an appropriate sentence context. An example of this is given in 3.

3. Sie weiss, dass er Kegel sammelt. (*She knows that he cones collects.*)

However, the absence of a sentence context in the current setting renders the occurrence of a noun after a subject NP a highly unexpected event that is in all probability perceived as incorrect. In these terms, the critical words in both 2b and 2c violate the word category predicted on the basis of the preceding word, which disrupts processes of phrase structure building. Like in the AGREEMENT set, the orthogonal combination of pronoun and article with the critical word endings ensured that the manipulation of syntactic correctness was phoneme-independent.

In total, 50 items were selected to create the two stimulus sets. A list of all items is given in the Appendix. The most important criterion for selecting the items was that their word stem had to be ambiguous with respect to the word category to which it belongs (i.e. verb vs. noun). Additionally, items for which 'er' or 'ein' frequently function as prefixes, as illustrated in the examples in 4, were avoided.

4. (a) finden → erfinden (*to invent*)
 (b) reiten → einreiten (*to break in a horse*)

Furthermore, only male or neutral nouns were included as female nouns would have required the adaptation of the indefinite article to satisfy gender agreement.

The two stimulus sets provide a means by which syntactic-relational and phrase structure processing can be investigated under maximally comparable circumstances. Most importantly, the point at which the grammaticality of the stimuli can be detected is identical for both violation types. This rules out potential temporal advantages for the detection of word category violations as compared to agreement violations (see Section 4.1). Moreover, both violation types were realized at the local level and are thus detectable based on local predictions of inflectional morphology. Finally, the use of the same word stem in all conditions precludes influences of differences in word length, frequency and meaning to the greatest possible extent, although obviously some frequency and semantic differences between the verb forms and the nouns remained inevitable.

Preparation of speech sounds Section 4.1 demonstrated that it is of great importance to control not only for the linguistic, but also for the physical stimulus properties when using auditory speech stimuli. The specific recording and splicing techniques applied during the preparation of the two-word utterances to fulfil this requirement will be described in the following. For the recording of the speech signals, the common word stems were embedded into a syntactically neutral context consisting of the pseudoword 'lub' and the pseudosuffix '-k'. These were chosen because [b] and [k] produce little coarticulation and can be separated easily from the word stem¹. Several recordings of the resulting pseudophrase (e.g. 'lub kegelk') and of the three syntactically correct combinations ('er kegelt', 'du kegelst', and 'ein Kegel') were taken. A trained female speaker pronounced the word pairs with natural sentence prosody. She was

¹I would like to thank Dirk Köster for giving me the crucial advice concerning this point.

further instructed to avoid coarticulation between the two words by inserting a short pause into the speech stream. The recordings were digitized at a sampling rate of 44.1 kHz (16 bit; mono). The four acoustically most similar recordings of each item were selected and normalized to the same sound intensity. The pause between the two words was adjusted to 120 ms in all cases. The experimental stimuli were then produced from the recordings as illustrated for one item in Figure 5.1. The common word stem was extracted from the recording of the pseudophrase and combined with the recordings of each of the pronouns and the indefinite article from the correct utterances by splicing together the respective sound segments. Finally, the correct and incorrect experimental stimuli were created by adding the segments containing the matching or mismatching suffixes or noun endings. The onset of these were marked as the trigger points for the ERP. The signals were cut at zero crossings only. The splicing points were determined by a careful visual inspection of the oscillogramms. An auditory control of all experimental stimuli ensured that the splicing procedure resulted in inconspicuous speech sounds. All signal manipulations were performed using the Cool Edit 2000 software (Syntrillium Software Corp., Phoenix, Az).

The procedure applied for the production of the stimuli resulted in pairs of correct and incorrect two-word utterances that were *physically identical* until the point that determined their grammaticality (see Figure 5.1). This point will be referred to as the divergence point (DP) in the following. All ERP responses were calculated with respect to the DP, regardless of the type of violation investigated, thus ensuring a precise time-locking of the ERPs to the point at which the violation occurs. This is preferable to the commonly applied method of time-locking the ERP responses to the onset of the critical word, because ERP effects can be assessed without artificial delay, and the impact of latency jitter caused by different word lengths is considerably reduced (see Section 4.1). Furthermore, the physical identity of the input prior to the DP guarantee a valid baseline for ERP calculation, a need that is not easily satisfied when naturally produced sentences are used for stimulation.

5.2 ERP data acquisition and analysis

Recording For the duration of the experiments the participants were seated in a comfortable chair that was positioned inside an acoustically and electrically shielded chamber. The auditory stimuli were presented binaurally via headphones (Sennheiser HD 414) at a comfortable

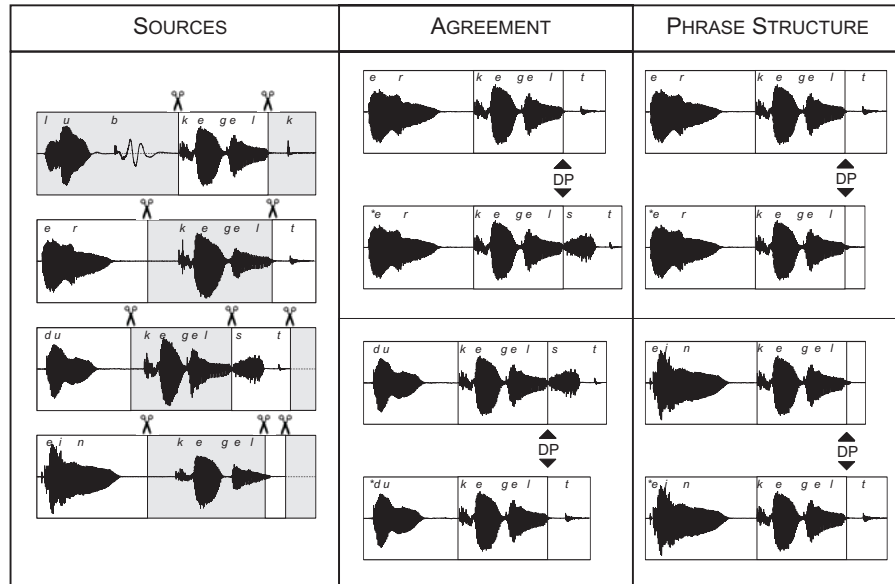


Figure 5.1: Preparation of the stimulus material, exemplified for one item. *Left column:* Normalized recordings of the pseudophrase and the three correct two-word utterances. Sections underlayed with a grey background were removed. *Middle and right columns:* Experimental stimuli of the agreement and phrase structure manipulation, spliced together by combining the respective source segments from the left column (presented in white). The arrows mark the physical divergence point (DP) between pairs of correct and *incorrect two-word utterances.

sound intensity. Visual components of the experimental stimulation were presented on a 17 inch monitor that was positioned at a distance of approximately 150 cm as measured from the participants' eyes. They either comprised colored movies (Experiments 1 - 3) or experimental cues presented in white on black background (Experiment 4). During the experimental stimulation, continuous EEG recordings were obtained from the array of electrodes demonstrated in Figure 5.2. The 50 scalp electrodes (Ag/AgCl) were positioned at scalp sites corresponding to an extended version of the traditional 10-20 system by Jasper (1958) by means of an elastic cap (Electro Cap International). They were labelled according to the nomenclature proposed by the American Electroencephalographic Society (Sharbrough et al., 1991). Additional electrodes were placed at left and right mastoid positions and at the nose, with the latter serving as the online reference. Grounding of the participant was provided by an electrode placed at the sternum. To control for eye-movement artifacts, bipolar horizontal and vertical electrooculograms (EOGs) were calculated from monopolar recordings of electrode pairs positioned lateral

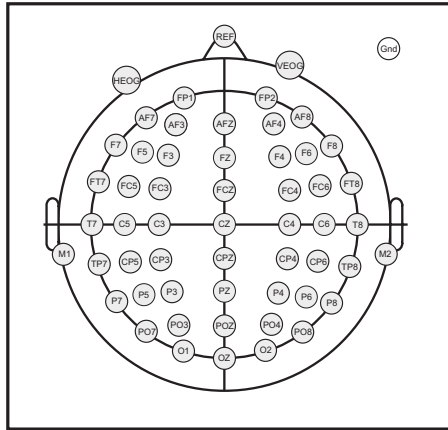


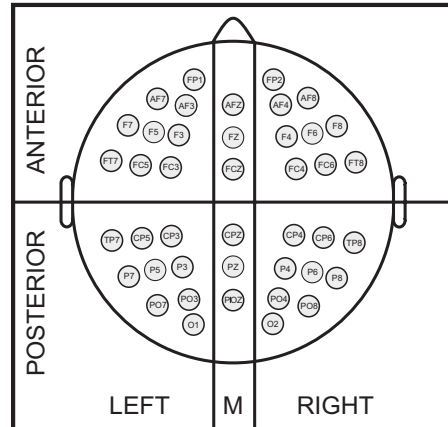
Figure 5.2: Array of electrodes used for the EEG recording. The 50 scalp electrodes are numbered in rows, with odd numbers referring to the left hemisphere and even numbers referring to the right hemisphere. The letters represent cortical regions in the vicinity of the electrodes, e.g. F = frontal, T = temporal, C = central, P = parietal, O = occipital. Additional electrodes are: M1 and M2 = Left and right mastoids, REF = on-line reference, Gnd = ground, V/HEOG = bipolar vertical/horizontal electrooculogram.

to the outer canthus of each eye and above and below the right eye, respectively. Electrode impedances were kept below 10 k Ω throughout the recordings. All electrodes were connected to a Refa amplifier (Twente Medical Systems, The Netherlands). The digital sampling rate was 500 Hz. An anti-aliasing filter of 135 Hz was applied during recording.

Processing After recording, the continuous EEG signals were processed in the following steps. First, the data were treated with an automatic artifact rejection criterion applied to the EOG channels and channel Cz to mark trials contaminated by eye-movement artifacts. If the voltage variation within a 200 ms sliding time window exceeded 40 μ V in one of these channels, this section was marked and excluded from further processing across all channels. In a second step all channels were scanned manually to mark any additional disturbances. Artifact-free trials were then averaged separately for each participant and condition. The length of the averaged epoch depended on the time range of interest in each experiment. All ERPs were time-locked to the divergence point of the stimuli (see Section 5.1) and calculated with respect to a baseline covering the 100 ms prior to this point. The final processing step comprised the re-referencing of the averaged responses to the arithmetic mean of the mastoid recordings.

Statistical analysis The focus on the temporal characteristics of the investigated syntactic subprocesses necessitates a reasonably exact and impartial definition of the onset and the duration of the resulting ERP effects. This was achieved by analyzing the mean amplitude of the ERPs as calculated for nonoverlapping short sections of the entire epoch. The length of the short section was either 30 or 50 ms depending on the temporal extension of the observed

Figure 5.3: Groups of electrodes included in the two-level topographical factors HEM (left vs. right) and REG (anterior vs. posterior) for the analysis of the lateral electrode sites, as well as in the two-level factor REG (anterior vs. posterior) for the midline analysis (M).



components. In a second step, this preliminary analysis was complemented with the more conventional method of analyzing the mean amplitude in larger time windows covering the effects. These time windows were defined on the basis of both the preliminary analysis and a careful visual inspection of the grand average data (for a similar approach, see for example Gunter et al., 1997, 2000; Schirmer & Kotz, 2003).

The mean amplitudes from the short sections and larger time windows were subjected to repeated measure Analysis of Variance (ANOVA). Factors included the respective experimental conditions as well as the topographical factors HEMISPHERE (HEM: left vs. right) and REGION (REG: anterior vs. posterior) corresponding to groups of electrodes over certain regions of the scalp (see Figure 5.3). The grouping of electrodes into topographical factors has two important methodological advantages over an analysis of single electrodes. First, it allows for the statistical assessment of topographical differences between the ERP effects in a concise manner, and second, it dramatically reduces the risk of committing α - errors by decreasing the number of variables to be analyzed (Oken & Chiappa, 1986).

The ANOVAs of the mean amplitudes in the defined time windows were organized in a hierarchical manner. A global ANOVA including all factors was performed and evaluated for significant effects at an α -level of 0.05. If this analysis revealed significant interactions involving at least one of the condition factors, these were resolved with respect to the condition factor(s). Interactions will be reported only if this post hoc analysis revealed significant effects. Main effects or interactions involving only topographical factors will not be reported, as they

do not reveal any information on the targeted processes. Where appropriate, effect sizes (Δ) will indicate the mean amplitude difference in μV in addition to the significant F- and p-values.

Presentation of the results ERPs will be presented in the form of grand average waveforms plotted for 9 selected electrodes as μV over time. All presented waveforms were treated with a 14 Hz lowpass filter that was applied for display purposes only. The topographical distribution of the ERP effects will be illustrated in spherical spline interpolated maps (Perrin, Pernier, Bertrand, & Echallier, 1989) of the mean amplitude in the time windows selected for statistical analysis.

Software All data processing steps were conducted using the software package EEP 3.2.1 that was developed at the Max Planck Institute for Human Cognitive and Brain Sciences. This package was also used to prepare the graphical illustrations of the data. Statistical analyses were performed with the SAS 8.2 software package.

Chapter 6

Experiment 1: Different types of syntactic Mismatch Negativities

As pointed out in Chapter 4, a first step towards an unbiased comparison of the supposedly different brain mechanisms underlying syntactic-relational and phrase structure processing is the strict control of linguistic and acoustic stimulus features. The syntactic MMN paradigm developed by Pulvermüller and colleagues (Pulvermüller & Shtyrov, 2003; Shtyrov et al., 2003; Pulvermüller et al., 2008) is suited best for this purpose. First, it investigates syntactic processing in a well-controlled, minimal context. This procedure minimizes the risk of confounding syntactic effects with acoustic or semantic stimulus features. Second, it relies upon a clearly defined, well established ERP component that can be elicited in the absence of a stimulus-related task and the participants' attention. Third, it allows for conclusions concerning the automaticity of the mechanisms underlying the observed effects.

Experiment 1 makes use of these advantages. It provides a within-subject comparison between syntactic MMN effects in response to subject-verb agreement and word category violations. Experiment 1A contrasts one item from the AGREEMENT stimulus set developed for the present study in a syntactic MMN protocol according to Pulvermüller and colleagues. It thus aims at the first replication of the syntactic MMN effect for subject-verb agreement in German. In Experiment 1B, the correctness of the contrasted two-word utterances is manipulated by a switch in the critical word's category causing a match or a mismatch with respect to the expected phrase structure. As the syntactic MMN effect has so far only been shown for subject-verb agreement, case- or gender agreement, this is the first attempt to extend the paradigm to

the investigation of phrase structure processing. Furthermore, Experiment 1 presents the first instance in which the syntactic subprocesses underlying the establishment of local agreement relations and phrase structure building are compared in the absence of directed attention and within-subject¹.

The following experimental hypotheses were formulated with respect to the previous findings on the syntactic MMN and the general assumptions guiding the current study as set forth in Chapter 4.

1. The acoustic change between standard and deviant two-word utterances is expected to elicit an MMN in the time range between 100 and 200 ms following change onset in all sequences, irrespectively of the linguistic manipulations.
2. The syntactic context should modulate the amplitude of the MMN. Specifically, grammatically incorrect deviants should produce larger MMN amplitudes than correct deviants. Due to the local nature of the syntactic violations and the unbiased time-locking of the ERP responses to the violation point this syntactic MMN effect should occur for both agreement and word category violations.
3. However, if there are functional differences between phrase structure building and syntactic-relational processing, these processes may involve different brain areas. This in turn may be reflected in variations in amplitude, latency, or topography of the syntactic MMN effects as a function of violation type.

6.1 Experiment 1A: The agreement MMN

6.1.1 Methods

Participants 24 healthy native speakers of German (12 male, 12 female) aged 20 - 29 (mean age = 24.71, SD = 2.75) agreed to participate. All of them were right-handed as determined by the Edinburgh Inventory (Oldfield, 1971). The mean Laterality Quotient (LQ) was 91.67 (SD = 11.67). Participants received 7 Euros per hour as compensation for their efforts.

¹The results of Experiment 1 were also published in the *Journal of Cognitive Neuroscience* (Hasting, Kotz, & Friederici, 2007)

Design and procedure As explicated above, the current experiment was designed in close relation to the syntactic MMN paradigm established by Pulvermüller and colleagues (Pulvermüller & Shtyrov, 2003; Shtyrov et al., 2003; Pulvermüller et al., 2008). One item of 50 that formed the two stimulus sets (see Section 5.1) was selected. Since the same item was also used in Experiment 1B to test the effect of word category violations on the MMN, the selection was based on the equal word form frequency between verb and noun as determined by the "Wortschatz Lexikon"² The correct and incorrect two-word utterances containing the selected item "falten" (to fold) were assigned to the syntactic MMN paradigm as depicted in Table 6.1.

Table 6.1: Experimental design for testing the impact of subject-verb agreement on the MMN (GRAM = grammaticality, SUF = suffix, cor = correct, inc = incorrect; factor levels are assigned to the deviant stimulus)

AGREEMENT MMN				
Sequence	Standard (750)	Deviant (150)	Factor Level	
			GRAM	SUF
a	er faltet	*er faltest	inc	-st
b	*du faltet	du faltest	cor	-st
c	du faltest	*du faltet	inc	-t
d	*er faltest	er faltet	cor	-t

The design incorporates two important features that allow to disentangle acoustic and syntactic influences on the MMN response. First, the acoustic change between the standard and deviant stimuli in each of two sequences relevant for the grammaticality effect is identical. In both sequences **a** and **b** the only acoustic difference between standard and deviant stimulus is that the standard suffix *-t* is replaced by the deviant suffix *-st*. Therefore, the acoustic MMNs resulting from these two sequences should be identical. Any differences in the MMNs elicited in these two sequences must therefore be due to the switched grammaticality of the stimuli and should be reflected in effects including the condition factor GRAMMATICALITY (GRAM: correct vs. incorrect). In principle, the same is true for sequences **c** and **d** that test the grammaticality effect

²The "Wortschatz Lexikon" is a corpus that is permanently updated using publicly available texts. It was developed and is maintained by the Department of Computer Science of the University of Leipzig and can be accessed at <http://www.wortschatz.uni-leipzig.de>.

under the opposite direction of change. These sequences are included in the design because it is unclear from the literature whether the parameters of the MMN are fully determined by the *magnitude* of the acoustic change (Näätänen & Alho, 1997), or whether the *direction of the change* exerts an influence as well. The latter is suggested by studies showing different MMN characteristics for inclusions as compared to omissions of the same stimulus feature (Nordby, Hammerborg, Roth, & Hugdahl, 1994; Sabri & Campbell, 2000). Sequences **c** and **d** thus control for the possibility that the inclusion of an [s] in the deviants in sequences **a** and **b** promotes the targeted grammaticality effects. Possible influences of the direction of acoustic change as captured by the independent condition factor SUFFIX (SUF: *-t* vs. *-st*) on the syntactically induced modulations of the MMN should emerge in significant SUF x GRAM interactions.

Sequences were pseudo-randomized with a minimum of two and a maximum of eight standards occurring between any two deviants. After randomization, ten standard stimuli were added to the beginning of each sequence to establish the regularity to which the deviant was to be compared. These trials were not included in the analysis. The stimulus onset asynchrony (SOA) was adjusted to the length of the speech signals. It was 440 ms longer than the longest stimulus in each sequence (i.e. sequences **a** and **d**: 1780 ms, sequences **b** and **c**: 1700 ms). This resulted in a presentation time of approximately 26 minutes per sequence. The order of the four sequences was counterbalanced across participants with an equal number of male and female participants in each group. Participants were instructed to focus their attention on a silent movie and to ignore any auditory input. To reduce artifacts they were further asked to refrain from moving, swallowing or blinking to the greatest possible extent. Every time a sequence was completed participants were allowed to take a break for as long as they needed.

MMN calculation, quantification and analysis The recording of the ERPs abided by the description given in Section 5.2. ERPs were averaged for an epoch of 700 ms (-100 to 600 ms with respect to the DP), separately for each participant, sequence, and stimulus type. Epochs containing artifacts or representing standard stimuli directly following deviant stimuli were discarded. The MMN was calculated in the traditional way by subtracting the ERPs to the standard stimuli from those to the deviant stimuli from the same sequence. All further analysis steps were conducted on the resulting difference waves. To assess whether the acoustic difference between standard and deviant stimulus elicited reliable negativities with temporal

and topographical characteristics that match those of the typical MMN component, a quantification procedure was employed on the 100 ms enclosing the first clear negative peak of the difference waves, as determined by visual inspection of the grand average data. The mean amplitude in this time window was compared to zero by means of paired two-tailed t-tests separately for each sequence and topographical quadrant (see Figure 5.3). Afterwards, the impact of the linguistic manipulations on the mean amplitude of the difference waves was assessed for the entire epoch using repeated measure ANOVAs including the factors HEM x REG x SUF x GRAM. The preliminary timeline analysis was conducted on nonoverlapping sections of 30 ms length. Based on this and the visual inspection of the grand average data, hierarchically organized ANOVAs were then performed on three larger time windows.

6.1.2 Results

MMN quantification The grand average deviant-minus-standard difference waves from all four presented sequences showed a broadly distributed negativity that appears maximal at fronto-central electrodes, and peaks between 100 and 200 ms after the divergence point of the stimuli. Accordingly, the MMN quantification procedure was conducted in this time window. The results of the t-tests are listed for each sequence and topographical quadrant in Table 6.2. With exception of the left posterior quadrant in sequence **d**, all quadrants exhibited highly significant negativities in all sequences. The statistical effect sizes are stronger over the anterior half of the scalp.

Visual inspection for condition effects Figure 6.1 depicts the impact of grammaticality on the MMN responses. Sequences containing grammatically incorrect deviants appear to have elicited larger MMN responses than sequences containing correct deviants. A second grammaticality-related negativity is visible in the time range between 300 and 500 ms. Figure 6.2 suggests an additional impact of the deviating suffix, as the early negativity appears to be larger for sequences in which the deviant ended with *-st* rather than *-t*, an effect that is particularly prominent over the left hemisphere. Furthermore, these sequences seem to produce a stronger decline of the response following the negativity over anterior electrodes.

Timeline analysis The timeline analysis confirmed the observed modulations of the waveforms by the condition factors. It showed significant GRAM effects between 120 and 180 ms

Table 6.2: Experiment 1A, MMN quantification. T-test of the mean amplitude between 100 - 200 ms after DP against zero in the four topographical quadrants (LA = left anterior, RA = right anterior, LP = left posterior, RP = right posterior). Insignificant p-values are in bold.

AGREEMENT MMN QUANTIFICATION					
Sequence	Factor Level	Quadrant	Mean Ampl.	T-value	p-value
a	incorrect / -st	LA	-1.42	-8.03	< 0.0001
		RA	-1.25	-6.45	< 0.0001
		LP	-1.11	-5.74	< 0.0001
		RP	-1.16	-5.85	< 0.0001
b	correct / -st	LA	-0.92	-5.0	< 0.0001
		RA	-1.04	-6.61	< 0.0001
		LP	-0.83	-5.62	< 0.0001
		RP	-0.80	-4.82	< 0.0001
c	incorrect / -t	LA	-1.44	-7.64	< 0.0001
		RA	-1.54	-7.84	< 0.0001
		LP	-0.53	-3.39	< 0.01
		RP	-0.61	-5.04	< 0.0001
d	correct / -t	LA	-1.14	-6.47	< 0.0001
		RA	-1.42	-7.11	< 0.0001
		LP	-0.29	-1.79	0.0859
		RP	-0.55	-3.26	< 0.01

(lateral and midline electrodes) and between 300 and 510 (lateral) or 570 ms (midline). The impact of the factor SUF became manifest in a significant HEM x SUF interaction between 120 and 180 ms at lateral electrodes and a subsequent REG x SUF interaction between 180 and 240 (lateral) or 270 ms (midline). An additional main effect of SUF occurred between 450 and 510 ms at the lateral electrodes. This effect was only marginally significant at the midline electrodes.

Based on the timeline analysis and the visual inspection, the time windows between 120 and 180 ms, 180 and 240 ms, and 300 and 500 ms were selected for detailed statistical analy-

sis, because they provide the best reflection of the modulation of the difference waves by the condition factors.

Time window analysis, 120 - 180 ms (MMN) The ANOVA of the mean amplitude around the MMN peak yielded a main effect of GRAM (lateral: $F_{1,23} = 5.71$, $p < 0.05$, $\Delta = 0.3$; midline: $F_{1,23} = 7.2$, $p < 0.05$, $\Delta = 0.5$) indicating that incorrect deviants produced a larger MMN amplitude than correct deviants. A significant three-way-interaction with both topographical factors in the analysis of the lateral electrodes ($F_{1,23} = 5.82$, $p < 0.05$) revealed a focus of this effect over the left anterior quadrant ($F_{1,23} = 6.97$, $p < 0.05$, $\Delta = 0.5$), while the other three quadrants merely showed marginally significant effects ($F_{1,23} \approx 3.5$, $p < 0.1$). In addition, the resolution of a significant HEM x SUF interaction ($F_{1,23} = 5.63$, $p < 0.05$) reflected the fact that the MMN was larger for sequences in which the deviant ended with *-st* rather than *-t* over the left hemisphere only ($F_{1,23} = 4.71$, $p < 0.05$, $\Delta = 0.4$).

Time window analysis, 180 - 240 ms A highly significant interaction of REG and SUF (lateral: $F_{1,23} = 38.72$, $p < 0.0001$; midline: $F_{1,23} = 35.49$, $p < 0.0001$) confirmed the observed stronger decline following the MMN for *-st* sequences that was restricted to anterior electrode sites (lateral: $F_{1,23} = 16.78$, $p < 0.001$, $\Delta = 0.8$; midline: $F_{1,23} = 6.45$, $p < 0.05$, $\Delta = 0.7$).

Time window analysis, 300 - 500 ms The second negativity in response to sequences with incorrect deviants was reflected in a main effect of GRAM (lateral: $F_{1,23} = 11.41$, $p < 0.01$, $\Delta = 0.5$; midline: $F_{1,23} = 10.83$, $p < 0.01$, $\Delta = 0.7$). The late suffix effect revealed by the timeline analysis did not persist in this larger window.

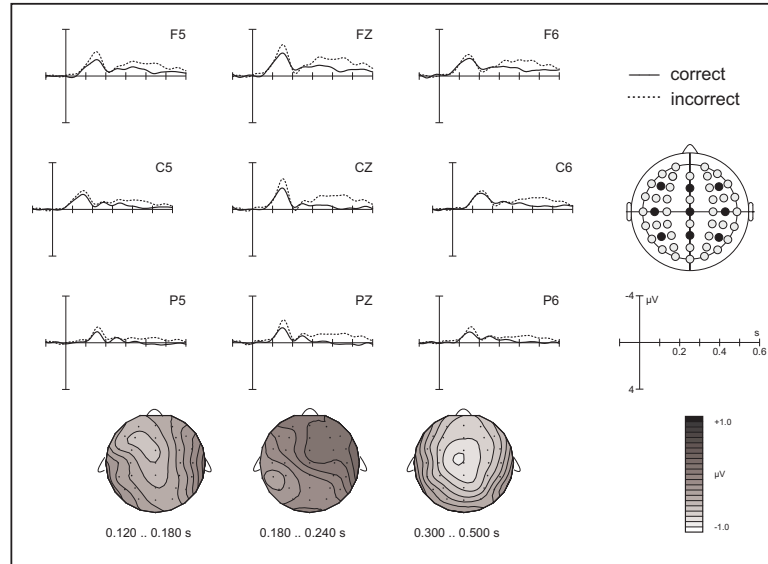


Figure 6.1: Experiment 1A: MMN modulation by GRAM collapsed over SUF. MMN waves and topographical difference maps (incorrect - correct) of the mean amplitude in the time windows selected for statistical analysis.

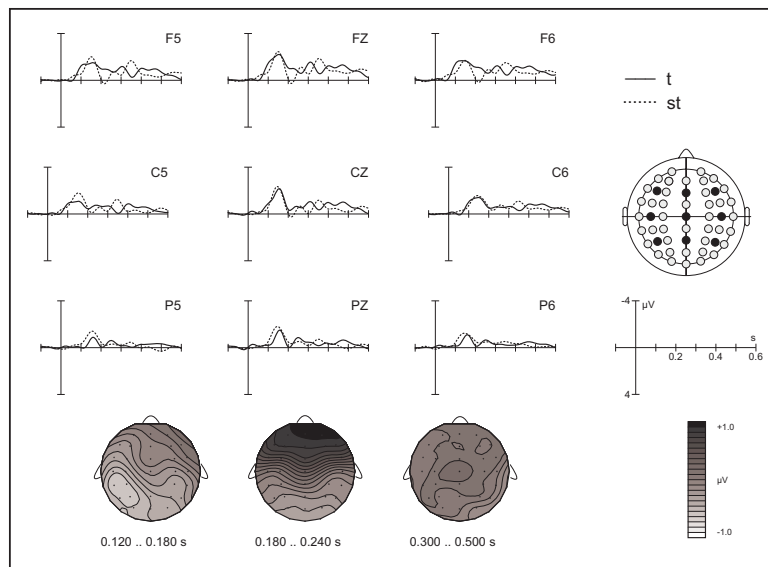


Figure 6.2: Experiment 1A: MMN modulation by SUF collapsed over GRAM. MMN waves and topographical difference maps (st - t) of the mean amplitude in the time windows selected for statistical analysis

6.1.3 Discussion

Elicitation of the MMN The polarity, latency as well as the topographical distribution of the first clear component observed in the deviant-minus-standard difference waves are in concordance with the common characteristics of the MMN (see Section 2.1.1), as determined by visual inspection and the MMN quantification procedure. Hypothesis 1 is unequivocally confirmed by this finding: An MMN was elicited by the acoustic change between standard and deviant stimulus in each of the sequences. An analysis of the MMN components for linguistically induced modulations is therefore licensed.

Grammaticality effects In concordance with Hypothesis 2, sequences in which the deviants contained subject-verb agreement violations produced enhanced MMN amplitudes as compared to sequences containing the identical acoustic change but grammatically correct deviant stimuli. The effect was focused over left anterior scalp sites. This finding constitutes a German replication of the syntactic MMN effect reported by Pulvermüller and colleagues for subject-verb agreement in English (Pulvermüller & Shtyrov, 2003; Pulvermüller et al., 2008) and Finnish (Shtyrov et al., 2003). Based on these previous and the present findings it can now be safely concluded that subject-verb agreement violations are detected automatically and within less than 200 ms after the violation point, at least when tested with the syntactic MMN paradigm. The latency of this effect is exceptionally early compared to numerous observations of agreement effects in the time range between 300 and 500 ms (see Section 3.1). Possible explanations for this divergency comprise the time-locking of the syntactic MMN responses to the violation point, the locality of the violation, as well as the repetitiveness of the stimulus material (see Section 4.1).

With respect to the time-locking, the observed syntactic MMN effect could be interpreted as a temporal concurrence of an MMN elicited by the acoustic change and a "real-time" LAN speeded up by the unbiased time-locking of the ERP. Evidence in support of this notion is provided by Hahne, Schröger, and Friederici (2002) who combined phrase structure violations with simultaneous location switches in the auditory presentation. The observed nearly additive effect on the MMN was interpreted as an indicator of the autonomy of early physical and syntactic feature processing. Alternatively, it could be assumed that both the acoustic and the syntactic deviation were captured by an MMN-intrinsic mechanism, as the present design

combined the two simultaneous deviations within the language domain. It is a well known fact that the MMN amplitude is additive for deviations in more than one stimulus dimension even within one processing domain (Schröger, 1995; Paavilainen, Valppu, & Näätänen, 2001; Wolff & Schröger, 2001).

The local nature of the employed violation offers an alternative explanation of the early agreement MMN. The short distance between the personal pronoun and the matching or mismatching suffix suggests that the processing of the syntactic relation may be accomplished by means of priming. The phenomenon of syntactic priming was first reported in the behavioral literature, where it refers to accelerated lexical decision times in the presence of a syntactically appropriate context (see for example Goodman, McClelland, & Gibbs, 1981; Wright & Garrett, 1984; Blumstein, Milberg, Dworetzky, Rosen, & Gershberg, 1991; Deutsch & Bentin, 1994; Schriefers et al., 1998). In fact, Pulvermüller and Shtyrov (2006) point out that the syntactic MMN effect is most likely produced by a lack of experience-dependent syntactic priming rather than by the detection of a violation, because they could show that the MMN amplitude is actually *reduced* in correct syntactic context as compared to the same acoustic change presented out of syntactic context (Pulvermüller & Shtyrov, 2003). With respect to the neuronal mechanism underlying syntactic priming as reflected in the syntactic MMN effect, Pulvermüller (2002) suggests so-called "sequence detectors" linking the lexical representations of morphemes that are likely to occur in succession. According to this theory, a sequence detector automatically pre-activates or *primes* morphemes that are licensed by the syntactic context and thereby facilitates their processing. With regard to the present material, the occurrence of the personal pronoun would prime the matching inflectional suffix. This in turn would lead to a reduced MMN amplitude as compared to when the deviant contains the unprimed, mismatching suffix.

The current data do not allow for a distinction between these alternative interpretations of the early syntactic MMN effect. The left anterior focus of the effect is consistent with both alternatives, as agreement violations are associated with activation changes in left superior temporal and inferior frontal cortex across paradigms and methods (Ni et al., 2000; Moro et al., 2001; Newman, Just, Keller, Roth, & Carpenter, 2003; Pulvermüller & Shtyrov, 2003). Nevertheless, Hypothesis 2 is clearly supported by the enhanced amplitude of the automatic MMN component in response to agreement violations.

Following the MMN, a second grammaticality-related negativity occurred between 300 and 500 ms. Although a similarly biphasic pattern of the agreement MMN effect was reported before (Pulvermüller & Shtyrov, 2003) the function underlying this second negativity is still unclear. Sustained negativities following initial syntactic ERP responses have also been observed in response to other types of syntactic violations in other paradigms (Neville et al., 1991; Friederici et al., 1996). Friederici et al. (1996) interpret their sustained negativity as a reflection of elevated verbal working memory processes triggered by the beginning of a new phrase under the aggravated closing of a violated preceding phrase. However, this interpretation appears implausible for the current case in which the violation occurred at the end of each utterance and working memory demands were generally low. Another perhaps more suitable interpretation of the observed late grammaticality effect is that it reflects additional resource allocation perhaps in order to evaluate the syntactic violation at a more conscious level, as opposed to the automatic violation detection presumably involved in the early syntactic ERP modulation.

Suffix effects Independently of the grammaticality of the stimuli, sequences in which the deviant ended with the suffix *-st* produced larger MMN amplitudes than sequences in which the deviants ended with *-t*. This effect was lateralized to the left hemisphere and followed by a stronger decline of the MMN for *-st* deviants over anterior sites. Since the focus of the current experiment was on syntactic modulations of the MMN, there was no a priori prediction concerning the impact of the respective suffix. Furthermore, the applied experimental design does not allow for a separation of inflectional and acoustic features of the stimuli. Post hoc interpretations of the observed effects can therefore follow two fundamentally different lines of argument.

First, the effects could be attributed to differences in the mere acoustic features of the respective suffixes (i.e. differences in pitch, duration, and / or intensity). As pointed out above, it cannot be excluded that the direction of acoustic change affects the MMN amplitude even if the magnitude of acoustic change is identical. Along these lines, it is conceivable that a deviant utterance ending with the suffix *-st* presented among standard utterances ending with *-t* is more salient than a deviant utterance ending with *-t* in the reverse scenario because the acoustic features included in the phoneme *s* are added in the former case and omitted in the latter (Nordby et al., 1994; Sabri & Campbell, 2000). Such a difference in the saliency of the

deviant stimuli may account for the observed effects, since it is well known that the amplitude of the MMN increases as a function of the amount of deviation (e.g. Tiitinen et al., 1994; Näätänen, 1995; Jaramillo, Paavilainen, & Näätänen, 2000). Furthermore, the stronger decline of the MMN to *-st* may reflect a beginning P300 component as a sign of an attention switch towards the more salient deviant.

The second possible interpretation of the suffix effect considers the linguistic features of the divergent suffix to play a role in the observed modulation of the MMN response. According to this view, the amplitude modulation of the MMN is caused by differences in the automatic processing of the verb inflections that is mediated by long term memory traces for inflectional suffixes. This interpretation has the advantage that it can better account for the left-hemispheric focus of the effect suggesting an involvement of language-related areas rather than the exclusive activity of acoustic MMN generators. Especially against the background of an earlier study that investigated the processing of inflectional affixes by means of the MMN and reported a similarly left-lateralized effect (Shtyrov & Pulvermüller, 2002), this possibility does not seem too unlikely. In this respect, the present finding extends the existing evidence by showing that the MMN is reflecting the automatic processing of inflectional morphology even in addition to and independently of syntactic context effects. The effect should however be re-investigated with adequate acoustic control conditions before firm conclusions about underlying mechanisms can be drawn.

6.2 Experiment 1B: The phrase structure MMN

6.2.1 Methods

Participants To make sure that the data sets from the two parts of Experiment 1 are maximally comparable, they were conducted within subject. The participants in Experiment 1B are therefore identical to those in Experiment 1A (see Section 6.1.1). The two parts were completed in separate sessions held at intervals of at least one week. Their order was counterbalanced across participants, with an equal number of male and female participants in each group.

Design and procedure Experiment 1B was designed and evaluated according to Experiment 1A, the only difference being the replacement of the stimuli from the AGREEMENT set by the

corresponding stimuli from the PHRASE STRUCTURE set. In the resulting experimental design, which is depicted in Table 6.3, the occurrence of an acoustic deviance coincides with a switch in the word category and hence the grammaticality of the deviant stimulus. Like in Experiment

Table 6.3: Experimental design for testing the impact of phrase structure on the MMN (GRAM = grammaticality, CAT = word category, cor = correct, inc = incorrect; factor levels are assigned to the deviant stimulus)

PHRASE STRUCTURE MMN				
Sequence	Standard (750)	Deviant (150)	Factor Level	
			GRAM	CAT
a	ein falter	*ein faltet	inc	verb
b	*er falter	er faltet	cor	verb
c	er faltet	*er falter	inc	noun
d	*ein faltet	ein falter	cor	noun

1A, the impact of the syntactic manipulation is tested independently of acoustic change detection, as the acoustic contrast in each of two sequences relevant for the grammaticality effect (i.e. **a** vs. **b** and **c** vs. **d**) is identical. Likewise, the syntax effect is validated independently of the direction of acoustic change due to the complete balancing of the sequences (i.e. **a** and **b** vs. **c** and **d**). During the preparation of the speech stimuli used in this experiment, it was necessary to exchange the entire final syllable of the critical word because its vowel differs phonetically between the inflected verb form and the noun ([ˈfaltət] vs. [ˈfaltɐ]), and coarticulation did not permit inconspicuous splicing after the preceding consonant [t]. The SOA was again approximately 440 ms longer than the longest stimulus in each sequence (i.e., sequences **a** and **d**: 1740 ms, sequences **b** and **c**: 1660 ms) resulting in an approximate sequence duration of 26 minutes. Randomization constraints, instruction of the participants, as well as ERP calculation and statistical analysis were identical to Experiment 1A. The factor SUF was replaced by the factor CATEGORY (CAT: verb vs. noun) to account for possible influences of the direction of acoustic change.

6.2.2 Results

MMN quantification The visual inspection of the grand average deviant-minus-standard difference waveforms revealed a negativity with an onset shortly after 100 ms and a latency of about 100 ms in all four conditions. The MMN quantification procedure was applied to the time range between 120 and 220 ms (for results see Table 6.4). Comparable to Experiment 1A, the sequences in which the deviant contained the inflected verb form (i.e., sequences **a** and **b**) resulted in a significant negativity in all topographical quadrants that was stronger over the anterior half of the scalp. In contrast, the negativity from those sequences in which the deviant contained the noun (i.e., sequences **c** and **d**) produced a conspicuously smaller negativity that differed significantly from zero over the posterior half of the scalp only.

Visual inspection for condition effects Figure 6.3 shows the effect of grammaticality on the MMN. The MMN amplitude appears to be enhanced in response to sequences in which the deviant contained a word category violation. Furthermore, there seems to be a second negativity in response to incorrect deviants at around 300 ms. Figure 6.4 visualizes the result of the quantification procedure, as it shows the dramatic modulation of both MMN amplitude and topography by the critical word's category. Additionally, it reveals a strong negative deflection between 350 and 550 ms for sequences in which the critical word was a noun.

Timeline analysis The timeline analysis confirmed the above observations but also revealed some additional effects. It showed strong main effects for CAT between 120 and 270 ms as well as between 360 and 540 ms at both lateral and midline electrodes. These were specified by significant REG x CAT interactions. The factor GRAM showed a significant impact between 150 and 210 ms and between 270 and 360 ms (lateral and midline analysis). No interactions of GRAM with any other factor were observed.

To capture the observed effects most effectively, the time windows between 150 and 210 ms, 210 and 270 ms, 270 and 360 ms and 360 and 540 ms were selected for the detailed ANOVA.

Time window analysis, 150 - 210 ms This earliest time window covered the modulating influence of the factors GRAM and CAT on the amplitude of the MMN. It confirmed significant main effects of GRAM (lateral: $F_{1,23} = 9.46$, $p < 0.01$, $\Delta = 0.3$; midline: $F_{1,23} = 10.04$, $p <$

Table 6.4: Experiment 1B, MMN quantification. T-test of the mean amplitude between 120 - 220 ms after DP against zero in the four topographical quadrants (LA = left anterior, RA = right anterior, LP = left posterior, RP = right posterior). Insignificant p-values are in bold.

PHRASE STRUCTURE MMN QUANTIFICATION					
Sequence	Factor Level	Quadrant	Mean Ampl.	T-value	p-value
a	incorrect / verb	LA	-2.29	-12.17	< 0.0001
		RA	-2.52	-12.06	< 0.0001
		LP	-1.18	-7.46	< 0.0001
		RP	-1.28	-7.95	< 0.0001
b	correct / verb	LA	-2.04	-9.37	< 0.0001
		RA	-2.07	-9.15	< 0.0001
		LP	-0.89	-5.98	< 0.0001
		RP	-0.82	-4.48	< 0.001
c	incorrect / noun	LA	-0.35	-1.84	0.0789
		RA	-0.36	-1.60	0.1238
		LP	-0.54	-3.54	< 0.01
		RP	-0.60	-4.01	< 0.001
d	correct / noun	LA	-0.43	-2.04	0.0534
		RA	-0.29	-1.24	0.2288
		LP	-0.51	-3.25	< 0.01
		RP	-0.42	-3.79	< 0.001

0.01, $\Delta = 0.5$) and CAT (lateral: $F_{1,23} = 36.99$, $p < 0.0001$, $\Delta = 1.3$; midline: $F_{1,23} = 26.01$, $p < 0.0001$, $\Delta = 1.5$) that indicated larger MMN amplitudes in response to incorrect as opposed to correct deviants and in response to deviants containing the inflected verb form as opposed to those containing the noun. While the GRAM effect did not receive any topographical specification, the CAT effect was further characterized by a significant REG x CAT interaction (lateral: $F_{1,23} = 44.35$, $p < 0.0001$; midline: $F_{1,23} = 39.6$, $p < 0.0001$), which showed that the amplitude difference between verb and noun deviants was much more pronounced over the anterior (lateral: $F_{1,23} = 47.87$, $p < 0.0001$, $\Delta = 2.1$; midline: $F_{1,23} = 36.82$, $p < 0.0001$, $\Delta = 2.3$) than over

the posterior half of the scalp (lateral: $F_{1,23} = 10.30$, $p < 0.01$, $\Delta = 0.6$; midline: $F_{1,23} = 8.86$, $p < 0.01$, $\Delta = 0.8$). Additionally, a HEM x CAT interaction reached significance in the analysis of the lateral electrodes in this time window ($F_{1,23} = 4.84$, $p < 0.05$) indicating that the CAT effect was shifted slightly towards the right hemisphere (left: $F_{1,23} = 37.11$, $p < 0.0001$, $\Delta = 1.2$; right: $F_{1,23} = 34.96$, $p < 0.0001$, $\Delta = 1.4$).

Time window analysis, 210 - 270 ms This second time window captured the second half of the early CAT effect. The ANOVA revealed a further main effect of CAT (lateral: $F_{1,23} = 30.68$, $p < 0.0001$, $\Delta = 1.4$; midline: $F_{1,23} = 22.79$, $p < 0.0001$, $\Delta = 1.6$) along with a REG x CAT interaction (lateral: $F_{1,23} = 44.79$, $p < 0.0001$; midline: $F_{1,23} = 33.3$, $p < 0.0001$). These findings showed that the responses to deviants containing inflected verb forms were still significantly more negative than those to deviants containing nouns during the decline of the MMN component and that this effect was still stronger over anterior (lateral: $F_{1,23} = 43.01$, $p < 0.0001$, $\Delta = 2.3$; midline: $F_{1,23} = 34.44$, $p < 0.0001$, $\Delta = 2.5$) than over posterior electrodes (lateral: $F_{1,23} = 5.98$, $p < 0.05$, $\Delta = 0.5$; midline: $F_{1,23} = 5.02$, $p < 0.05$, $\Delta = 0.7$).

Time window analysis, 270 - 360 ms Between 270 and 360 ms, the mean amplitude in response to incorrect deviants was again more negative than the mean amplitude following correct deviants. This was reflected in a significant main effect of GRAM in this time window (lateral: $F_{1,23} = 7.39$, $p < 0.05$, $\Delta = 0.3$; midline: $F_{1,23} = 8.09$, $p < 0.01$, $\Delta = 0.5$). Again, no interaction with topographical factors reached significance.

Time window analysis, 360 - 540 ms This late time window covered the second prominent word category effect observable in the waveforms. The ANOVA confirmed a strong CAT effect reflecting stronger negative responses for noun deviants than for verb deviants irrespectively of the stimuli's grammaticality (lateral: $F_{1,23} = 21.85$, $p < 0.001$, $\Delta = 1.0$; midline: $F_{1,23} = 36.21$, $p < 0.0001$, $\Delta = 1.8$). The larger statistical impact in the midline analysis confirms the central focus of this effect that is also observable in Figure 6.4.

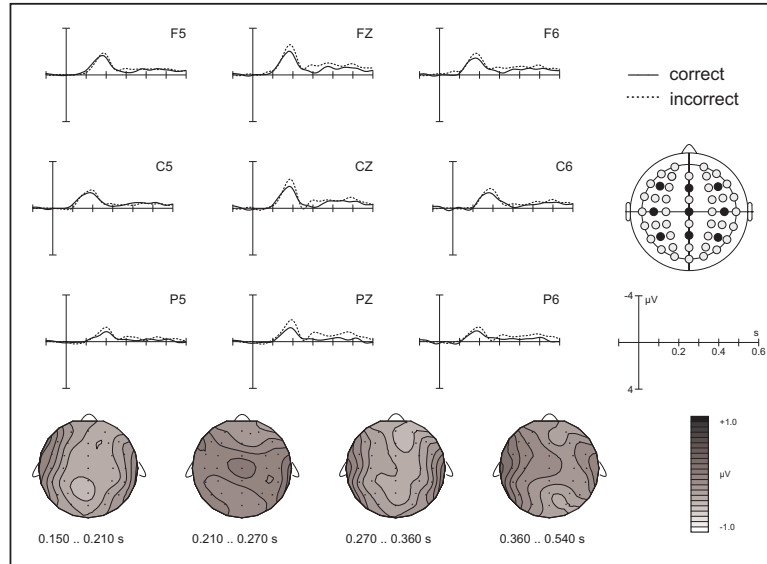


Figure 6.3: Experiment 1B: MMN modulation by GRAM collapsed over CAT. MMN waves and topographical difference maps (incorrect - correct) of the mean amplitude in the time windows selected for statistical analysis.

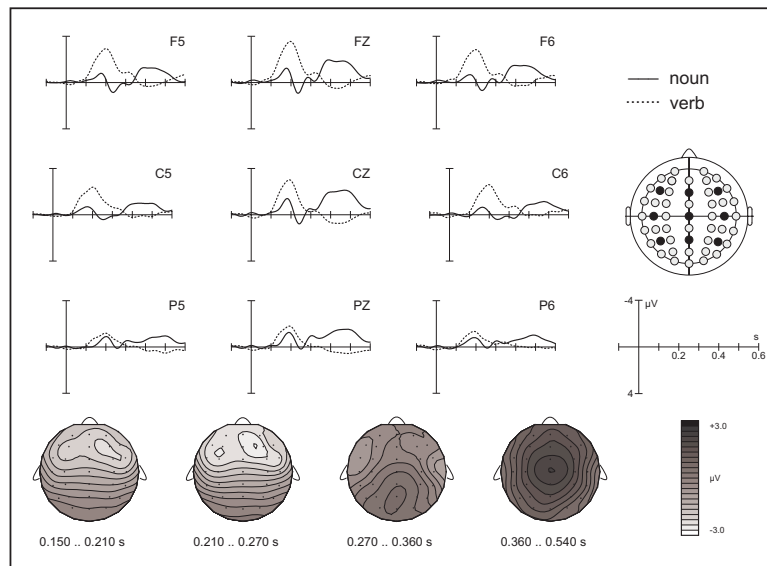


Figure 6.4: Experiment 1B: MMN modulation by CAT collapsed over GRAM. MMN waves and topographical difference maps (verb - noun) of the mean amplitude in the time windows selected for statistical analysis

6.2.3 Discussion

Elicitation of the MMN The deviant-minus-standard difference waves from the four sequences presented in this second part of Experiment 1 showed a more varied pattern than those in the first part. Sequences **a** and **b**, containing the inflected verb form as the deviant stimulus, elicited typical MMN components with the same fronto-central focus but an enhanced amplitude and a slightly delayed latency as compared to the agreement part. In contrast, the negativity obtained from the noun-deviant sequences **c** and **d** was greatly reduced in amplitude and differed significantly from zero over the posterior half of the scalp only. While it is well known that the amplitude of the MMN can vary extensively depending on the salience of the deviation (e.g. Tiitinen et al., 1994; Näätänen, 1995; Jaramillo et al., 2000), and generators of the MMN have been reported to differ slightly depending on the nature of acoustic change (Alho, 1995; Molholm, Martinez, Ritter, Javitt, & Foxe, 2005) a posterior scalp distribution of the MMN is very uncommon. The atypical characteristics of the MMN responses in sequences **c** and **d** will be discussed carefully below and re-investigated in an additional control experiment presented in Chapter 7.

Grammaticality effects The MMN amplitude was significantly larger in response to sequences in which the deviant stimulus contained a word category violation than following grammatically correct deviants. Even though one of the incorrect deviants in the present experiment (i.e. **er Falter*) constituted a highly unexpected formation rather than an outright word category violation (see also page 42), the statistical analysis confirmed in a main effect of grammaticality only. Thus, both parts of Experiment 1 resulted in enhanced MMN amplitudes in response to incorrect deviants. This result extends previous findings on the syntactic MMN effect by showing that it is not only elicited in response to agreement violations, but also in response to phrase structure violations. Furthermore, it clearly confirms the current Hypothesis 2 that predicted higher MMN amplitudes for incorrect deviants regardless of the syntactic violation type. However, the comparison between the two syntactic MMN effects also reveal some differences that deserve to be discussed. First, the onset of the present grammaticality effect was delayed by approximately 30 ms as compared to the effect in Experiment 1A. This is most probably due to the properties of the stimulus material and does not represent a genuine temporal difference between the two violation types. As explicated on page 61, it was neces-

sary to exchange the final syllable of the experimental item in order to produce the noun and the verb form. Therefore, the first phoneme following the DP in the phrase structure condition is the same for standard and deviant (i.e. [t]) and the violation does not become apparent before the discriminating vowel (i.e. [ə] vs. [e]). In contrast, the acoustic change is apparent immediately after the DP in the agreement condition. This explains the slight temporal difference of syntactic MMN effects in the two experimental parts. A second, more meaningful difference between the syntactic MMN effects in response to the two violation types can be observed in their scalp distribution. While the effect in the agreement condition (Experiment 1 A) had displayed a left anterior focus, the presently observed effect did not receive any statistically significant topographical specification. This may suggest the involvement of different cortical generators in the processing of agreement and phrase structure violations. The implications are discussed in the following.

In principle, the mechanisms underlying the phrase structure MMN in the present experiment could be the same as for the agreement MMN observed in Experiment 1A. That is, the enhanced MMN amplitude in response to incorrect deviants could either reflect an additive effect of the MMN triggered by the acoustic change between standard and deviant stimulus and an independent syntactic error detection response, or a lack of syntactic priming registered within the MMN system. However, in contrast to the left-anterior focus in Experiment 1A, the rather whole-headed distribution of the effect following the word category violations in Experiment 1B appears to be inconsistent with the additive effect supposition. The latter would predict a similar left anterior focus based on the typical scalp distribution of the ELAN observed in response to word category violations in standard violation paradigms (e.g. Neville et al., 1991; Friederici et al., 1993, 1996), as well as evidence from the neuroimaging literature linking phrase structure processing to activations in left inferior frontal and anterior temporal cortices (Gross et al., 1998; Meyer et al., 2000; Friederici et al., 2000, 2003). On the other hand, the syntactic priming supposition would allow for the assumption that the priming of an entire word category involves more widespread and potentially bilateral neuronal networks than the priming of a specific inflectional suffix, thus leading to the observed whole-headed scalp distribution of the syntactic MMN effect in the phrase structure condition. This theoretical distinction motivates a re-investigation of the cortical generators underlying the syntactic MMN effects in response to the two violation types that will be provided by means of an MEG-based

source localization in Experiment 2 (Chapter 8). Meanwhile, the fact that the scalp distributions clearly differ in the two parts of Experiment 1 strongly suggests a functional separation of syntactic-relational processes and phrase structure building despite their temporal concurrence at this earliest automatic stage of processing. The present data thus lend preliminary support to Hypothesis 3 that predicted such a functional separation based on the assumptions of Friederici's *Neurocognitive Model of Auditory Sentence Comprehension* (Friederici, 2002, see Section 3.1).

As in Experiment 1A, analyses of the time range following the MMN revealed a second grammaticality-related negativity. Again, this effect was not anticipated and can therefore only be interpreted post hoc. As pointed out in the discussion of Experiment 1A (see Section 6.1.3), an involvement of verbal working memory, as suggested by Friederici et al. (1996), is unlikely in the present case. The speculation given above that the effect reflects the allocation of additional processing resources after a violation has been detected is equally applicable in the current case, should however be substantiated by further research.

Word category effects The most striking result of the present experiment was the large impact of the diverging syllable encoding the word category of the critical word. It affected both the amplitude and the topography of the MMN. Sequences in which the deviant contained the syllable *-ter*, and therefore a noun, elicited a much reduced and unusually posteriorly distributed MMN as compared to sequences in which the deviant contained the verb-ending syllable *-tet*. In parallel to the suffix effect in Experiment 1A, this finding could in principle be interpreted as an effect of the different acoustic saliency of the respective deviant stimulus. However, such a pure acoustic interpretation cannot account for the specific topography of the effect. On the other hand, an interpretation in terms of a genuine word category effect appears plausible for several reasons. First, it is a common assumption in theories of syntax processing that word category information is accessed very early and automatically as a primary step in syntactic analysis (Frazier, 1987; Friederici, 2002; Friederici & Kotz, 2003; Friederici & Weisenborn, 2007). In this light, an impact of word category information on the early automatic MMN response is not unlikely. Furthermore, there is pervasive evidence from neuropsychological, psychophysiological and neuroimaging studies suggesting that verbs and nouns differ in their neuronal representations (e.g. Damasio & Tranel, 1993; Perani et al., 1999; Federmeier, Segal, Lombrozo, & Kutas, 2000), although it is still a matter of debate what the basis

of these differences might be as the two word categories differ with respect to a variety of factors including syntactic role and semantic content (for a review, see Shapiro & Caramazza, 2003). In any case, the posterior distribution of the MMN in response to the noun deviant is consistent with a wide range of studies linking the processing of verbs to prefrontal and the processing of nouns to temporo-occipital regions (Damasio & Tranel, 1993; Daniele, Giustolisi, Silveri, Colosimo, & Gainotti, 1994; Pulvermüller, Mohr, & Schleicher, 1999; Shapiro, Pascual-Leone, Mottaghy, Gangitano, & Caramazza, 2001). Thus, although it should be kept in mind that contributions of the mere acoustic stimulus features cannot be excluded, the present data suggest that the MMN paradigm might be useful for the study of representational differences between verbs and nouns. This aspect is investigated and discussed in greater detail in Chapter 7.

The prominent negativity observed between 360 and 540 ms after the DP in response to noun deviants occurs in a time window that is often associated with semantic processing (Friederici, 2002). Its latency and topography strongly resemble a well-studied centroparietal ERP component termed "N400" (Kutas & Hillyard, 1980, 1983). This component is modified by several factors like word frequency, word repetition and semantic congruity and is most commonly interpreted as reflecting enhanced lexical-semantic processing (for reviews, see Kutas & Federmeier, 2000; Friederici & Kotz, 2003). In the current case, word frequency and repetition were held constant across conditions and can therefore not be consulted for explanation. It could rather be speculated that the observed N400 effect reflects a difference in the amount of resources allocated to the processing of the noun as opposed to the verb deviant. This could be explained by the different roles the two word categories fulfill within sentence context: verbs usually carry more syntactic information than nouns, that in turn convey more of the utterances semantic content. Thus, while the inflected verb forms appear to have been analyzed primarily for their syntactic markers during the early automatic processing phase, the noun, once detected as such, seems to have triggered further processing according to its semantic properties.

6.3 Summary and conclusions

The syntactic MMN experiment presented in the current chapter provided evidence that the occurrence of local syntactic violations is reflected in ERP responses at about 150 ms after

the violation point. By using acoustically well controlled stimulus material in a within-subject setting it was shown that this early syntactic brain response occurs independently of whether the deviant violates subject-verb agreement or phrase structure. The observed effects are interpreted in terms of an automatic syntactic error detection response based on syntactic priming. This interpretation comprised the assumption that the local nature of the investigated syntactic dependencies allowed the syntactic processing system to compare the incoming morphemes against specific predictions, resulting in the comparable temporal dynamics of the brain responses to the two violation types. The diverging topographies of the resulting syntactic MMN effects suggested that the specific content of the respective prediction (i.e. suffix vs. word category) activated at least partially different neuronal networks. This speaks in favour of a functional separation of the neuronal mechanisms underlying syntactic-relational and phrase structure processing. However, it is impossible to make reliable inferences about the cortical generators involved in an ERP effect on the basis of its scalp distribution alone (see Section 2.1.1). Therefore, the issue is going to be re-investigated by means of a distributed source analysis based on spatially more revealing MEG data in Experiment 2 (Chapter 8).

The relevance of the current findings for natural language comprehension is certainly limited by the restricted and highly repetitive nature of the syntactic MMN paradigm. In particular, it cannot be excluded that the frequent repetition of the utterances in the oddball setting accelerated syntactic analysis, which would render the lack of a temporal difference between the agreement and phrase structure MMN effects an experimentally induced ceiling effect. This objection will be tackled in Experiment 3 and 4 (Chapters 9 and 10).

In addition to the syntax-related findings, Experiment 1 revealed some interesting side effects that, although unexpected and not directly relevant to the question of the current thesis, might be insightful and stimulating for further research. First, the MMN in Experiment 1A was shown to be modulated by the inflectional suffix. This finding confirms the existence of long term memory traces for inflectional morphology and provides renewed evidence for the automatic activation of these during auditory language comprehension (see also Shtyrov & Pulvermüller, 2002). Second, Experiment 1B revealed a strong modulation of the MMN response by the word category of the deviant stimulus. This observation was taken as further evidence that word category information is accessed early and automatically as a primary step in syntactic analysis (Frazier, 1987; Friederici, 2002). Furthermore, it was related to the assumption

that verbs and nouns are represented differentially in the human brain (Shapiro & Caramazza, 2003). However, as the effect cannot be separated from a possible influence of the direction of acoustic change in the absence of acoustic control conditions, the interpretation in terms of a genuine word category effect is rather speculative. The following Chapter presents a brief excursus experiment that provides such a control and sheds light on this issue.

Chapter 7

Excursus: Is there a word category MMN?

Experiment 1B revealed an interesting side effect that is not immediately related to the research questions addressed in the current dissertation. Namely, both the amplitude and the topography of the MMN response were tremendously modulated depending on whether the syllable determining the change between standard and deviant stimulus completed an inflected verb form or a noun. This finding represents the first indication that the MMN might reflect differences in the processing of the two word categories. This is theoretically interesting for two reasons: First, it is compatible with the notion of an early and automatic access to word category information during syntactic parsing (Frazier, 1987; Friederici, 2002). Second, it provides corroborating evidence for results suggesting differences in the neuronal representations of verbs and nouns (Shapiro & Caramazza, 2003). However, the interpretation of the effect in terms of word category differences is problematic, because it was deduced from a comparison of MMNs obtained in sequences in which the role of deviant and standard stimulus was reversed. This comparison does not provide adequate acoustic control for evaluating non-acoustic MMN effects, because some studies have shown that the direction of acoustic change can affect the MMN amplitude, e.g., depending on whether the deviance comprises the inclusion or the omission of a given stimulus feature (Nordby et al., 1994; Sabri & Campbell, 2000). Particular caution is required when standard and deviant are complex sounds that differ from each other in several acoustic features (i.e. frequency, duration, and intensity). This is clearly the case for the speech stimuli used in the present study. Thus, the MMN modulation interpreted as a word category effect

could also have reflected differential processing of the same acoustic contrast depending on which speech sound was the standard and which was the deviant.

The aim of the present excursus was therefore to compare the striking MMN amplitude and topography modulation that may be caused by the word category switch in Experiment 1B with the effect that would have been elicited by the direction of acoustic change alone. To this end, an additional experiment was conducted in which the deviant syllables that determined the words' category in Experiment 1B were presented in isolation, that is, outside the syntactic and lexical context, in two control sequences as standard and deviant stimuli. Three possible outcomes of this experimental setup allow differentiated conclusions about the nature of the previously observed MMN modulation.

1. If the MMN responses from the two control sequences are indistinguishable, the MMN modulation observed in Experiment 1B reflects a genuine word category effect.
2. If the MMN responses from the two control sequences show the same modulations as the MMN responses to verb vs. noun deviants in Experiment 1B, the ostensible word category effect in Experiment 1B is in fact caused by the direction of acoustic change.
3. If the MMN responses from the two control sequences are distinguishable but show different characteristics than the MMN responses to verb vs. noun deviants in Experiment 1B, the MMN modulation in Experiment 1B reflects a combination of the direction of acoustic change and genuine processing and / or representational differences between verbs and nouns.

The present approach will thus clarify whether MMN can serve as a reliable index of processing differences between verbs and nouns in the human brain¹.

7.1 Methods

Participants The participants of the isolated syllable experiment were 18 healthy native speakers of German (9 male, 9 female) aged 19 - 31 (mean age = 26.33, SD = 3.27) who

¹The results of this experiment were also published in the *European Journal of Neuroscience* (Hasting, Winkler, & Kotz, 2008)

had not taken part in Experiment 1. All of them were right-handed as determined by the Edinburgh Inventory (Oldfield, 1971). The mean LQ was 95.67 (SD = 6.90). Participants received 7 Euros per hour as compensation for their efforts.

Stimuli, design and procedure In order to isolate the part of the previously observed word category effect that is driven by the acoustic rather than the categorical change, the divergent syllables *tet* and *ter* that previously determined the words' category were extracted from the speech signal. Without the word context, the two syllables are reduced to meaningless speech segments. Two oddball-sequences were constructed in which the two syllables served as the standard and deviant stimuli. In sequence **a**, the syllable *tet* was the standard and the syllable *ter* was the deviant. Sequence **b** presented the two syllables in reversed roles. The randomization of the sequences was carried out according to the same constraints as in Experiment 1 (more than two and less than eight standards between any two deviants). Likewise, ten standard stimuli were added to the beginning of each sequence after its randomization to establish the regularity against which the deviant was to be compared. These trials were not included in the analysis. The SOA in both sequences was 850 ms (500 ms longer than the longer syllable *tet*). This resulted in a sequence duration of 13 minutes. The two sequences were presented in a counterbalanced order, with an equal number of male and female participants in each group. The instruction of the participants was identical to Experiment 1. After the presentation of the two sequences, participants rated the two syllables as to how meaningful they were and whether they could be associated with an existing word. The rating confirmed that the isolated syllables were meaningless and did not trigger any particular associations.

The impact of the divergent syllable on the MMN within word context was assessed from the original data obtained in Experiment 1B. The syntactic manipulation in this experiment was disregarded by re-averaging the data across the grammaticality of the stimuli, thus yielding the same standard-deviant combinations as presented in the current experiment but within word context (i.e. sequences **a*** and **b***).

The resulting 2 x 2 design including the within-subject factor DEVIANT (DEV: *tet* vs. *ter*) and the between-subject factor EXPERIMENT (EXP: isolated syllable vs. word context) is depicted in Table 7.1.

Table 7.1: Experimental design for testing the impact of the acoustic change on the word category MMN (wc = word context; is = isolated syllable. Data for sequences **a*** and **b*** were recorded in Experiment 1B.)

ISOLATED SYLLABLE vs WORD CONTEXT MMN				
Sequence	Standard (750)	Deviant (150)	Factor Level	
			DEV	EXP
a	tet	ter	ter	is
b	ter	tet	tet	is
a*	er/ein faltet	er/ein falter	ter	wc
b*	er/ein falter	er/ein faltet	tet	wc

EEG recording For organizational reasons, the isolated syllable experiment was conducted in another laboratory than the previous MMN experiments. Technical differences to the other EEG recordings comprised the use of a BrainAmp DC amplifier (Brainvision, Germany) and the electrode M1 as the online reference. After recording, the data were converted to Refa format and re-referenced to the arithmetic means of the mastoid recordings.

MMN calculation, quantification and analysis As in Experiment 1, ERP signals were averaged for an epoch of 700 ms (-100 to 600 with respect to the DP, i.e. syllable onset) and MMN difference waves were calculated within sequence by subtracting the ERPs to the standard from those to the deviant stimuli. As pointed out above, the data from Experiment 1B were re-analyzed by computing single subject averages across grammaticality and the corresponding MMN difference waves. The MMN quantification for both data sets was conducted for the mean amplitude in the same time range as for Experiment 1B (120 - 220 ms). Afterwards, the difference waves were analyzed by means of a 30 ms timeline per experiment to capture possible temporal differences between the observed components. For maximal comparability with Experiment 1 B, detailed ANOVAs were conducted in identical time windows.

7.2 Results

MMN quantification The grand average deviant-minus-standard difference waves from the present isolated syllable experiment (sequences **a** and **b**) are depicted in Figure 7.1 and those from the word context experiment (sequences **a*** and **b***) in Figure 7.2. All waveforms show a clear negative deflection starting at around 100 ms following deviance onset. The results of the paired t-tests of the mean amplitude between 120 and 220 ms against zero are listed for each sequence and topographical quadrant in Table 7.2. All sequences resulted in significant negativities that were stronger over the anterior than over the posterior half of the scalp, with the exception of sequence **a*** (*ter* in context) for which the topographic distribution was shifted to posterior scalp sites.

Visual inspection for condition effects A visual comparison of Figures 7.1 and 7.2 reveals some remarkable aspects in the overall morphology of the responses across the two experiments. First, the amplitude variations in the difference waves obtained from the sequences in the isolated syllable experiment appear to be generally enhanced as compared to the responses from the word context experiment. Furthermore, the deviant syllable *tet* seems to elicit larger MMN responses than the deviant syllable *ter* across experiments. This effect appears earlier and is more pronounced in the word context than in the isolated syllable experiment. On the other hand, the deviant syllable *ter* elicits a larger subsequent positive deflection in the isolated syllable experiment, whereas the late negative deflection is more prominent within word context.

Timeline analysis The timeline analysis of the data from the word context experiment had revealed strong main effects for DEV between 120 and 270 ms as well as between 360 and 540 ms at both lateral and midline electrodes along with significant REG x DEV interactions. In contrast, the earliest impact of the deviant syllable on the MMN responses in the isolated syllable experiment occurred after 150 ms. This finding confirms the visual impression of a delayed onset of the effect when tested out of context. It is reflected in a brief but highly significant EXP x DEV interaction at both lateral and midline electrodes between 120 and 150 ms. A subsequent main effect of DEV that is highly significant in all sections between 150 and 390 (lateral) versus 360 ms (midline), is complemented by REG x DEV interactions. A further

Table 7.2: Excursus, MMN quantification isolated syllable vs. word context. T-test of the mean amplitude between 120 - 220 ms after DP against zero in the four topographical quadrants (LA = left anterior, RA = right anterior, LP = left posterior, RP = right posterior; is = isolated syllable, wc = word context). Data in sequences a* and b* were recalculated from Experiment 1B.

ISOLATED SYLLABLE vs WORD CONTEXT MMN QUANTIFICATION					
Sequence	Deviant	Quadrant	Mean Ampl.	T-value	p-value
a	ter / noc	LA	-1.94	-7.59	< 0.0001
		RA	-1.87	-6.93	< 0.0001
		LP	-0.81	-3.51	< 0.01
		RP	-0.91	-3.88	< 0.01
b	tet / noc	LA	-2.85	-9.83	< 0.0001
		RA	-2.92	-10.98	< 0.0001
		LP	-1.07	-5.28	< 0.0001
		RP	-1.03	-5.77	< 0.0001
a*	ter / con	LA	-0.39	-2.09	< 0.05
		RA	-0.32	-1.54	0.1381
		LP	-0.48	-5.28	< 0.0001
		RP	-0.55	-4.74	< 0.0001
b*	tet / con	LA	-2.17	-12.45	< 0.0001
		RA	-2.30	-11.51	< 0.0001
		LP	-1.00	-6.83	< 0.0001
		RP	-1.08	-7.99	< 0.0001

REG x DEV interaction is significant towards the end of the epoch between 420 (midline) versus 450 (lateral) and 600 ms. The analysis of the lateral electrodes additionally revealed a significant HEM x DEV interaction between 330 and 450 ms.

Joint time window analysis, 150 - 210 ms The joint ANOVA of the time window covering the supposed word category effect on the MMN in Experiment 1B yielded a main effect of the between-subject factor EXP (lateral: $F_{1,40} = 11.77$, $p < 0.01$; midline: $F_{1,40} = 5.88$, $p <$

0.05) that indicated globally enhanced MMN amplitudes in the isolated syllable experiment as compared to the word context experiment. An interaction with the topographical factor REG (lateral: $F_{1,40} = 23.38$, $p < 0.0001$; midline: $F_{1,40} = 19.92$, $p < 0.0001$) revealed that this amplitude enhancement was restricted to the anterior half of the scalp (lateral: $F_{1,40} = 19.78$, $p < 0.0001$; midline: $F_{1,40} = 11.74$, $p < 0.01$). In addition to this global amplitude difference, the MMN amplitude was significantly larger in response to the deviant syllable *tet* as compared to the deviant syllable *ter* in both experiments, as indicated by a main effect of DEV (lateral: $F_{1,40} = 38.34$, $p < 0.0001$, $\Delta = 1.1$; midline: $F_{1,40} = 24.01$, $p < 0.0001$, $\Delta = 1.2$). This effect was further specified by a REG x DEV interaction (lateral: $F_{1,40} = 31.73$, $p < 0.0001$; midline: $F_{1,40} = 28.41$, $p < 0.0001$) showing that the amplitude difference was larger over anterior scalp sites (lateral: $F_{1,40} = 48.88$, $p < 0.0001$, $\Delta = 1.7$ vs. $F_{1,40} = 9.01$, $p < 0.01$, $\Delta = 0.5$; midline: $F_{1,40} = 34.59$, $p < 0.0001$, $\Delta = 1.8$ vs. $F_{1,40} = 7.34$, $p < 0.01$, $\Delta = 0.6$). However, a marginally significant three-way interaction between REG, DEV and EXP (lateral: $F_{1,40} = 3.02$, $p = 0.09$; midline: $F_{1,40} = 3.36$, $p = 0.0742$) indicates that whereas the DEV effect is pronounced and shows an anterior tendency within word context (lateral: $F_{1,23} = 47.87$, $p < 0.0001$, $\Delta = 2.1$ vs. $F_{1,23} = 10.3$, $p < 0.01$, $\Delta = 0.6$; midline: $F_{1,23} = 36.82$, $p < 0.0001$, $\Delta = 2.3$ vs. $F_{1,23} = 8.86$, $p < 0.01$, $\Delta = 0.8$), it is much weaker and restricted to anterior scalp sites in the isolated syllable experiment (lateral: $F_{1,17} = 10.82$, $p < 0.01$, $\Delta = 1.2$; midline: $F_{1,17} = 6.58$, $p < 0.05$, $\Delta = 1.2$).

Joint time window analysis, 210 - 270 ms The joint ANOVA of the second time window resulted in a further EXP effect (lateral: $F_{1,40} = 9.87$, $p < 0.01$; midline: $F_{1,40} = 5.03$, $p < 0.05$) indicating global amplitude differences between the two experiments. Again, these occurred primarily over the anterior half of the scalp (lateral: $F_{1,40} = 14.5$, $p < 0.001$ vs. $F_{1,40} = 4.94$, $p < 0.05$; midline: $F_{1,40} = 8.33$, $p < 0.01$) as indicated by a REG x EXP interaction (lateral: $F_{1,40} = 17.24$, $p < 0.001$; midline: $F_{1,40} = 12.48$, $p < 0.01$). A strong main effect of DEV (lateral: $F_{1,40} = 55.98$, $p < 0.0001$, $\Delta = 1.5$; midline: $F_{1,40} = 44.51$, $p < 0.0001$, $\Delta = 1.8$) in combination with a REG x DEV interaction (lateral: $F_{1,40} = 80.78$, $p < 0.0001$; midline: $F_{1,40} = 63.35$, $p < 0.0001$) reflected the stronger positive deflection following the MMN when *ter* was the deviant. This positivity occurred in both experiments during this time window and was much more pronounced over anterior scalp sites (lateral: $F_{1,40} = 100.25$, $p < 0.0001$, $\Delta = 2.5$ vs. $F_{1,40} = 5.11$, $p < 0.05$, $\Delta = 0.5$; midline: $F_{1,40} = 83.47$, $p < 0.0001$, $\Delta = 2.8$ vs. $F_{1,40} = 7.28$, $p < 0.05$, $\Delta = 0.8$).

Joint time window analysis, 270 - 360 ms This time window did not contain any word category effects in Experiment 1B, as it was included in the analysis to capture a grammaticality effect. However, as can be observed in Figure 7.1, the difference waves in the isolated syllable experiment showed a small second negative deflection in response to the deviant syllable *tet* and a strong positive deflection in response to the deviant syllable *ter* during this time window. These deflections were reflected in the joint ANOVA as follows. An EXP x DEV interaction (lateral: $F_{1,40} = 25.33$, $p < 0.0001$; midline: $F_{1,40} = 25.2$, $p < 0.0001$) confirmed that the DEV effect was restricted to the isolated syllable experiment (lateral: $F_{1,17} = 68.48$, $p < 0.0001$, $\Delta = 2.4$; midline: $F_{1,17} = 49.17$, $p < 0.0001$, $\Delta = 2.9$). A three-way interaction between EXP, REG and DEV further revealed that the polarity difference was again strongest over anterior scalp sites (lateral: $F_{1,17} = 104.95$, $p < 0.0001$, $\Delta = 3.4$ vs. $F_{1,17} = 17.32$, $p < 0.001$, $\Delta = 1.4$; midline: $F_{1,17} = 86.1$, $p < 0.0001$, $\Delta = 3.9$ vs. $F_{1,17} = 15.11$, $p < 0.01$, $\Delta = 1.9$).

Joint time window analysis, 360 - 540 ms The last of the four time windows covered the late negativity in response to noun deviants in Experiment 1B. The joint ANOVA including the data sets from both experiments revealed a global EXP effect (lateral: $F_{1,40} = 8.85$, $p < 0.01$; midline: $F_{1,40} = 8.61$, $p < 0.01$) along with an EXP x DEV interaction (lateral: $F_{1,40} = 9.44$, $p < 0.01$; midline: $F_{1,40} = 10.45$, $p < 0.01$). A resolution of the latter showed that the late negativity following the deviant syllable *ter* was only present within word context (lateral: $F_{1,23} = 21.85$, $p < 0.001$, $\Delta = 1.0$; midline: $F_{1,23} = 36.21$, $p < 0.0001$, $\Delta = 1.8$).

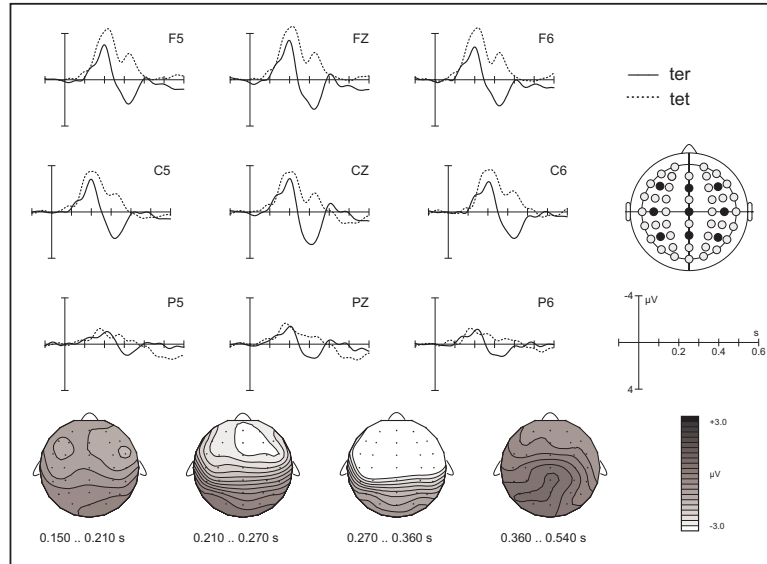


Figure 7.1: Excursus: MMN modulation by DEV for isolated syllables. MMN waves and topographical difference maps (tet - ter) of the mean amplitude in the time windows selected for statistical analysis.

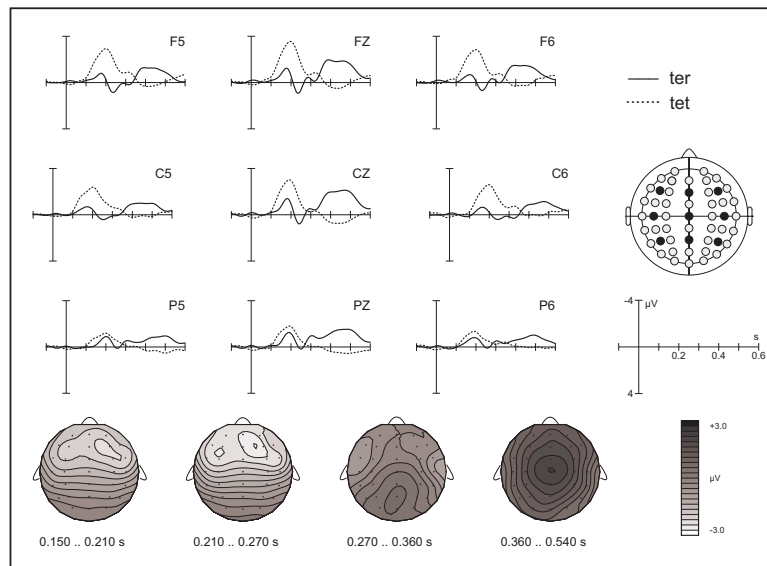


Figure 7.2: Excursus: MMN modulation by DEV within word context. MMN waves and topographical difference maps (tet - ter) of the mean amplitude in the time windows selected for statistical analysis.

7.3 Discussion

Elicitation of the MMN The morphology of the deviant-minus-standard difference waveforms presented in Figure 7.1 as well as the quantification procedure confirm that both sequences of the isolated syllable experiment elicited reliable MMN responses. Furthermore, the differences between the two waveforms in Figure 7.1 leave no doubt that the direction of acoustic change does affect the MMN, at least when acoustically complex stimuli are used. On the other hand, a comparison with the word context data from Experiment 1B (see Figure 7.2) reveals interesting differences that can only be attributed to the presence or absence of the lexical context. First, the amplitudes of the MMN in the isolated syllable experiment are larger independently of the deviant syllable. And second, the unusual posterior distribution of the MMN following the deviant syllable *ter* only occurs within word context. These effects as well as further differential effects in the time range following the MMN will be discussed in greater detail in the following.

Global amplitude differences The global amplitude difference between the two experiments indicates that although the deviating syllables were physically identical, the perceived deviance was larger when they were contrasted in isolation. This may be caused by differences in the ratio between the deviating fraction and the total stimulus length. Whereas this ratio was small in Experiment 1B where the deviating syllables were part of three-syllabic utterances, it was large in the isolated syllable experiment where they were presented on their own. This may have led to the enhanced MMN responses in the latter case. Another difference in the ERP responses from the two experiments that could be caused by a larger deviance ratio in the isolated syllable experiment is the enhanced positive deflection following the MMN in response to the deviant syllable *ter*. This effect most likely represents a P300 component (Sutton et al., 1965; Hruby & Marsalek, 2003) that is usually taken as an indicator of an attention shift towards a novel or deviant stimulus (Schröger & Wolff, 1998b, 1998a; Escera, Yago, & Alho, 2001; Friedman, Cycowicz, & Gaeta, 2001, see also page 18). In the current context, it is however unclear why the syllable *ter* as presented among a string of *tet* would capture more attention than *tet* as presented among a string of *ter*, since according to the participants, neither syllable stimulated any meaningful associations. The critical factor must therefore lie in the acoustic stimulus characteristics. Possible candidates that could have affected the amount of

attention drawn to the two syllables are their different length as well as a change in their vowel quality.

MMN modulation by direction of change and word context In addition to the global amplitude enhancements in the isolated syllable experiment, the MMN was modulated by the deviant syllable itself, and therefore by the direction of acoustic change. In both experiments, its amplitude was larger in response to the deviant syllable *tet* presented among strings of *ter* than in the opposite case. This suggests that the syllable *tet* comprised a more salient deviant than the syllable *ter* due to its acoustic properties. However, the timeline analysis revealed that the onset of the amplitude difference occurred at least 30 ms earlier in the word context experiment. Furthermore, the MMN amplitude difference between 150 and 210 ms was much more pronounced and more broadly distributed when tested within context. In contrast, the effect was considerably smaller and only significant over the anterior half of the scalp in the isolated syllable experiment. This pattern of results suggests that whereas the direction of acoustic change affects the amplitude of the MMN over anterior scalp sites classically associated with acoustic deviance detection, both MMN amplitude and topography are *additionally* modulated by the word category information provided by the two contrasted syllables when they are presented within context. This view is further supported by the fact that the unusual posterior distribution of the MMN in response to the deviant syllable *ter* was only observed when it completed the noun "Falter". The MMN quantification procedure (see Table 7.2) clearly showed that the same acoustic change presented out of context in the isolated syllable experiment resulted in an ordinary MMN response with a fronto-central maximum. Thus, the impact of word category information on the MMN appears to become manifest mainly in the topographical distribution of the responses. The cortical generators of MMN effects have previously been shown to differ according to lexico-semantic stimulus features by Pulvermüller and colleagues (Pulvermüller, Shtyrov, & Ilmoniemi, 2005; Shtyrov, Hauk, & Pulvermüller, 2004). These effects are most likely driven by the "representational negativity" (RN), an assumed subcomponent of the MMN that is elicited by the activation of experience-dependent long-term memory representations (Pulvermüller & Shtyrov, 2006). In the light of this interpretation the currently observed word category effect on the MMN suggests the automatic activation of differential cortical networks representing the inflected verb form *faltet* and the visual noun *Falter*. As noted earlier, the topographical shift in the anterior-posterior dimension is in concordance with previous evi-

dence on representational differences between the two word categories (as reviewed in Shapiro & Caramazza, 2003). Furthermore, the early latency and automatic nature of the observed effect support the assumption that word category information is accessed as a primary step in syntactic analysis (Frazier, 1987; Friederici, 2002).

The present data provide the first evidence that differences in the processing and neuronal representations of verbs and nouns can be reflected by the automatic MMN component. However, the exact linguistic basis of the effect cannot be determined by the present data, as the contrasted items differ in a variety of features that are discussed in relation to differences between the two word categories, including inflectional morphology (Tyler, Bright, Fletcher, & Stamatakis, 2004) and semantic content (Pulvermüller et al., 1999). For this reason, it is essential to replicate the putative word category specific modulation of the MMN with more than just the single verb-noun-pair of the present investigation, for example by using variable verbs and nouns in the roles of standard and deviants.

Contextual dependence of the late negativity Another clear impact of the word context on the difference waves was shown for the time window between 360 and 540 ms. The centrally distributed negativity in this time window was significant only when the deviant syllable *ter* occurred within the noun context. There appears to be no impact of the acoustic stimulus features in this late time window. This finding is consistent with the tentative interpretation given in Experiment 1B, which assumed that the negativity represents an N400 effect elicited by enhanced lexical-semantic processing of the noun as opposed to the inflected verb form, possibly caused by the different syntactic and semantic functions of the two word categories during sentence comprehension.

7.4 Summary and Conclusions

The present Excursus demonstrated that the striking modulations of the MMN observed within the word category context in Experiment 1B in fact reflected a combination of effects of the direction of acoustic change and genuine processing and representational differences between verbs and nouns. It appears that whereas the direction of acoustic change affects the amplitude of the MMN over anterior scalp sites traditionally associated with acoustic deviance detection, quantitative and qualitative processing differences between verbs and nouns mainly affect the

MMN topography independently of the acoustic effects. The documentation of an impact of word category information on the automatic MMN response points out a promising new approach to study early differences in the neuronal processing and representation of verbs and nouns outside the focus of attention. However, the current results also draw attention to the fact that the MMN amplitude is not fully determined by the magnitude, but also by the direction of acoustic change, at least when complex stimuli like speech sounds are being used. This finding demonstrates once more the high impact of acoustic stimulus features on early ERP responses, as well as the necessity to provide adequate control conditions for the separation of linguistic from acoustic MMN effects.

Chapter 8

Experiment 2: Localization of the syntactic MMNs using MEG

Experiment 1 showed that local agreement and phrase structure violations both modulated the MMN component in a comparably early time window, thus providing evidence for equally early and automatic processing of syntactic relations and structure. At the same time, the effects displayed differences in scalp distribution depending on the violation type. This suggests that different neuronal populations are activated by the two syntactic subprocesses. In particular, it seemed that, consistent with previous localizations (Pulvermüller & Shtyrov, 2003; Shtyrov et al., 2003), the effect in the agreement condition was primarily driven by generators in the temporal and inferior frontal cortex of the left hemisphere. On the other hand, the MMN modulation in the phrase structure condition appeared to be mediated by more widely distributed, possibly bilateral neuronal networks. Such a neuronal differentiation is theoretically interesting, because it would provide a neural correlate for the functional separation of the two syntactic subprocesses in spite of their temporal concurrency. Although recent fMRI studies were successful in identifying subregions in the left inferior frontal cortex that are differentially activated by different syntactic operations (Friederici, Bahlmann, et al., 2006; Friederici, Fiebach, et al., 2006), a direct dissociation according to violation type is yet to be shown (see also Section 3.2). This may be due to the limited temporal sensitivity of the fMRI method that makes it impossible to determine which syntactic processing stage is reflected in the observed activations. Furthermore, the application of different tasks may have affected the results in previous studies. In contrast, the differential scalp distribution of the syntactic MMN effects

in response to agreement and word category violations in Experiment 1 was observed under temporally and attentionally unbiased circumstances. Thus, the comparative syntactic MMN design seems to be a promising approach for the identification of differential neural correlates of syntactic subprocesses. However, without a detailed source analysis incorporating information in addition to the scalp potential, the conclusions that can be drawn from Experiment 1 regarding this issue do not exceed the level of speculation.

Experiment 2 was conducted to dispel this limitation. It comprises an abbreviated version of the comparative syntactic MMN design from Experiment 1 that should allow for an exact replication of the observed effects. In addition, it calls upon the enhanced spatial information contained in MEG data as compared to EEG data (see Section 2.1.2) to investigate possible differences in the cortical generators underlying these effects. For data analysis, a distributed source modelling approach based on brain surface current density (BSCD) mapping was taken. This approach uses the brain surface as a source space. Although all depth information is lost in this model, it is particularly suitable for situations in which rather complex and non-focal patterns of activity are to be expected. This is likely to be the case in the present investigation, because the simultaneous acoustic and syntactic changes contained in the syntactic MMN effect are presumably processed in different brain areas.

The specific hypotheses to be tested in the current MEG experiment were the following:

1. The acoustic difference between standard and deviant stimulus in each sequence should elicit the magnetic counterpart of the MMN, namely the MMNm, characterized by a clear peak between 100 - 200 ms and main generators located in the auditory cortices of both hemispheres (Näätänen et al., 2001).
2. As a replication of the syntactic MMN effects obtained in Experiment 1, the ERFs should show higher amplitudes in response to sequences in which the deviant produced a syntactic violation as compared to syntactically correct deviants, independently of the violation type. This effect should also cause significant differences in the BSCD amplitudes in MMNm-related brain areas.
3. The BSCD maps should further reveal areas of activation that differ in location depending on the violation type. Based on the specific scalp distributions of the effects observed in Experiment 1, one could speculate that the left inferior frontal cortex is particularly

involved in the processing of agreement violations, whereas bilateral regions in temporal and inferior frontal cortices may be activated in response to word category violations.

8.1 Methods

Participants 22 healthy native speakers of German aged 21 to 32 (mean age: 25.82, SD = 3.03, 11 male) agreed to participate. All of them were right-handed (mean LQ = 96.4, SD = 6.82), as determined by the Edinburgh Inventory (Oldfield, 1971). Participants received 7 Euros per hour as compensation for their efforts during the experiment, as well as 11 Euros travel refunds per session as the MEG laboratory is situated in a rural area outside the city of Leipzig.

Design and procedure In Experiment 1, syntactic MMN effects were shown to be independent of the direction of acoustic change. As identical stimuli were used in the present MEG experiment to replicate these effects it appeared justified to reduce the design to one direction of acoustic change per type of syntactic structure only. This reduced overall recording time to one hour per session. Furthermore, the abbreviated design (see Table 8.1) allowed the introduction of the superordinate factor TYPE (agreement violation vs. word category violation), and therefore a direct statistical comparison of the syntactic MMN effects in response to the two violation types. These were again tested in separate sessions held at intervals of at least one week. The order of the sessions and conditions within a session was counterbalanced across participants, with an equal number of male and female participants in each group.

For the recording of the MEG, the participants lay on a comfortable examination couch situated in a magnetically shielded room. Prior to recording, the participants' individual hearing thresholds were determined for each ear using one of the experimental stimuli. During the experiment, stimulation was applied binaurally at 48 dB above the mean threshold of the two ears via a plastic tube (as normal headphones would have caused electromagnetic artefacts). Unlike in EEG experiments, the sensor array in MEG recordings is not fixed to the participants' head. It is therefore essential to keep the head position identical for the duration of each MEG run. To make this task achievable for the participants, their head was placed in a fixating rest and the sequences were each split in half and presented in two blocks of approximately 13 minutes each. Before and after each block, the head position in relation to the sensor array was localized by

Table 8.1: Experimental design for the localization of the syntactic MMNs using MEG (TYPE = violation type, GRAM = grammaticality, ps = phrase structure, agr = agreement, cor = correct, inc = incorrect). Grammaticality level is assigned to deviant stimulus.

AGREEMENT vs PHRASE STRUCTURE MMNm				
Sequence	Standard (750)	Deviant (150)	Factor Level	
			TYPE	GRAM
a	er faltet	*er faltest	agr	inc
b	*du faltet	du faltest	agr	cor
interval \geq one week				
c	ein Falter	*ein faltet	ps	inc
d	*er Falter	er faltet	ps	cor

means of five head-mounted coils. These data were later used for the computation of average sensor positions across blocks and for the monitoring of head movements during each block. For the duration of each block, the MEG was continuously recorded with a whole-head multi-channel magnetometer allowing the simultaneous registration of the magnetic field responses from 148 sites (MAGNES WHS 2500, 4D-Neuroimaging, San Diego, CA, USA). Additionally, signals from four EOG electrodes were recorded to monitor eye movements. These were placed above and below the right eye as well as lateral to the outer canthus of each eye. The sampling rate was 508.63 Hz, and the data were bandpass-filtered online from 0.1-100 Hz. Participants were instructed not to move during a block, and to blink and swallow as little as possible. They were further instructed to focus their attention on a silent movie and to ignore any auditory stimulation. In between blocks they were allowed to take breaks for as long as they needed.

Pre-processing of the data Offline data processing comprised the following steps: The raw data were treated with a 0.5 - 20 Hz bandpass filter to remove slow drifts and high frequency noise. ERFs were computed for an epoch of 700 ms (-100 to 600 ms with respect to the DP), separately for each participant, block and stimulus type. The 100 ms prior to the DP served as baseline. Epochs were excluded from the averaging procedure analysis if a) they contained the

first standard trial after a deviant trial, b) the standard deviation within a 200 ms sliding time window exceeded a threshold of 40 μV on the EOG channels or 1500 fT on any MEG channel, or c) the standard deviation within a 20 ms sliding time window exceeded a threshold of 6000 fT. The latter two criteria cleared the data from biological artifacts and signal jumps caused by amplifier discharges. Additionally, cross-correlation coefficients between adjacent channels were calculated to identify channels that were dysfunctional during recording. If the median correlation coefficient of a given channel with its immediate neighbours reached a value below 0.72, this channel was rejected. If the number of rejected channels per block was lower than 10, the signals of the dysfunctional channels were reconstructed by means of interpolation. Three participants (two of them male), who turned out to have 10 or more dysfunctional channels in some of the blocks, were excluded from further analysis. The MMNm was calculated for the remaining 19 participants for each block by subtracting the ERF elicited by the standard stimulus from the ERF elicited by the deviant stimulus. As the position of the participants' head in relation to the sensors was different for each block, an extrapolation algorithm was employed to convert all measurements to the average sensor position (Knösche, 2002). As a final step, the average of the difference fields from the two blocks of each sequence was calculated.

Computation, quantification and statistical analysis of BSCD maps Volume conductors as well as source spaces were constructed on the basis of individual MR scans using the ASA software package (Advanced Neuro Technology ANT, The Netherlands). The MR scans had been pre-segmented using the LIPSIA software (Lohmann et al., 2001) and contained reflections of brain tissue only (without skin, skull and cerebrospinal fluid). The brain surfaces were dilated by 1 mm to create the volume conductors and eroded by 8 mm to approximate the position of activated cortical tissue for the source spaces. The latter were modelled as a mesh of 3872 triangles. The edges of the triangles represented the dipole positions. Brain surface current density (BSCD) estimates were computed for these positions based on the minimum norm least squares (MNLS) method (e.g. Wang, Williamson, & Kaufman, 1993) with lead field normalization (Knösche, 1997; Fuchs, Wagner, Köhler, & Wischmann, 1999) for each participant, condition, and sampling point. The pseudo-inverse of the weighted lead field matrix was regularized using truncated singular value decomposition (e.g. Sullivan & Liu, 1984), where all singular values smaller than 0.1% of the largest one were set to zero. The threshold of 0.1% was obtained empirically from L-curves computed from a number of data sets that had

been recorded in a different study from the same laboratory. The BSCD data were quantified based on nonoverlapping regions of interest (ROIs). To capture MMNm-related activity, ROI definition was conducted on the sum of the BSCD grand average maps from all conditions at 180 ms, that is, at the mean peak latency of the MMNm as estimated from the ERFs (see Figure 8.1). Each ROI consisted of a manually selected dipole as a starting position and a maximum of 9 neighboring dipole positions within a radius of 10 mm whose activation reached at least 75 % of the starting position value. The mean of the Talairach coordinates (Talairach & Tournoux, 1988) of the dipole positions included in a ROI was used for its anatomical classification in terms of Brodmann Areas (BA). This was based on the "find nearest grey matter" approach provided by the Talairach Daemon Client (Lancaster, Summerlin, Rainey, Freitas, & Fox, 1997; Lancaster et al., 2000)¹. This activity-based approach resulted in four ROIs that were located over the mid-portion of the superior and middle temporal gyri (STG and MTG; BA 22 and 21) of both hemispheres. Additional ROIs were defined over left and right inferior frontal cortex (IFG; BA 45 and 47) to test the predictions of Hypothesis 3. Table 8.2 indicates the defined ROIs and the mean Talairach coordinates on which their classification was based.

Table 8.2: Regions of interest (ROIs) as defined for the BSCD analysis

ROI	BA	Left Hemisphere			Right Hemisphere		
		x	y	z	x	y	z
STG (middle portion)	22	-59	-14	7	54	9	1
MTG (middle portion)	21	-60	-18	-9	55	-15	13
IFG (pars triangularis)	45	-50	16	4	48	21	11
IFG (pars orbitalis)	47	-46	30	-4	43	33	-2

BSCD time courses were then computed per ROI, condition and participant. To account for peak latency differences between the two violation types (see also Experiment 1), condition effects were assessed by means of a peak analysis instead of a mean amplitude analysis. Peak amplitudes and latencies were extracted from the time range of the MMNm (100 - 250 ms, as determined by visual inspection of the grand average ERFs) with an automatic peak detection device provided by the EEP 3.2.1 software package (Max Planck Institute for Human Cognitive

¹Version 2.0, available at <http://ric.uthscsa.edu/resources/>

and Brain Sciences, Leipzig, Germany). ANOVAs including the 2-level factors TYPE (agreement vs. phrase structure) and GRAM (correct vs. incorrect) were conducted per ROI and evaluated for main effects and interactions in a hierarchical fashion. Motivated by the results of the EEG study, peak amplitudes were additionally assessed per ROI by means of a one-way ANOVA with the factor GRAM for each level of the factor TYPE in order to identify brain regions that are activated differentially according to violation type. Likewise, peak latencies were subjected to a one-way ANOVA with the factor TYPE for each level of the factor GRAM in order to submit the observed latency differences of the syntactic MMN effects to statistical testing. To keep the report of the statistical data concise, the results of the peak amplitude and peak latency analyses are listed in Table 8.3 and 8.4, respectively. The pattern of results is commented on in the text.

8.2 Results

MMNm assessment based on averaged ERFs Figure 8.1 shows the time courses of the deviant-minus-standard ERFs per condition, plotted as femto-Tesla (fT) over time, as well as spherical spline interpolated maps at the peak latency of the first clear component. Three patterns can be deduced from a visual inspection of these data. First, a clear component peaks at 160 ms in the agreement condition and approximately 40 ms later in the phrase structure condition. Second, the amplitudes at the time points of this first peak are larger in each condition in which the deviant was grammatically incorrect as compared to the respective correct condition, suggesting larger responses to incorrect deviants irrespectively of the violation type. And third, the topographical maps reveal clear bilateral two-lobed patterns in all conditions that are compatible with the assumption of two main generators in the auditory cortices. In addition, the maps indicate that the sources in the left hemisphere are slightly stronger than in the right hemisphere. The impression of higher field amplitudes in response to incorrect conditions is also confirmed by the maps.

Localization of the syntactic MMNm based on BSCD mapping Figure 8.2 shows the sum of the BSCD grand average maps at the mean peak latency of the MMNm (180 ms) as well as the locations of the selected ROIs for the left and the right hemisphere. The grand average BSCD time courses per ROI are shown in the boxes plotted as nano-Ampere-meter (nAm)

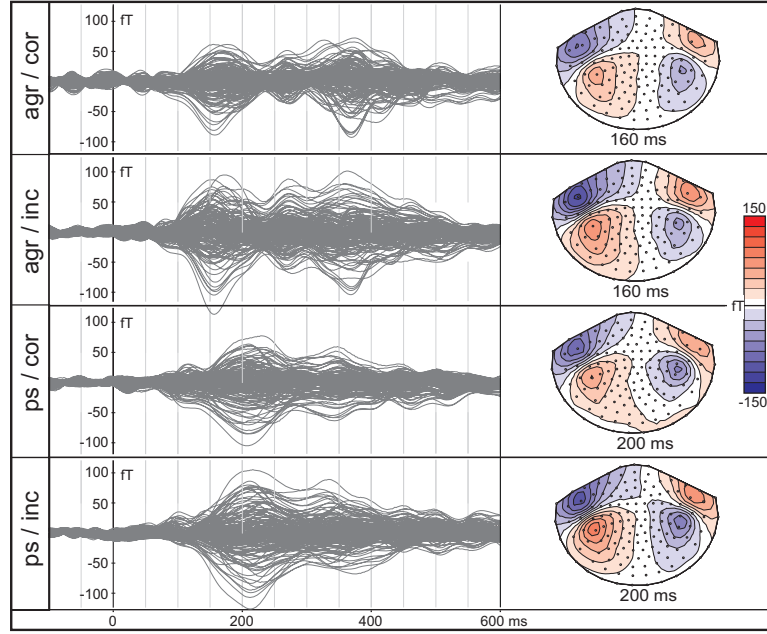


Figure 8.1: Experiment 2: ERFs per condition. Left column: Time courses. Right column: Spherical spline interpolated maps (view from the top; nose pointing upwards) at the peak latency of the first clear component. agr = agreement condition, ps = phrase structure condition, cor = correct deviant, inc = incorrect deviant.

over time. As expected from the difference maps of the ERFs (see Figure 8.1), the main MMNm-related activity is observable in the mid-temporal regions of both hemispheres. The BSCD time courses from the respective ROIs show clear peaks in the critical time range. These components seem to reflect the pattern observed both in the ERFs as well as in the EEG study (Experiment 1) in that their amplitude appears larger for incorrect conditions and their latency slightly earlier in the agreement condition, although the latter effect appears to be restricted to the left hemisphere. In comparison to the temporal regions, the inferior frontal regions show much less activation. Nevertheless, the morphology of their BSCD time courses seems to retain the observed condition effects, as they too show enhanced activity for incorrect as opposed to correct conditions.

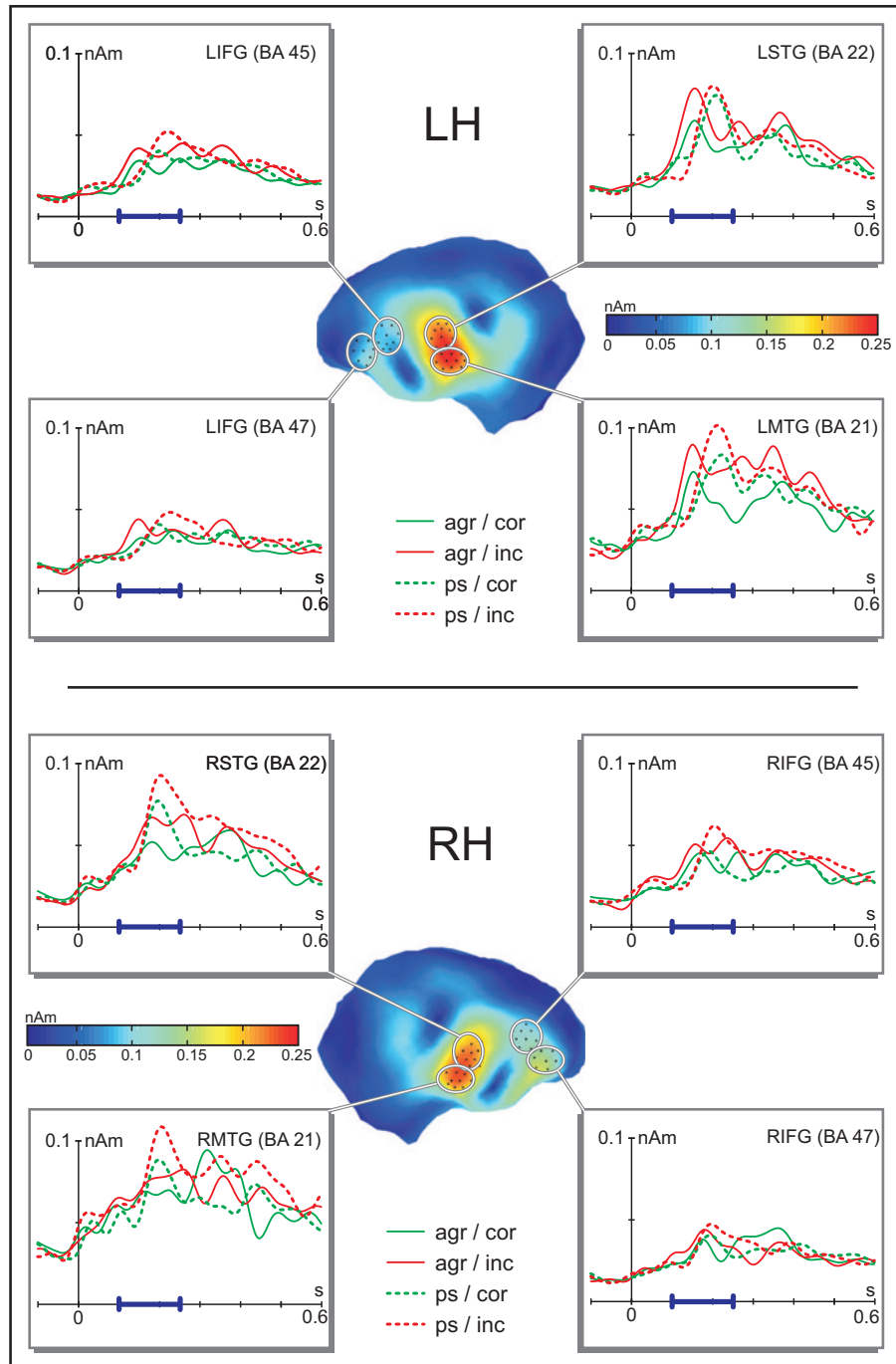


Figure 8.2: Experiment 2: Grand average BSCD maps at 180 ms; ROIs and corresponding grand average BSCD time courses for the left hemisphere (LH; upper panel) and the right hemisphere (RH; lower panel), respectively. The blue bars highlight the time range considered for MMNm peak analysis (100 - 250 ms). agr = agreement condition, ps = phrase structure condition, cor = correct deviant, inc = incorrect deviant.

BSCD peak amplitude analysis The results from the peak amplitude analysis of the MMNm-related activity (see Table 8.3) can be summarized as follows. The TYPE x GRAM ANOVA revealed that the peak amplitudes were generally stronger for incorrect as opposed to correct conditions, as revealed by a significant main effect for GRAM in all ROIs. A significant main effect of TYPE was obtained in RSTG (BA 22), where the amplitudes of the MMNm in the phrase structure condition were more pronounced than in the agreement condition. Marginally significant TYPE x GRAM interactions in LSTG (BA 22) and in pars orbitalis of the LIFG (BA 47) showed that these ROIs displayed significant grammaticality effects in the agreement condition only. The additional ANOVA per TYPE revealed that this was a tendency in most of the ROIs, with the exception of the LMTG (BA 21) and pars orbitalis of the RIFG (BA 47) that showed significant GRAM effects in the phrase structure condition whereas the GRAM effects in the agreement condition were only marginally significant.

BSCD peak latency analysis The peak latency analysis of the MMNm (see Table 8.4) confirmed the impression of slightly earlier responses in the agreement condition for the temporal ROIs in the left hemisphere that showed significant main effects of TYPE. The resolution of significant TYPE x GRAM interaction in pars orbitalis of LIFG (BA 47) revealed that an equivalent effect was present in this region also, but restricted to the incorrect conditions. Main effects of GRAM in the right inferior frontal ROIs attested delayed peaks in response to grammatically incorrect as opposed to correct deviants in these brain areas.

Table 8.3: BSCD peak amplitude analysis of the MMNm per ROI

PEAK AMPLITUDE						
ROI / BA	ANOVA TYPE x GRAM			ANOVA GRAM per TYPE		
	Effect	F _{1,18}	p	Level	F _{1,18}	p
LSTG / 22	TYPE	< 1				
	GRAM	13.17	< 0.01	agr	12.16	< 0.01
	TYPE x GRAM	3.91	0.0634	ps	2.0	0.1745
LMTG / 21	TYPE	< 1				
	GRAM	8.63	< 0.01	agr	3.42	0.0808
	TYPE x GRAM	< 1		ps	12.02	< 0.01
LIFG / 45	TYPE	< 1				
	GRAM	17.01	< 0.001	agr	11.45	< 0.01
	TYPE x GRAM	< 1		ps	4.39	0.0505
LIFG / 47	TYPE	< 1				
	GRAM	22.66	< 0.001	agr	29.33	< 0.0001
	TYPE x GRAM	3.96	0.0708	ps	2.51	0.1303
RSTG / 22	TYPE	10.68	< 0.01			
	GRAM	19.07	< 0.001	agr	17.64	< 0.001
	TYPE x GRAM	< 1		ps	3.27	0.0875
RMTG / 21	TYPE	1.85	0.1908			
	GRAM	14.39	< 0.01	agr	7.41	< 0.05
	TYPE x GRAM	< 1		ps	2.88	0.1069
RIFG / 45	TYPE	< 1				
	GRAM	13.22	< 0.01	agr	5.25	< 0.05
	TYPE x GRAM	< 1		ps	2.22	0.1535
RIFG / 47	TYPE	< 1				
	GRAM	13.39	< 0.01	agr	3.81	0.0666
	TYPE x GRAM	< 1		ps	9.53	< 0.01

Table 8.4: BSCD peak latency analysis of the MMNm per ROI

PEAK LATENCY						
ROI / BA	ANOVA TYPE x GRAM			ANOVA TYPE per GRAM		
	Effect	F _{1,18}	p	Level	F _{1,18}	p
LSTG / 22	TYPE	11.00	< 0.01			
	GRAM	< 1		cor	2.75	0.1148
	TYPE x GRAM	1.89	0.1866	inc	12.90	< 0.01
LMTG / 21	TYPE	11.10	< 0.01			
	GRAM	< 1		cor	8.71	< 0.01
	TYPE x GRAM	< 1		inc	4.82	< 0.05
LIFG / 45	TYPE	3.24	0.0886			
	GRAM	< 1		cor	< 1	
	TYPE x GRAM	2.03	0.1717	inc	5.91	< 0.05
LIFG / 47	TYPE	1.75	0.2023			
	GRAM	< 1		cor	< 1	
	TYPE x GRAM	5.89	< 0.05	inc	7.51	< 0.05
RSTG / 22	TYPE	2.67	0.1194			
	GRAM	2.90	0.1055	cor	2.91	0.1053
	TYPE x GRAM	< 1		inc	1.26	0.2756
RMTG / 21	TYPE	2.95	0.1032			
	GRAM	< 1		cor	< 1	
	TYPE x GRAM	2.23	0.1526	inc	7.57	< 0.05
RIFG / 45	TYPE	< 1				
	GRAM	7.33	< 0.05	cor	< 1	
	TYPE x GRAM	< 1		inc	< 1	
RIFG / 47	TYPE	1.64	0.2170			
	GRAM	4.41	0.05	cor	< 1	
	TYPE x GRAM	2.71	0.1173	inc	4.25	0.0540

8.3 Discussion

Elicitation of the MMNm The ERF time courses and topographical maps presented in Figure 8.1 closely match the predictions from Hypothesis 1. All conditions exhibit a clear component in the latency range of the MMNm. The topography of this component is best explained by assuming the main generators to be located in the medial superior temporal gyri of both hemispheres, thus probably reflecting activity in the auditory cortices. This assumption is supported by the BSCD time courses (Figure 8.2) that show the strongest deflection in the ROIs located in left and right mSTG across conditions. Although the acoustic MMN(m) to simple tones is generally lateralized to the right hemisphere (Paavilainen, Alho, Reinikainen, Sams, & Näätänen, 1991; Deouell, Bentin, & Giard, 1998), the left-lateralization of the MMNm in the current study is consistent with previously reported lateralizations of the MMN and localizations of the MMNm when elicited by speech sounds (Shtyrov et al., 2000; Näätänen, 2001; Knösche, Lattner, Maess, Schauer, & Friederici, 2002). This shift in lateralization has been interpreted in terms of an involvement of language-specific permanent memory traces predominantly located in the left hemisphere that are activated in addition to the acoustic change detection process (Näätänen, 2001; Pulvermüller & Shtyrov, 2006). The enhanced amplitude of the MMNm in response to sequences in which the deviant is grammatically incorrect is in line with the data pattern obtained in Experiment 1 and supports Hypothesis 2. Another striking parallel to Experiment 1 is the slightly delayed peak latency of the MMNm in the phrase structure as compared to the agreement conditions. Both of these observations will be discussed in greater detail based on the results of the BSCD peak amplitude and latency analyses in the following.

Brain areas involved in the syntactic MMN(m) effects The results of the BSCD peak amplitude analysis suggest that the syntactic MMNm effects are mediated by neuronal networks distributed over temporal and inferior frontal cortices of both hemispheres. Significant main effects of grammaticality were obtained in each of the tested ROIs. While these findings unequivocally support Hypothesis 2 by replicating the syntactic ERP effects from Experiment 1, they do not provide firm statistical support for differentially activated brain areas depending on the violation type, as predicted in Hypothesis 3. This is due to the fact that the statistical evidence concerning this point is restricted to two marginally significant TYPE x GRAM inter-

actions in the left STG and the pars orbitalis of the left IFG, that - strictly speaking - do not allow for any conclusions concerning this point.

Nevertheless, a hypothesis-driven GRAM per TYPE analysis was conducted in search for tendencies that could explain the differential scalp distribution for agreement versus phrase structure processing observed in Experiment 1. This exploratory analysis revealed that most ROIs showed significant grammaticality effects for the agreement condition only. The strongest effect in this condition was situated over the pars orbitalis of the left inferior frontal gyrus (BA 47). Additional activation foci can be suspected over the middle portion of the superior temporal gyri (BA 22) bilaterally. In contrast, the effect in the phrase structure condition appeared to be mediated mainly by the left medial temporal gyrus (BA 21) and the pars orbitalis of the right inferior frontal gyrus (BA 47). These were the only areas that did not show significant effects for the agreement condition. This pattern of results is consistent with the condition-specific scalp topographies observed in Experiment 1 (i.e., left anterior focus in the agreement condition and broad distribution in the phrase structure condition) and fuels the hope for a spatial analogy of the functional differentiation between phrase structure and agreement processing.

However, a mapping of the activated brain regions to specific syntactic functions is fairly challenging. While the overall activation pattern in the agreement condition appears compatible with previous syntax-related findings from the neuroimaging literature (see Section 3.2), the fact that the strongest effect was observed over the pars orbitalis of the left inferior frontal gyrus (BA 47) is surprising because syntactic activity in inferior frontal cortex is usually observed in the superiorly situated Broca's Area (BA 44/45). Based on the depth-insensitive BSCD mapping approach, it could however be speculated that the strong activation assigned to BA 47 in fact reflects activity in the frontal operculum lying underneath. The frontal operculum has recently been shown to be activated in response to violations of local predictions (Friederici, Bahlmann, et al., 2006). Thus, activation of this brain region in the present context would match well with the interpretation of the syntactic MMN effect in terms of a lack of syntactic priming (see also Discussion to Experiment 1A in Section 6.1.3).

The activations of left middle temporal gyrus and right inferior frontal gyrus in the phrase structure condition are more difficult to interpret in terms of underlying syntactic operations. Like agreement processing, phrase structure processing is usually associated with activations in left superior temporal and inferior frontal brain regions (Gross et al., 1998; Embick, Marantz,

Miyashita, O'Neil, & Sakai, 2000; Friederici et al., 2003). The left middle temporal gyrus is sporadically reported to be co-activated in fMRI studies varying the degree of syntactic complexity (Just, Carpenter, Keller, Eddy, & Thulborn, 1996; Keller, Carpenter, & Just, 2001; Newman et al., 2003; Friederici, Bahlmann, et al., 2006). The right inferior frontal gyrus has been associated with the processing of prosodic information (Meyer, Alter, & Friederici, 2003; Friederici & Alter, 2004). Both of these functional interpretations appear implausible with respect to the current stimulus material that was restricted to two-word utterances of very low complexity and rigidly controlled for any acoustic differences. At best, it could be speculated that variations in complexity (and hence the left middle temporal activation) are induced by the fact that the incorrect utterances in the phrase structure condition require another element to fulfill phrase structure constraints (e.g.: "ein faltet" [a folds] → "ein Mann faltet" [a man folds]) as opposed to the correct utterances and the utterances from the agreement condition. Furthermore, the right inferior frontal gyrus may have been drawn upon because the differentiation between standard and deviant stimulus in the phrase structure condition was mainly determined by a vowel change (i.e. [ə] vs. [ɐ]) mediated by voiced and therefore prosodic acoustic parameters, as opposed to the unvoiced acoustic information contained in the suffix change in the agreement condition. These speculations are however rather stimulus specific and do not contribute much to the knowledge about neural sources supporting phrase structure processing in general.

Peak latency differences according to violation type The peak-based analysis applied for the present data set allowed for a direct statistical evaluation of the peak latency differences between the MMNm responses in the agreement and phrase structure condition. It showed that the MMNm responses in the agreement condition peaked significantly earlier than those in the phrase structure condition. This latency difference was consistent across Experiment 1 and 2. As argued in the discussion of Experiment 1B (see Section 6.2.3), it is most likely due to the delayed perceptibility of the acoustic change in the phrase structure stimuli caused by the fact that the first phoneme after the DP is the same in both standard and deviant stimulus. Interestingly, the present data revealed that the peak latency effect was largely mediated by the left temporal areas under investigation. This observation can be understood in terms of the superior temporal processing capacity of the left hemisphere (for a review, see Nicholls, 1996).

Limitations of the applied analysis In view of the lack of statistically significant spatial differentiations of the two investigated violation types, it should be noted that the applied analysis entails methodological difficulties that may have affected the current results. First, the number and locations of the ROIs selected for the statistical analysis of the BSCD data are fairly arbitrary. Although constraints for ROI definition were based on both previous empirical evidence and presently observed activation patterns, it can by no means be guaranteed that the selected ROIs covered all regions involved in the syntactic MMNm effects. Second, the analysis of the BSCD time courses merely captures information about the dipole strength (as reflected in amplitude variations), whereas differences in the direction of the dipoles are disregarded. However, such differences could indicate the activation of different neuronal populations even if these are located within the same area. Thus, the fact that each of the tested ROIs revealed a main effect of grammaticality without showing strong differentiations according to violation type does not exclude the possibility that the two underlying syntactic subprocesses were nevertheless subserved by different neuronal populations. And third, the analysis was restricted to the time window of the MMNm for economic reasons. Although certainly present and worth investigating, later effects were not covered and excluded from further discussion.

8.4 Summary and Conclusions

The present MEG experiment aimed at a specification of the respective brain regions involved in the topographically different syntactic MMN effects in response to agreement and phrase structure manipulations that had been observed in Experiment 1. The acoustic changes between the standard and deviant speech stimuli reliably elicited the MMNm in each condition. Furthermore, the MMNm was consistently modulated by the grammaticality of the deviant stimuli, a finding that replicates the results from the corresponding EEG experiment and confirms the early and automatic nature of processes involved in the establishment of local syntactic agreement relations as well as phrase structure building. However, the ROI based analysis of BSCD solutions computed from the ERFs did not result in the aspired statistically secured spatial differences in the activations in response to the two violation types. A hypothesis-driven analysis of the data according to violation type revealed spatial tendencies that are not implausible with respect to the differential scalp distributions obtained in Experiment 1 and allowed for speculations concerning a functional separation of the underlying syntactic processes. In par-

ticular, the left inferior frontal activation in response to agreement violations supports the idea that syntactic processing in this condition strongly relies on local syntactic priming. The left middle temporal and right inferior frontal activations observed in the phrase structure condition suggested rather stimulus-specific involvements of complexity-related and prosodic operations.

Chapter 9

Experiment 3: A little less repetition ...

The syntactic MMN(m) effects reported in Chapters 6 and 8 provide strong evidence for the hypothesis that the processing of phrase structure and syntactic relations is reflected in equally fast and automatic ERP responses provided that the acoustical parameters of the stimuli and the time-locking of the ERPs are controlled for, and that the syntactic dependencies under investigation are implemented at the local level. Furthermore, the topographical differences between the syntax effects in Experiment 1 as well as the BSCD results of the Experiment 2 suggested a structural differentiation of the underlying brain mechanisms that points towards functional differences between the two syntactic subprocesses.

However, the restrictive and highly repetitive nature of the syntactic MMN paradigm makes generalizing conclusions and comparisons with other relevant ERP studies rather difficult. In particular, it cannot be excluded that the frequent repetition of the stimuli accelerated syntactic analysis. In this sense, the lack of a temporal difference between phrase structure and syntactic-relational processing in the MMN results could reflect a repetition-induced ceiling effect rather than natural syntax processing.

The aim of Experiment 3 was to see whether the early negative ERP deflection observed in response to local subject-verb agreement as well word category violations would persist outside the repetitive oddball paradigm. This question was approached by increasing the variability of the speech stimuli and presenting them in a non-repetitive paradigm with an equal proportion of correct and incorrect utterances. All other experimental parameters, including the properties of the speech stimuli, the acoustic balancing of the conditions, and the visual distraction by means of a silent movie, were left unchanged. The presentation of variable, non-repetitive two-word

utterances precludes that the syntax processor "tunes in" on the analysis of a specific utterance, as it may have been the case in the syntactic MMN experiments. At the same time, it most likely affects the amount of attention drawn towards the acoustic stimulation, as a sequence of variable utterances is much more difficult to ignore than a repetitive sequence of the same utterance occasionally interrupted by a slight modification of that utterance. Accordingly, the attentional state in the current experiment with respect to the syntactic manipulations can be regarded as passive rather than automatic¹.

Based on the assumptions that the relative timing of phrase structure building and syntactic-relational processing is determined by the locality of the syntactic dependency to be processed rather than by its type, and that this is not only the case within the settings of a repetitive MMN paradigm, the following two hypotheses were tested in the current experiment:

1. An early negative ERP deflection is expected to occur in response to local syntactic violations implemented in variable two-word utterances, irrespectively of the violation type.
2. As suggested by the previous syntactic MMN evidence, the topography of this early syntactic ERP effect should differ between the two parts of the experiment, with a left anterior focus in the agreement condition and a more widespread distribution in the phrase structure condition, thus indicating an involvement of different cortical generators in the processing of the two violation types.

In correspondence to Experiments 1 and 2, the effect of the two types of syntactic manipulations on the ERP responses were tested in two separate, acoustically balanced parts. Part A, described in Section 9.1, investigated the passive processing of subject-verb agreement in variable two-word utterances. Part B tests phrase structure processing under otherwise comparable conditions and is presented in Section 9.2. In contrast to the MMN studies, the recording time was quite short due to the different presentation mode. For economical reasons, Part A and B were therefore run within the same experimental session. The order in which the two parts were presented was nonetheless counterbalanced across participants, with an equal number of male and female participants in each group. The findings of the two parts will be discussed conjointly in Section 9.3.

¹The results of Experiment 3 and 4 were conjointly published in the *Journal of Cognitive Neuroscience* (Hasting & Kotz, 2008)

9.1 Experiment 3A: Passive processing of subject-verb agreement in variable two-word utterances

9.1.1 Methods

Participants 24 healthy native speakers of German (12 male, 12 female) aged 19 - 30 (mean age = 25.29, SD = 2.89) agreed to participate. All of them were right-handed, as determined by the Edinburgh Inventory (Oldfield, 1971). The mean LQ was 91.67 (SD = 8.06). Participants received 7 Euros per hour as compensation for their efforts.

Design and procedure In contrast to the syntactic MMN experiments, the design of the present experiment employed all of the 50 items included in the AGREEMENT set. Table 9.1 clarifies the experimental design by assigning the stimuli from example 1 (page 42) to the respective conditions. Possible influences of the acoustic parameters of the suffix determining the grammaticality of the utterance are still controlled in this design as the condition factors (GRAM and SUF) are fully crossed.

Table 9.1: Experimental design for testing the processing of subject-verb agreement in variable two-word utterances (GRAM = grammaticality, SUF = suffix, cor = correct, inc = incorrect)

AGREEMENT			
Condition	Stimulus Example	Factor Level	
		GRAM	SUF
a	er kegelt	cor	-t
b	*er kegelst	inc	-st
c	du kegelst	cor	-st
d	*du kegelt	inc	-t

The 200 two-word utterances (50 items x 4 conditions) were presented in a pseudo-randomized order in two blocks of 100 trials each. The randomization complied with the rules that a) at least 10 trials had to occur between any two conditions with identical items, b) a maximum of 3 items of the same condition were allowed in succession, c) a maximum of 3 correct and incorrect conditions were allowed in succession, and d) the four conditions were distributed

equally between the two presentation blocks. Separate randomizations were prepared for each participant. The trials were presented in continuous sequences with a constant ISI of 2000 ms. Participants were instructed to focus their attention on a silent movie and to ignore the auditory input. To reduce artifacts, they were also asked to refrain from moving, swallowing or blinking to the greatest possible extent for the duration of each block. In between blocks, participants were allowed to take breaks for as long as they required. The overall duration of this experiment amounted to approximately 12 minutes of recording time plus the duration of the break between the two blocks.

The recording and analysis of the ERPs abided by the description given in Section 5.2. ERPs were calculated for an epoch of 1000 ms (-100 to 900 with respect to DP). The length of the short sections submitted to the preliminary timeline analysis was 50 ms.

9.1.2 Results

Visual inspection and timeline analysis The grand average ERP waveforms in Figure 9.1 show a broadly distributed negativity with an early onset and a peak at about 150 ms in response to utterances that contain a subject-verb agreement violation. This negativity is sustained until about 650 ms. Although the topographical difference maps seem to suggest a left anterior focus of this effect, the timeline analysis merely confirmed a significant main effect of the factor GRAM for the sections between 150 and 600 ms at the lateral electrodes and between 100 and 600 ms at the midline, as well as an interaction of REG and GRAM in the sections between 350 and 600 ms for both groups of electrodes. Figure 9.2 contrasts the ERP responses to acoustically different suffixes (-*t* vs. -*st*) across grammaticality. Two short negativities in response to -*st* as opposed to -*t* are observable, one around 100 ms and the other one around 300 ms after the divergence point (i.e. the onset of the suffix). They are reflected in the timeline analysis by significant main effects of SUF for the sections from 100 to 150 ms and from 300 to 350 ms. In addition to the effects visible in the waveforms, the timeline analysis revealed a significant three-way interaction of the factors REG, SUF and GRAM between 400 and 650 ms at the lateral electrodes.

To account for the different topography of the early and the late part of the observed negativity in response to incorrect stimuli, the detailed ANOVA was conducted on the two time windows between 100 and 300 ms and 300 and 600 ms.

Time window analysis, 100 - 300 ms This time window covered the early effect of GRAM as well as the brief effect of SUF observed in the preliminary analysis. However, the global ANOVA merely yielded a highly significant main effect of GRAM that confirmed a stronger negative ERP deflection in response to grammatically incorrect as opposed to correct utterances (lateral: $F_{1,23} = 19.50$, $p < 0.001$, $\Delta = 0.7$; midline: $F_{1,23} = 15.03$, $p < 0.001$, $\Delta = 0.9$). Contrary to the visual impression of a left anterior focus but in line with the timeline analysis, there was no statistically significant topographical differentiation of this early negativity.

Time window analysis, 300 - 600 ms The sustained negativity observed in response to the incorrect utterances was reflected in a highly significant main effect of GRAM in this later time window (lateral: $F_{1,23} = 26.38$, $p < 0.0001$, $\Delta = 1.0$; midline: $F_{1,23} = 19.73$, $p < 0.001$, $\Delta = 1.2$). An interaction with REG (lateral: $F_{1,23} = 4.98$, $p < 0.05$; midline: $F_{1,23} = 5.79$, $p < 0.05$) indicated that this effect was stronger over anterior than over posterior scalp sites (lateral: $F_{1,23} = 27.46$, $p < 0.0001$, $\Delta = 1.3$ vs. $F_{1,23} = 8.93$, $p < 0.01$, $\Delta = 0.7$; midline: $F_{1,23} = 27.20$, $p < 0.0001$, $\Delta = 1.6$ vs. $F_{1,23} = 7.23$, $p < 0.05$, $\Delta = 0.9$), a topographical focus that is clearly visible in the second map in Figure 9.1. The three-way interaction of the factors REG, SUF and GRAM that had been observed in the timeline analysis did not persist in the analysis of this larger time window.

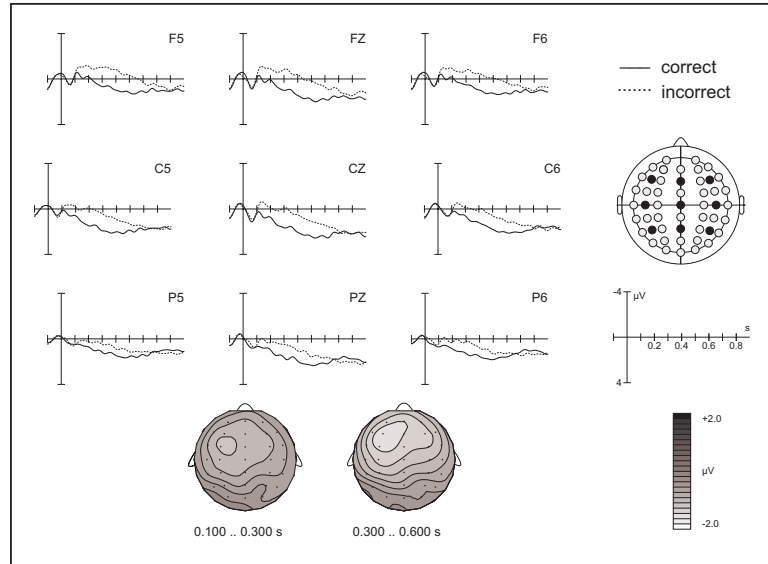


Figure 9.1: Experiment 3A: Main effect of GRAM collapsed over SUF. ERP waveforms and topographical difference maps (incorrect - correct) of the mean amplitude in the time windows selected for statistical analysis.

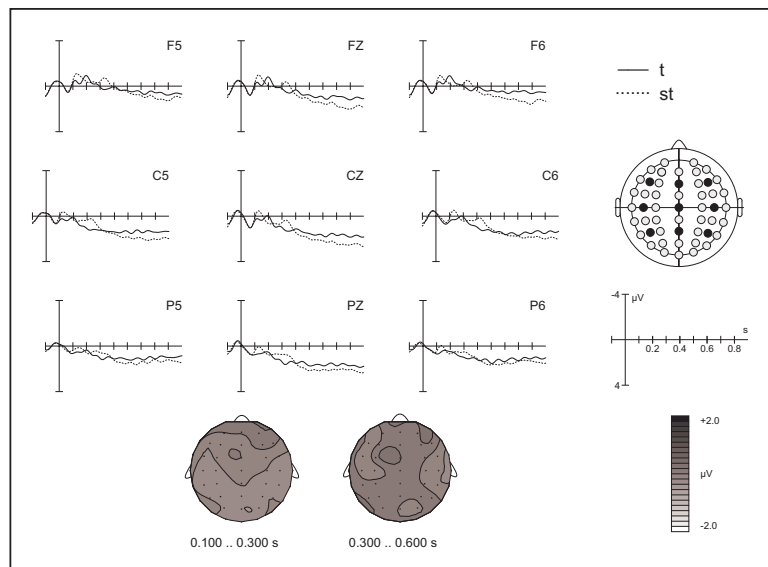


Figure 9.2: Experiment 3A: Main effect of SUF collapsed over GRAM. ERP waveforms and topographical difference maps ($st - t$) of the mean amplitude in the time windows selected for statistical analysis.

9.2 Experiment 3B: Passive processing of phrase structure in variable two-word utterances

9.2.1 Methods

Participants As mentioned at the beginning of this chapter, Experiment 3A and 3B were conducted within-subject in one recording session. The participants of Experiment 3B were therefore identical to those in Experiment 3A.

Design and procedure The only difference in the experimental parameters as compared to Experiment 3A was the replacement of the stimuli of the AGREEMENT set by those of the PHRASE STRUCTURE set. The experimental design is clarified in Table 9.2. The critical information with respect to the grammaticality of the two-word utterances is now the word category of the second word. Again, the condition factors GRAM and CAT are fully crossed to control for possible influences of the acoustic differences on early ERP effects.

Table 9.2: Experimental design for testing phrase structure processing in variable two-word utterances (GRAM = grammaticality, CAT = word category, cor = correct, inc = incorrect)

PHRASE STRUCTURE			
Condition	Stimulus example	Factor Level	
		GRAM	CAT
a	er kegelt	cor	verb
b	*er Kegel	inc	noun
c	ein Kegel	cor	noun
d	*ein kegelt	inc	verb

9.2.2 Results

Visual inspection and timeline analysis The effect of the word category violations in this experiment is displayed in Figure 9.3. It is strikingly similar to the effect of the subject-verb agreement manipulations in Experiment 3A (see Figure 9.1). Grammatically incorrect utterances elicited a broadly distributed early negativity with an onset around 100 ms and a sustained

latency until about 600 ms. This was reflected in significant main effects of GRAM for the timeline sections between 150 and 550 ms (both lateral and midline analyses). Additionally, visual inspection of the contrast between the responses to the two word categories seems to suggest a brief early negativity for verb endings as opposed to nouns (see Figure 9.4). However, the timeline analysis did not confirm any early effects involving the factor CAT. Instead, an interaction between CAT and GRAM reached significance in the sections between 350 to 850 ms (lateral) and 350 to 600 ms (midline). The additional Figures 9.5 and 9.6 visualize this interaction by plotting the GRAM effects per CAT.

Based on the results from the timeline, the time windows for the hierarchical statistical analysis were shifted by 50 ms as compared to Experiment 3A.

Time window analysis, 150 - 350 ms The early negativity in response to the incorrect utterances was reflected in a highly significant main effect for GRAM (lateral: $F_{1,23} = 23.41$, $p < 0.0001$, $\Delta = 0.8$; midline: $F_{1,23} = 21.16$, $p < 0.001$, $\Delta = 1.1$). Like in Experiment 3A, there was no interaction with any topographical factor, despite the visual impression of a left anterior focus in the topographical difference map. As already suggested by the timeline analysis, no effects involving the factor CAT were obtained in this early time window.

Time window analysis, 350 - 650 ms The second time window also showed a significant main effect for GRAM that confirmed the sustained negativity in response to grammatically incorrect utterances (lateral: $F_{1,23} = 11.09$, $p < 0.01$, $\Delta = 0.8$; midline: $F_{1,23} = 6.93$, $p < 0.05$, $\Delta = 0.9$). However, the resolution of a CAT x GRAM interaction (lateral: $F_{1,23} = 6.60$, $p < 0.05$; midline: $F_{1,23} = 6.27$, $p < 0.05$) revealed that this negativity was only significant in response to nouns presented in incorrect context (lateral: $F_{1,23} = 19.71$, $p < 0.001$, $\Delta = 1.5$; midline: $F_{1,23} = 16.17$, $p < 0.001$, $\Delta = 1.7$). The analysis of the midline electrodes additionally revealed a marginally significant REG x GRAM interaction ($F_{1,23} = 4.42$, $p = 0.051$), which indicated that, similar to the sustained negativity in response to the agreement violations in Experiment 3A, the sustained negativity in response to word category violations showed an anterior tendency ($F_{1,23} = 10.63$, $p < 0.01$, $\Delta = 1.1$ vs. $F_{1,23} = 3.26$, $p = 0.08$, $\Delta = 0.7$).

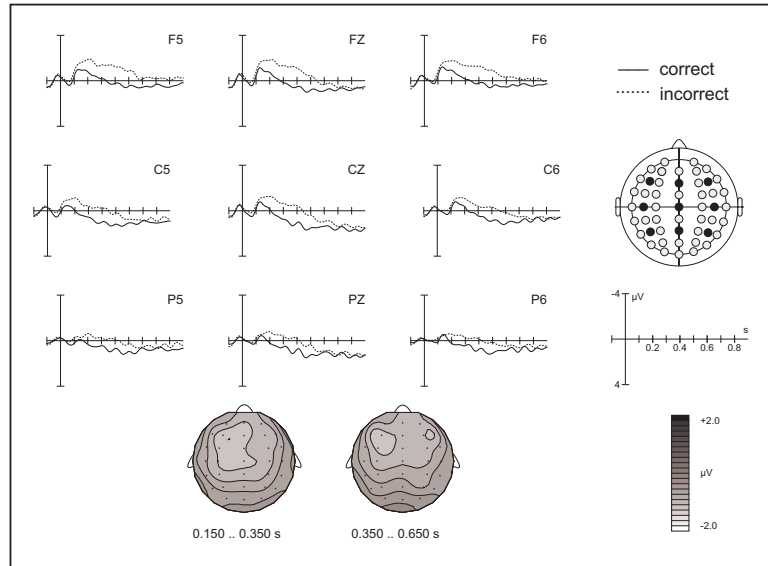


Figure 9.3: Experiment 3B: Main effect of GRAM collapsed over CAT. ERP waveforms and topographical difference maps (incorrect - correct) of the mean amplitude in the time windows selected for statistical analysis.

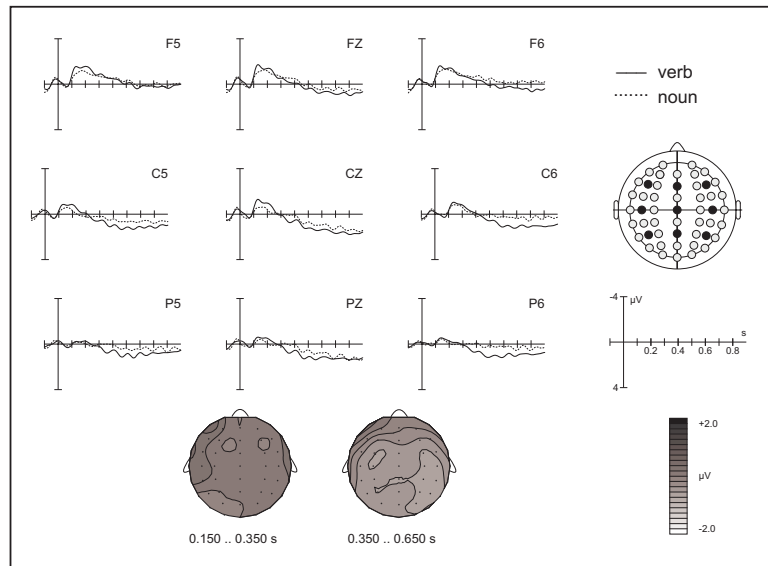


Figure 9.4: Experiment 3B: Main effect of CAT collapsed over GRAM. ERP waveforms and topographical difference maps (noun - verb) of the mean amplitude in the time windows selected for statistical analysis

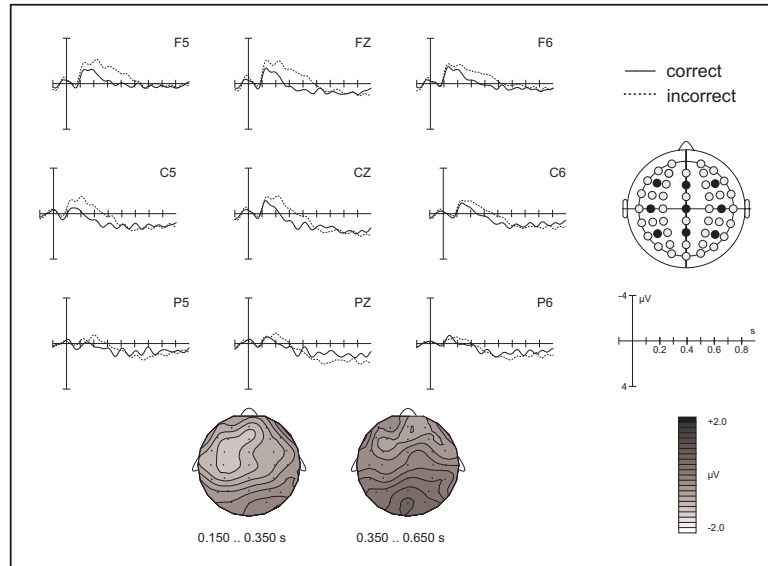


Figure 9.5: Experiment 3B: GRAM effect for verbs. ERP waveforms and topographical difference maps (incorrect - correct) of the mean amplitude in the time windows selected for statistical analysis.

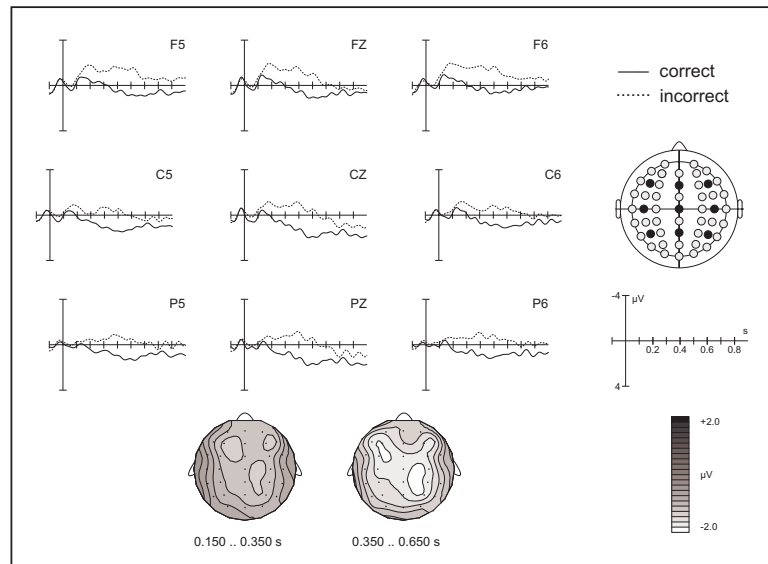


Figure 9.6: Experiment 3B: GRAM effect for nouns. ERP waveforms and topographical difference maps (incorrect - correct) of the mean amplitude in the time windows selected for statistical analysis

9.3 Discussion

Early syntactic negativities: Timing Both subject-verb agreement (Experiment 3A) and word category violations (Experiment 3B) elicited a highly significant negativity with an invariably early onset at approximately 100 ms. In confirming Hypothesis 1, this finding shows that the variability of the stimulus material and the equal proportion of correct and incorrect utterances in the presented sequences did not affect the onset latency of the negativity in response to either of the violation types. The current result proves that the unusually early syntactic-relational effect observed in the present as well as in previous syntactic MMN studies (Pulvermüller & Shtyrov, 2003; Shtyrov et al., 2003; Menning et al., 2005; Pulvermüller et al., 2008) is not restricted to the repetitive nature of the MMN paradigm. This observation lends further support to the notion that the relative timing of ERP effects representing specific syntactic subprocesses is influenced by methodological factors more than by their linguistic classification. In the present data, the effect of the word category violations occurred even slightly later than that of the subject-verb agreement violations. This contradicts earlier ERP findings (e.g. Rossi et al., 2005) as well as the assumptions of the *Neurocognitive Model of Auditory Sentence Comprehension* (Friederici, 2002). However, as in the syntactic MMN studies presented in Chapters 6 and 8, this slight delay may have been caused by differences in the stimulus characteristics rather than by a linguistically relevant difference between the two violation types. At the DP in the agreement condition, the system is confronted with one of two critical phonemes (-t vs. -st) that can instantaneously be identified as correct or incorrect in the given context. The stimulus material in the phrase structure condition is, however, more heterogenous. In some cases, the grammaticality of the utterances results from the presence or absence of a phoneme (e.g. *kegelt* vs. *Kegel_*). It is an established fact in the ERP literature that the omission of an expected acoustic event is more difficult and thus takes longer to detect than the occurrence of an unexpected acoustic event (Nordby et al., 1994; Sabri & Campbell, 2000). In other cases, as in the item used in the MMN studies, the divergent element comprised the entire second syllable of the critical word (e.g. *fal-tet* vs. *Fal-ter*) due to a change in vowel quality. For this subset of items (14 out of the 50, as indicated by the column "DP = early" in the list of items provided in the appendix), the point of actual violation detection may have been delayed until slightly after the acoustic DP. Furthermore, the phrase structure condition involves a greater amount of phonetic variation than the agreement condition due to the differ-

ent noun endings (-*el* and -*er*, again, see appendix) that make it more difficult for the system to arrive at specific phonological expectancies. Taken together, these three factors may have caused a larger variance and a greater latency jitter in the responses to the word category violations as compared to the agreement violations. Nevertheless, both types of syntactic violations reliably elicited negativities well before 200 ms. This finding substantiates the existence of early syntactic processing mechanisms for phrase structure and local agreement relations even outside the repetitive syntactic MMN setting.

Early syntactic negativities: Topography The topographical differences of the syntactic ERP effects of phrase structure versus agreement manipulations that had been observed consistently in the experiments on the syntactic MMN(m) were not replicated in the current experiment. By visual inspection, the effects of GRAM showed a left anterior focus in both parts of the experiment. However, the statistical analyses resulted in main effects of GRAM only, thus providing no confirmation for this topographical focus of the effects. The current data are therefore inconsistent with Hypothesis 2. At this point, it should be noted again that there is strictly no way to make reliable inferences about the cortical generators underlying a given ERP scalp distribution due to the inverse problem introduced in Section 2.1.1. The fact that there is a theoretically infinite number of possible source solutions for a given topography also includes the possibility that topographically identical ERP effects are caused by different cortical generators. Thus, although the present data do not provide evidence for a structural separation of the generators underlying the processing of syntactic-relational and phrase structure information, they still cannot disprove the possibility that the two syntactic subprocesses are supported by different brain regions.

Early syntactic negativities: Automaticity The present experiment shows again that the brain is able to detect local violations of both phrase structure and agreement without explicitly focusing on this task. Just like in the MMN experiments, the participants were instructed to divert their attention away from the acoustic stimulation towards the silent movie. However, the claim of automaticity certainly cannot be as strong for the present as for the MMN experiments. As pointed out in the introduction to this chapter, variable utterances are likely to be more attention-catching than the monotonous sequences presented in the MMN paradigm. Furthermore, the claim cannot be based on the modulation of an ERP component known to reflect

automatic processing as in the case of the MMN. However, the early onset of the negativity in response to local subject-verb agreement and word category violations speaks in favour of a rather automatic mechanism underlying the detection of the two violation types. The lack of a P600 in either case further underlines this interpretation, as it shows that no attentive processing and repair of the syntactic violations (Hahne & Friederici, 1999, 2002) has taken place.

Sustained negativities An unexpected finding of the current experiment was the extended latency of the negativities in response to incorrect utterances at frontal electrode sites. Although similar effects were observed in the syntactic MMN experiments of the present study as well as in several other ERP instances involving violations of specificity constraints (Neville et al., 1991), subject-verb agreement violations (Pulvermüller & Shtyrov, 2003) or word category violations (Friederici et al., 1996), it has remained unresolved with regard to its functional relevance in most cases. As elaborated in the discussion of Experiment 1A, the interpretation in terms of a working memory effect provided by Friederici et al. (1996) does not hold in the present case, in which working memory load was reduced to a minimum due to the shortness of the utterances. In face of the absence of a syntactic or stimulus-related task in the present experiment, it could instead be argued that the sustained frontal negativity reflects processes complementary to those that would lead to the P600 effect under active task demands. Interestingly, the sustained negativity shows considerable similarity in wave shape and topography to the processing negativity (PN / Nd) observed in response to task-relevant stimuli in selective attention paradigms (e.g. Hansen & Hillyard, 1983; Teder, Alho, Reinikainen, & Näätänen, 1993; Eimer, 1999; Teder-Sälejärvi, Münte, Sperlich, & Hillyard, 1999). This component is taken as a sign of the selection of an incoming stimulus for further processing. The selection is thought to be based on a comparison between the features of the stimulus against a neuronal representation of the target features (Alho, Töötölä, Reinikainen, Sams, & Näätänen, 1987). With regard to the present setting, it appears plausible to assume that the sustained negativity reflects the automatic allocation of neuronal resources to the processing of stimuli that do not match with existing syntactic templates. In Experiment 3B, the sustained negativity was particularly pronounced for nouns presented in incorrect context. An inspection of the topographical difference maps of this effect (see Figure 9.6) further suggests a shift towards posterior scalp sites, although this was not reflected in the statistical analysis. Based on similar observations in Experiment 1, it is conceivable that the sustained negativity in this condition is superimposed

by a N400 (see page 69) indicating enhanced lexical search or semantic integration difficulties in response to the [NP + NP] combination (e.g. **er Kegel* [he cone]). This emphasises again the different roles of verbs and nouns during sentence comprehension.

9.4 Summary and Conclusions

Experiment 3 showed that local subject-verb agreement and word category violations as implemented in variable two-word utterances are detected equally fast and automatically if acoustic parameters and the violation point are being controlled for. Thus, the present data replicated the findings from Experiment 1 and 2 as well as from previous syntactic MMN studies and extended these findings by showing that early syntactic-relational processing is not restricted to the repetitive nature of the MMN paradigm. By increasing the variability in the speech input, the adaptations of the paradigm took a small step towards the conditions encountered in the natural language environment, thus enhancing the external validity of the findings as compared to syntactic MMN studies. In contrast to Experiment 1 and 2, the present experiment could however not provide any evidence in favour of a structural separation of the mechanisms underlying phrase structure and syntactic-relational processing.

The sustained negativities observed in both parts of the experiment were not anticipated in the hypotheses to the current investigation. The fact that similar effects were also observed in other experiments on syntax processing suggests that it may be worthwhile to scrutinize the preconditions of their occurrence in future studies to substantiate the tentative interpretations given in the present context.

Chapter 10

Experiment 4: ... a little more action!

The experiments reported so far investigated syntax processing outside the focus of attention. Participants were distracted from the auditorily presented two-word utterances by means of a silent movie. Despite this distraction the brain responded to phrase structure and agreement violations with an invariably early negative deflection that indicates rather automatic processing of the syntactic anomalies. Although it can certainly not be excluded that participants still occasionally listened to the speech stimuli and consciously perceived their grammatical (in)correctness, the lack of a stimulus-related task renders it unlikely that the syntactic aspects of the utterances were processed any more than they would have been in a natural situation requiring focused visual attention in the presence of background noise. This is underlined by the consistent absence of a late positivity (P600) that would be expected to occur if the violations had been detected and processed attentively (Osterhout & Holcomb, 1992; Hagoort et al., 1993; Friederici et al., 1996; Hahne & Friederici, 2002).

In spite of their internal consistency the findings as presented so far are difficult to integrate with previous ERP findings on syntax processing, as the vast majority of studies focused the participants' attention on the language input by comprehension questions, probe verifications, or correctness or acceptability judgement tasks (see for instance Neville et al., 1991; Friederici et al., 1996; Hahne & Friederici, 1999; Rossi et al., 2005). It is unquestionable that an experimental task critically influences cognitive processing and therefore greatly affects the obtained ERP responses, attention being one of the most important mediating factors (Hillyard et al., 1973; Hackley et al., 1990; Woldorff & Hillyard, 1991). As reported in Section 4.2, some of the ERP studies on syntax processing that directly manipulated the experimental task report a

task-related susceptibility of especially those processes that have been assigned to later stages in analysis, i.e. syntactic-relational processing and syntactic revision and repair (Gunter & Friederici, 1999; Hahne & Friederici, 2002).

With regard to the present study, it remains to be shown that the early syntactic ERP effects in response to word category and subject-verb agreement violations are reflections of a mechanism that is task independent, and in this sense truly automatic. To this end, the final experiment in this dissertation investigates phrase structure building and syntactic-relational processing in variable two-word utterances under the demands of a syntax-related task. While retaining the strict control of the acoustic stimulus properties, this experiment thus comes closest to the standard ERP violation paradigm applied in those studies that most influenced our current understanding of the temporal dynamics of syntax processing. Focusing the participants' attention on the two-word utterances may also shed light on the modulating effects of the critical word's category on the ERP responses that were observed in Experiment 1B and 3B. If these effects indeed were due to the semantic properties of the stimuli as speculated in Section 9.3, they should be replicated and possibly enhanced under attentive processing.

The experiment was designed in close relation to Experiment 3. The only difference was that the visual distraction task employed in the previous experiments was replaced by a correctness judgement task that draws the attention of the participants directly to the syntactic properties of the two-word utterances. The task prolonged the recording time considerably; therefore, similar to Experiment 1 and 2, two separate experimental sessions were held at intervals of at least one week. Like in the previous experiments, the order in which the two parts were presented was counterbalanced across participants.

The following hypotheses were formulated for this experiment:

1. In accordance with the previous experiments of the current study, an early negative deflection with an onset at approximately 100 ms is expected to occur in response to both subject-verb agreement and word category violations, thus demonstrating the task independence of these effects.
2. Based on the findings of other studies that tested the effects of syntactic violations under active task demands, a P600 is expected to be elicited in response to incorrect utterances as a reflection of active repair processes.

3. In Experiment 4B, the critical word's category is expected to modulate ERPs in addition to the above effects due to enhanced lexico-semantic processing of the nouns.

10.1 Experiment 4A: Attentional processing of subject-verb agreement in variable two-word utterances

10.1.1 Methods

Participants 24 healthy native speakers of German (12 male, 12 female) aged 20 - 29 (mean age = 24.71, SD = 2.75) agreed to participate. All of them were right-handed, as determined by the Edinburgh Inventory (Oldfield, 1971). The mean LQ was 91.67 (SD = 11.67). Participants received 7 Euros per hour as compensation for their efforts.

Design and procedure Apart from the task, the design was the same as in Experiment 3A (see Table 9.1). After having been seated in the acoustically and electrically shielded chamber and equipped with headphones and a response pad, participants received written instructions to fixate the star on the screen, to listen to the presented utterance, and to judge whether it was correct or incorrect by pressing either the left or the right button with their left or right thumbs as soon as the star was replaced by two smileys. The assignments of the two judgements to the buttons was counterbalanced across participants. Figure 10.1 shows one exemplary trial to clarify the sequence of events encountered by the participants. The star served both as a preparatory stimulus and as a means to prevent eye movements during the period of interest. It outlasted the auditory stimulus by 2000 ms to keep syntax-related ERP responses separate from motor responses. To further reduce artifacts, participants were instructed to blink and swallow only when the star was absent from the screen.

The participants received a practice block of 16 items that did not occur during the experiment to make sure that they had understood and were able to follow the instructions. Following the practice block, the EEG recording was started and two experimental blocks of 100 trials each were presented. Between the two blocks, the participants were allowed to take a break. The randomization procedure for the order in which the utterances were presented was the same as in Experiment 3 (see page 108). Separate randomizations were prepared for each

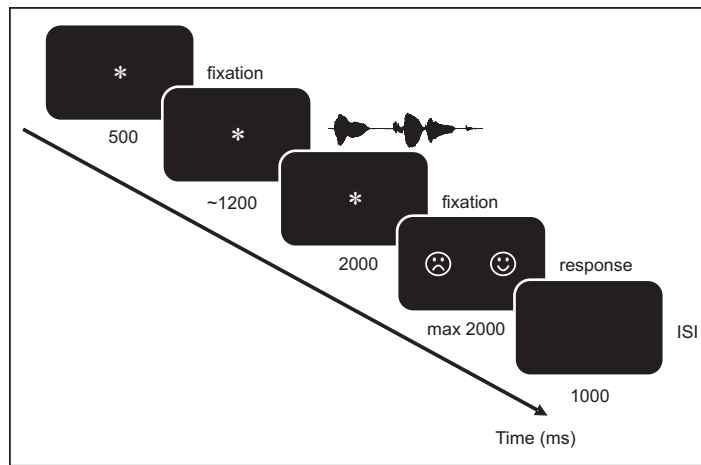


Figure 10.1: Sequence of events per trial

participant. The duration of the experiment including instructions, practice and experimental blocks and the break amounted to approximately 40 minutes.

ERPs were calculated for an epoch of 1000 ms (-100 to 900 with respect to DP). Trials for which the behavioral response was inappropriate (i.e. incorrect or too slow) were not included in the average ERPs. The timeline analysis was conducted on sections of 50 ms length.

10.1.2 Results

Behavioral responses The mean reaction time as measured from the response cue (i.e. the appearance of the two smileys) was 293 ms (SD = 115 ms). The mean error rate was 0.4 % (SD = 1.0 %). A repeated measure ANOVA including the two-level factors GRAM (correct vs. incorrect) and SUF (-*t* vs. -*st*) did not reveal any significant differences between the four conditions in either of these measures. While the reaction times certainly reflect a ceiling effect as participants were forced to delay their responses for 2 seconds, the high accuracy of the responses in all conditions substantiates the validity of the stimulus material. It further shows that the task was clear-cut and easy to accomplish.

ERPs: Visual inspection and timeline analysis Figure 10.2 presents the impact of the attended subject-verb agreement violations on the ERP responses. Incorrect utterances elicited a

prominent early negativity with an onset at about 100 ms and a latency of about 200 ms that is followed by a sustained positivity peaking at approximately 500 ms. This positivity seems to be maximal over the posterior electrodes of the midline. The impression of a biphasic response to agreement violations is clearly supported by the timeline analysis that reveals significant main effects of GRAM between 100 and 300 ms (negativity) and 350 and 650 (lateral) or 900 ms (midline; positivity). Furthermore, a significant interaction of REG and GRAM between 450 and 700 ms (both lateral and midline) points towards the suspected posterior focus of the late positivity.

Compared to the strong effects of the utterances' grammaticality, the ERPs in response to the two suffixes show merely very subtle differences (see Figure 10.3). The visual inspection of the waveforms seems to suggest a slightly longer latency of the early negativity in response to *-t* and a slightly stronger late positivity in response to *-st*. However, effects involving the factor SUF were merely marginally significant ($p < 0.1$) in the timeline analysis with the exception of a significant main effect between 450 and 600 ms for the midline and a brief but highly significant REG x SUF interaction in the 500 - 550 ms section for the lateral electrodes.

To test the statistical significance of the condition effects on the early negativity and the late positivity, the two time windows between 100 and 300 ms and 350 and 900 ms were subjected to the detailed ANOVA.

ERPs: Time window analysis, 100 - 300 ms The time window covering the early negativity contained a highly significant main effect for GRAM that confirmed a strong negative ERP deflection in response to incorrect as compared to correct utterances (lateral: $F_{1,23} = 17.99$, $p < 0.001$, $\Delta = 1.3$; midline: $F_{1,23} = 14.69$, $p < 0.001$, $\Delta = 1.7$).

ERPs: Time window analysis, 350 - 900 ms A significant main effect of GRAM confirmed that ERP responses to incorrect utterances were more positive than those to correct utterances in the time window covering the late positivity (lateral: $F_{1,23} = 9.69$, $p < 0.01$, $\Delta = 0.6$; midline: $F_{1,23} = 13.55$, $p < 0.01$, $\Delta = 1.2$). A significant interaction with REG (lateral: $F_{1,23} = 7.0$, $p < 0.05$; midline: $F_{1,23} = 4.93$, $p < 0.05$) showed that this effect was only significant over posterior scalp sites (lateral: $F_{1,23} = 15.98$, $p < 0.001$, $\Delta = 1.1$; midline: $F_{1,23} = 16.96$, $p < 0.001$, $\Delta = 1.7$). The SUF effects observed in the waveforms and timeline analysis were not retained in the analysis of the larger time windows.

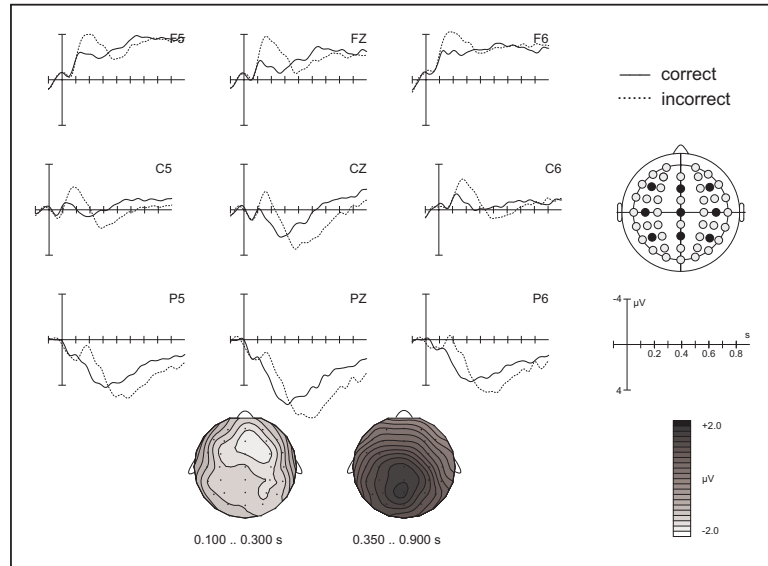


Figure 10.2: Experiment 4A: Main effect of GRAM collapsed over SUF. ERP waveforms and topographical difference maps (incorrect - correct) of the mean amplitude in the time windows selected for statistical analysis.

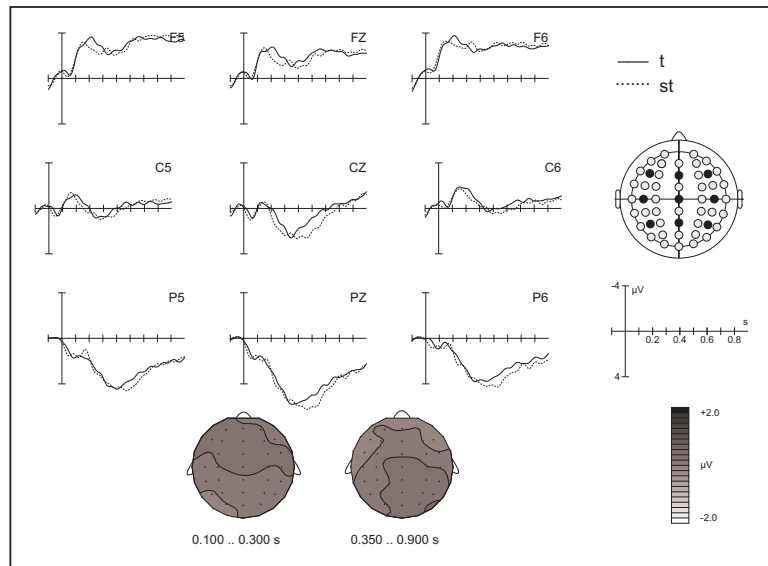


Figure 10.3: Experiment 4A: Main effect of SUF collapsed over GRAM. ERP waveforms and topographical difference maps ($st - t$) of the mean amplitude in the time windows selected for statistical analysis.

10.2 Experiment 4B: Attentional processing of phrase structure in variable two-word utterances

10.2.1 Methods

Participants As mentioned previously, the two parts of Experiment 4 were conducted within-subject in separate recording sessions. The participants of Experiment 4B were therefore identical to those in Experiment 4A. Again, they received 7 Euros per hour for their participation.

Design and procedure The experimental design was the same as in Experiment 3B (see Table 9.2). All other experimental parameters and the procedure were identical to Experiment 4A. Accordingly, participants judged the correctness of acoustically controlled two-word utterances manipulating phrase structure while ERPs were time-locked to the phonemes critical for the stimuli's grammaticality.

10.2.2 Results

Behavioral responses The mean reaction time was 298 ms (SD = 134 ms). The mean error rate was 0.3 % (SD = 1.0 %). A repeated measure ANOVA including the two-level factors GRAM (correct vs. incorrect) and CAT (verb vs. noun) revealed no significant differences between the four conditions in either of these measures. As in Experiment 4A, the reaction times probably reflect a ceiling effect due to the delayed response paradigm. Again, the high accuracy of the responses in all conditions substantiates the validity of stimulus material and task.

ERPs: Visual inspection and timeline analysis In contrast to the largely comparable results obtained in the two parts of Experiment 3, Experiment 4 showed considerable differences between the effects of agreement and phrase structure manipulations on the ERP responses. As can be inferred from a comparison between Figure 10.4 and Figure 10.2, both manipulations elicited an early negativity with a similar onset and latency in response to incorrect utterances that was followed by a positivity. However, the early negativity in response to the word category violations in the present part of the experiment displayed a strong focus over posterior scalp sites, as opposed to the rather anterior distribution of the effect observed in Experiment

4A. Furthermore, the effect on the late positivity was diminished in the present data. Accordingly, timeline analyses of the present data set showed a significant main effect for GRAM between 150 and 350 ms at both lateral and midline electrodes that was complemented with a REG x GRAM interaction. Additional interactions between REG and GRAM occurred between 600 and 900 ms at midline and between 200 and 400 ms at lateral electrode sites.

In addition to the grammaticality of the utterances, the word category of the critical word appeared to have quite a strong effect on the ERP responses (see Figure 10.5). Between approximately 200 and 500 ms, the waveforms were considerably more positive for inflected verbs than for nouns. This was reflected in a significant main effect for CAT in these sections. The lateral electrodes further showed a later effect of CAT (650 - 800 ms) as well as a CAT x GRAM interaction (600 - 800 ms) that is demonstrated in the additional Figures 10.6 and 10.7 and seems to be driven by a stronger posterior positivity in response to incorrect verb forms as opposed to a stronger (right-)anterior negativity in response to incorrect nouns.

As in the earlier experiments, manipulations of phrase structure affected the ERPs slightly later than agreement manipulations. Therefore, the first time window subjected to the detailed ANOVA of the current data set was shifted by 50 ms as compared to Experiment 4A. Additional time windows between 350 and 550 ms and 600 and 800 ms were analyzed to cover the second part of the CAT effect and the GRAM effect on the late positivity.

ERPs: Time window analysis, 150 - 350 ms A main effect of GRAM (lateral: $F_{1,23} = 18.05$, $p < 0.001$, $\Delta = 1.1$; midline: $F_{1,23} = 15.10$, $p < 0.001$, $\Delta = 1.4$) confirmed the significance of the early negativity observed in response to incorrect utterances. A significant REG x GRAM interaction for the lateral electrodes ($F_{1,23} = 7.19$, $p < 0.05$) attested the posterior focus of the early negativity (anterior: $F_{1,23} = 8.16$, $p < 0.01$, $\Delta = 0.8$ vs. posterior: $F_{1,23} = 23.82$, $p < 0.0001$, $\Delta = 1.3$). Additionally, the early grammaticality effect was specified by an interaction between REG x CAT x GRAM ($F_{1,23} = 4.58$, $p < 0.05$) as follows: For utterances in which the critical word was a noun, the grammaticality effect only reached significance over the anterior half of the scalp ($F_{1,23} = 4.51$, $p < 0.05$, $\Delta = 0.8$). If however the utterance contained an inflected verb form, the grammaticality effect was broadly distributed with a strong focus over posterior scalp sites (anterior: $F_{1,23} = 5.75$, $p < 0.05$, $\Delta = 0.7$ vs. posterior: $F_{1,23} = 43.02$, $p < 0.0001$, $\Delta = 1.7$). For the midline electrodes, this interaction was only marginally significant ($F_{1,23} = 4.05$, $p = 0.056$). Nevertheless, its resolution confirmed the tendency observed for the lateral electrodes.

Another effect of the word category observable within the range of this early time window is the onset of the enhanced positivity in response to inflected verb forms. It is reflected in a significant main effect of CAT that is spread across both lateral and midline electrodes (lateral: $F_{1,23} = 18.05$, $p < 0.001$, $\Delta = 1.1$; midline: $F_{1,23} = 15.10$, $p < 0.001$, $\Delta = 1.4$).

ERPs: Time window analysis, 350 - 500 ms This time window covered the second part of the word category effect. Like the early time window, it contained a main effect of CAT (lateral: $F_{1,23} = 11.41$, $p < 0.01$, $\Delta = 0.6$; midline: $F_{1,23} = 11.26$, $p < 0.01$, $\Delta = 1.1$), which showed that the ERP in response to inflected verbs continued to be significantly more positive. However, the resolution of a significant interaction with the factor REG (lateral: $F_{1,23} = 8.93$, $p < 0.01$; midline: $F_{1,23} = 7.98$, $p < 0.01$) yielded that this effect was now merely significant over posterior scalp sites (lateral: $F_{1,23} = 26.21$, $p < 0.0001$, $\Delta = 1.1$; midline: $F_{1,23} = 20.30$, $p < 0.001$, $\Delta = 1.5$).

ERPs: Time window analysis, 600 - 800 ms The statistical analysis of the late time window revealed a significant main effect of CAT at lateral electrodes ($F_{1,23} = 5.75$, $p < 0.05$, $\Delta = 0.4$) indicating that ERPs in response to verbs were again more positive relative to ERPs in response to nouns. An impact of GRAM in this time range became manifest in a significant interaction with CAT (lateral: $F_{1,23} = 5.78$, $p < 0.05$; midline: $F_{1,23} = 4.64$, $p < 0.05$) and in a marginally significant interaction with REG (lateral: $F_{1,23} = 4.14$, $p = 0.0535$; midline: $F_{1,23} = 4.75$, $p < 0.05$). The resolution of these interactions revealed that conditions in which the incorrect word was a verb resulted in a late posterior positivity (lateral: $F_{1,23} = 6.09$, $p < 0.05$, $\Delta = 0.8$; midline: $F_{1,23} = 7.44$, $p < 0.05$, $\Delta = 1.2$), whereas conditions in which the incorrect word was a noun produced a marginally significant anterior negativity (lateral: $F_{1,23} = 3.98$, $p = 0.0581$, $\Delta = 1.0$; midline: $F_{1,23} = 2.23$, $p = 0.1494$, $\Delta = 1.0$).

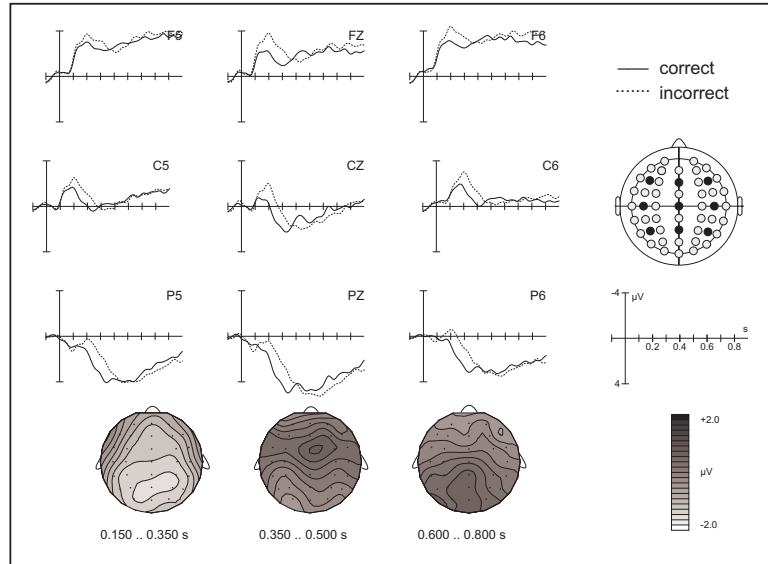


Figure 10.4: Experiment 4B: Main effect of GRAM collapsed over CAT. ERP waveforms and topographical difference maps (incorrect - correct) of the mean amplitude in the time windows selected for statistical analysis.

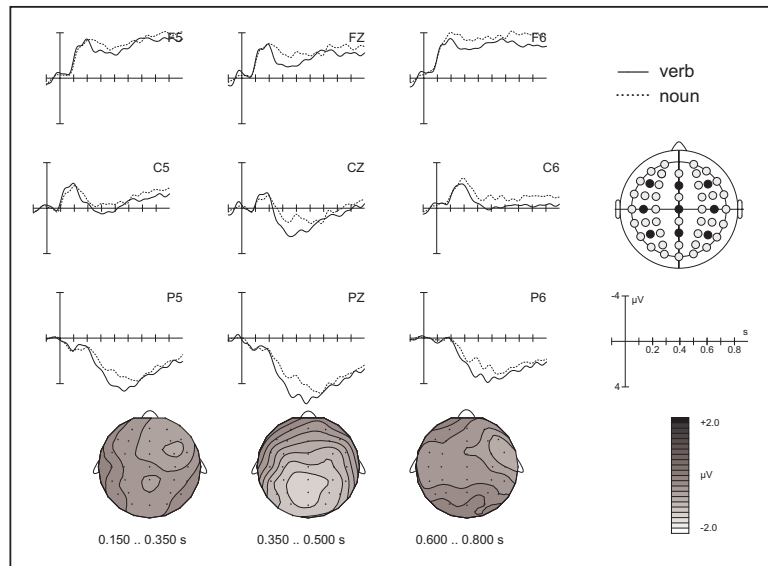


Figure 10.5: Experiment 4B: Main effect of CAT collapsed over GRAM. ERP waveforms and topographical difference maps (noun - verb) of the mean amplitude in the time windows selected for statistical analysis

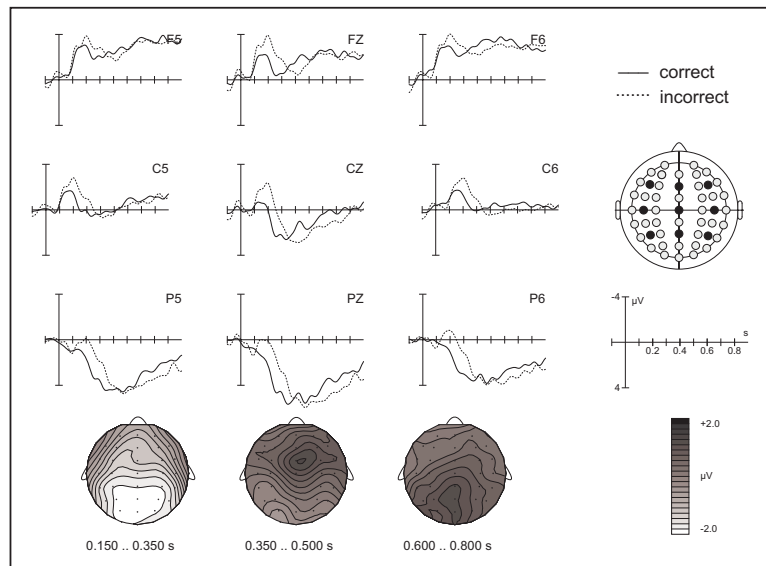


Figure 10.6: Experiment 4B: GRAM effect for verbs. ERP waveforms and topographical difference maps (incorrect - correct) of the mean amplitude in the time windows selected for statistical analysis.

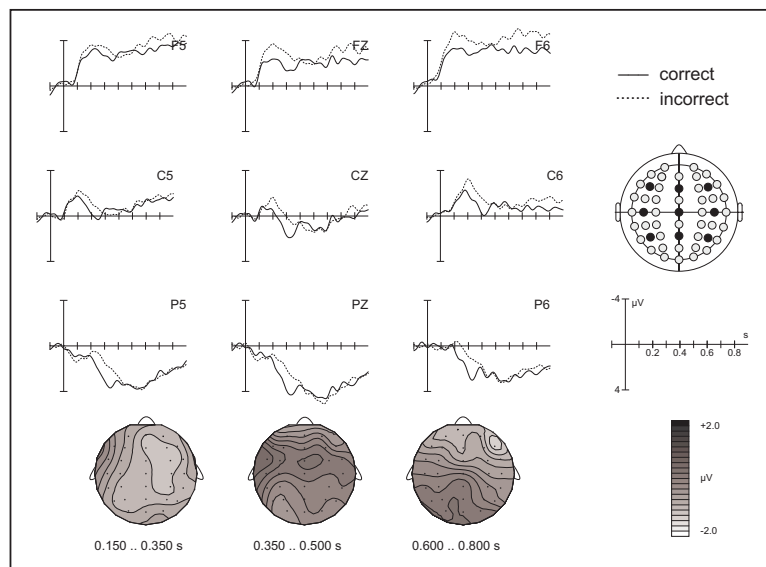


Figure 10.7: Experiment 4B: GRAM effect for nouns. ERP waveforms and topographical difference maps (incorrect - correct) of the mean amplitude in the time windows selected for statistical analysis

10.3 Discussion

Early syntactic negativities: Timing and automaticity In accordance with Hypothesis 1, the presence of an early negativity in response to incorrect utterances of both violation types underlines the task independence of this effect. The onset latency of the effect was identical to Experiment 3, including the slight delay in response to word category violations as opposed to subject-verb agreement violations that is probably due to the physical stimulus characteristics, as discussed in Section 9.3. This excludes the - rather theoretical - possibility that the early effects in the previous experiments are phenomena that are limited to situations in which attention is diverted from the speech input. On the contrary, the effect was even larger in the present as compared to the previous experiments of the current study. This could have two reasons. First, the stimulus-related task that the participants performed considerably increased SNR of the data. Blinking was restricted to intervals that were not of interest for the analysis of the ERPs, and the fixation cross that was present on the screen during the relevant interval reduced eye movements to a minimum. This improved data quality may have resulted in overall greater ERP responses. Second, the allocation of attentional resources is known to enhance several early ERP components such as the N1/P2 complex (Hillyard et al., 1973; Hackley et al., 1990; Woldorff & Hillyard, 1991), the N2b (Sams et al., 1985; Nager, Rosenthal, Bohrer, Teder-Sälejärvi, & Münte, 2001) and the MMN (Oades & Dittmann-Balcar, 1995; Alain & Woods, 1997). This is usually interpreted in terms of a gain-control or amplification process (Hillyard, Teder-Sälejärvi, & Münte, 1998) that may apply to the present syntactic negativity in the sense that the system is well prepared to detect syntactic cues under the explicit instruction to perform a correctness judgement task and allocates more neuronal resources to their processing. In light of this second interpretation, the conclusion would be that attention has a modulating influence on the early syntactic negativity, although the previous two experiments have shown that it is not abolished by the withdrawal of attention. This pattern of results clearly satisfies the definition of automaticity adopted for the present study (see page 11).

Early syntactic negativities: Topography The early syntactic negativity in response to the subject-verb agreement violations in Experiment 4A showed a broad distribution that appeared to be focused over fronto-central areas, a finding that largely parallels the corresponding data from Experiment 3. In contrast, the early syntactic negativity in Experiment 4B was shifted

to posterior scalp sites. Although no hypothesis was formulated with respect to scalp distribution of the syntactic negativity, the observed topographical difference in the two conditions is interesting with respect to structural differences between the neuronal mechanisms underlying agreement and phrase structure processing as discussed in previous chapters. However, breakdown analyses of the REG x CAT x GRAM interaction revealed that the posterior scalp distribution in the phrase structure condition was driven by conditions in which the critical word was the inflected verb form, whereas noun conditions paralleled the findings from the previous experiments by displaying the effect mainly over fronto-central electrodes. Across all experiments of the present study this is the only instance in which word category information modulated early syntactic processing. This suggests that top-down strategic influences triggered by the correctness judgement task may have affected phrase structure processing. Negative ERP deflections with a similar timing and scalp distribution as observed in the verb condition have previously been reported in response to rule violations in experiments on explicit sequence learning in the visual domain (Eimer, Goschke, Schlaghecken, & Stürmer, 1996; Rüsseler, Hennighausen, Münte, & Rösler, 2003; Bahlmann, Gunter, & Friederici, 2006). These effects were interpreted in terms of a conscious recognition of an unfulfilled expectation, an interpretation that matches well with the present experiment that allowed for strong predictions concerning the syntactically matching element. However, the questions why such explicit expectations should have had a particularly strong influence in the verb condition under phrase structure manipulations only, and which specific process underlies the anteriorly focused effect in the other conditions of the present experiment cannot be answered based on the present data.

Further effects of word category A further observation related to word category processing was the stronger negativity at around 400 ms in response to utterances in which the critical word was a noun. The presence of this effect confirms Hypothesis 3, which predicted a modulating influence of word category information on the ERP responses based on enhanced lexico-semantic processing for nouns as opposed to verbs. A similar effect had been observed in Experiment 3B for nouns presented in incorrect context. This instance had been interpreted as a reflection of semantic processing difficulties specific to the [NP + NP] condition. In light of the present data and the findings from Experiment 1B it rather seems that nouns in minimal context generally elicit a stronger N400 as opposed to verbs, independently of the grammaticality of the utterances. An effect of word frequency, known to be negatively correlated with the

N400 amplitude (Kutas & Federmeier, 2000), can be excluded. The employed nouns were on average more frequent than the respective verbs ($\text{mean}_{\text{nouns}} = 13.2$, $\text{SD} = 2.4$; $\text{mean}_{\text{verbs}} = 15.2$, $\text{SD} = 2.2$; $p < 0.0001$, as determined with a two-sample T-test)¹. This frequency pattern would predict the opposite effect on the amplitude of the N400. Instead, the present data support the tentative interpretation introduced in the discussion of Experiment 1B, which assumed that the observed N400 effects are due to the fact that nouns attract the attention of the lexical-semantic processing system to a greater extent than verbs because of the different syntactic and semantic functions of the two word categories during language comprehension.

Late positivity The most marked impact of attention directed towards the syntactic features of the stimuli was the enhancement of a late positivity in response to the incorrect utterances in Experiment 4A, and the verbs presented within incorrect context in Experiment 4B. The latency and topography of this effect resemble the P600 component often observed following syntactic violations under attentive processing (Osterhout & Holcomb, 1992; Hagoort et al., 1993; Friederici et al., 1996; Hahne & Friederici, 2002). It can thus be taken to reflect processes of syntactic repair and confirms Hypothesis 2. In addition, the occurrence of a P600 in spite of the minimal syntactic context of the two-word utterances speaks in favour of the external validity of the applied material and manipulations. The fact that the late positivity was only present for utterances containing inflected verb forms marks the [NP + NP] condition (e.g. **er Kegel* [he cone]) as an exception in this respect. It is possible that under active processing demands, this condition is perceived as incomplete rather than incorrect, either due to the lack of a verb phrase, or based on the fact that the direct adjacency of two noun phrases is possible within appropriate sentence context (see page 42). The late anterior negativity observed in this condition resembles that elicited in Experiment 3, where it was suggested to reflect the selection of a stimulus for further processing. In this light, the ERP pattern in the noun condition could be interpreted as a primary detection of an syntactically unexpected element (reflected in the early negativity), and the allocation of additional neuronal resources for further processing (reflected in the late anterior negativity) - as opposed to the consumption of these by syntactic repair mechanisms (reflected in the P600). However, this interpretation is merely post hoc and should be substantiated by further research.

¹The word frequency was determined according to the "Wortschatz Lexikon" (see also page 51). A frequency value of 12 indicates that the reference word "der" (*the*) is 2¹² times more frequent than the word in question.

10.4 Summary and Conclusions

The main aim of Experiment 4 was to demonstrate the task independence of the early syntactic negativities that had been observed in response to agreement and phrase structure manipulations in the previous experiments. A correctness judgement task was employed to focus the participants' attention on the syntactic properties of the auditorily presented variable two-word utterances, while all other experimental parameters were identical to Experiment 3.

The ERP responses showed a highly significant negative deflection in response to both subject-verb agreement violations (Experiment 4A) and word category violations (Experiment 4B) with an onset at about 100 ms and a duration of about 200 ms. This result closely parallels the observations from Experiment 3 with respect to the onset latency of the early syntactic negativities, thus proving the task independence of their occurrence. Nevertheless, the fact that the attention of the participants was directed towards the syntactic properties of the stimuli affected the ERP responses in several ways. First, the early syntactic ERP effects were more pronounced in the present as opposed to the previous experiments. This suggests that directed attention recruits more neuronal resources to the detection of syntactically unexpected elements. Second, the word category of the critical word in the phrase structure condition modulated the topography of the early syntax effect. This speaks in favour of a top-down influence on the specific neuronal mechanisms employed in the processing of this condition. Third, the attentive processing of the syntactic violations resulted in a P600 effect whenever the contrasted conditions contained an inflected verb form, suggesting that these instances were sufficiently sentence-like to trigger processes of syntactic repair. This finding lends further support to the notion that the P600 reflects controlled syntactic processing, as opposed to the early negativities that appear to be rather independent of attention (Friederici, 2002).

A final observation that is rather marginal with respect to the questions of the present study was an N400-like negativity in response to conditions containing nouns. This effect replicated observations from the previous experiments of the current study. It appears that in the stimulus material applied across the experiments, nouns generally triggered enhanced lexical-semantic processing as opposed to verbs. As pointed out previously, this may be due to the fundamentally different roles of the two word categories during language comprehension.

Part III

General Discussion

Chapter 11

Conclusions: Syntactic timing and automaticity revised

The interrelated experiments that added up to the present dissertation yielded largely consistent findings concerning the relative timing and automaticity of local syntactic-relational processing and phrase structure building. The current chapter presents a summary of the most important findings and discusses their implications with respect to general assumptions concerning the modularity of linguistically defined syntactic subprocesses, as introduced in Chapter 1, an existing neurocognitive serial model of parsing (Friederici, 2002, see Chapter 3), and brain mechanisms that could underlie the observed effects.

11.1 Summary of the study and its main findings

The aim of the present study was to determine whether syntactic subprocesses, in particular phrase structure building and the syntactic-relational processing of agreement, are distinguishable based on the timing and automaticity of specific ERP components. Previous research had suggested such a distinction based on the observation that disruptions of phrase structure building by word category violations elicit the ELAN, a very early and highly automatic ERP component, whereas agreement violations elicit the somewhat later and less automatic LAN. However, recent studies had repeatedly demonstrated correlates of agreement processing in the same time window as the ELAN and in the absence of focused attention. This inconsistency suggested that there may be methodological factors that influence the timing and automaticity

of syntactic ERP effects in addition to the targeted syntactic subprocesses. For these reasons a stimulus set was developed that allowed the comparison of phrase structure and syntactic-relational processing under extremely well controlled conditions. Equally local word category and subject-verb agreement violations were implemented in two-word utterances that were thoroughly controlled for acoustic parameters and violation point. The minimal syntactic context ensured that nothing but the violation type could modulate the syntactic ERP responses. These stimuli were employed in all experiments of the present study, both within syntactic MMN and in non-repetitive standard violation paradigm settings in order to assess the automaticity of the elicited ERP components.

Table 11.1 presents an overview of the conducted experiments, their main findings and the respective conclusions. Across all experiments, the grammaticality of the stimuli elicited significant ERP effects well before 200 ms, that is, in the time range of the ELAN, without any considerable temporal variation according to violation type. Furthermore, the local violations were processed independently of attentional resources. Experiment 4 showed that focused attention did enhance the early syntactic negativity in response to both violation types; however, the effects were also present under visual distraction both in the syntactic MMN (Experiments 1 and 2) and in a standard violation paradigm (Experiment 3). This suggests strong automaticity of the underlying processes. The absence of a P600 effect in all but the violation detection condition (Experiment 4) underlines the fact that the occurrence of the early syntactic negativities does not depend on the participants' attentive processing of the stimuli.

Supposed neurophysiological differences between the two syntactic subprocesses (following their linguistic specification and ideas based on the modularity principle) were expected to show up as modulations in the topography and hence the cortical generators of the early syntactic ERP effects. However, the aspired modulation was merely shown in the syntactic MMN experiments, and even there, the observed cortical activations could not be attributed unequivocally to brain areas known to be involved in the respective syntactic operations. In fact, the observed broad distribution of the early syntactic negativities is fairly unusual in light of the left anterior focus (ELAN and LAN) observed in most other ERP investigations on syntax processing. This instance raises the question whether the observed effects are based on mechanisms that are not only quantitatively, but also qualitatively different from those involved in the syntactic analysis of more complex sentence material.

Table 11.1: Experiments, objectives, main findings and conclusions of the present study

EXP	OBJECTIVE	MAIN FINDINGS
1	To contrast local agreement and phrase structure processing in syntactic MMN paradigm	Syntactic MMN effects before 200 ms, independent of violation type, but with different topography.
	<i>⇒ early automatic processing of local agreement and phrase structure</i>	
	<i>⇒ different neural networks process agreement and phrase structure?</i>	
2	To specify brain regions involved in topographically distinct syntactic MMN effects in Exp.1 by means of MEG-based BSCD mapping	Activation pattern generally replicates findings from Exp.1, but statistical differentiations of ROIs according to violation type are only tendential.
	<i>⇒ bilateral temporo-inferiofrontal networks induce syntactic MMN effects</i>	
	<i>⇒ foci of activity are in line with syntactic priming interpretation</i>	
E	To investigate impact of word category on the MMN	Verb deviant → anterior MMN Noun deviant → posterior MMN
	<i>⇒ early automatic access to word category information</i>	
	<i>⇒ verbs and nouns have different neural representations</i>	
3	To test local agreement and phrase structure processing in variable utterances outside the MMN paradigm	Broadly distributed N100-300, independent of violation type; sustained anterior N300-600
	<i>⇒ early onset of syntactic negativities not restricted to repetitive presentation</i>	
	<i>⇒ no evidence for different neural networks for agreement and phrase structure</i>	
	<i>⇒ incorrect stimuli are apparently selected for further processing</i>	
4	To investigate impact of focused attention on local agreement and phrase structure processing	Broadly distributed N100-300, independent of violation type; followed by P600 in response to incorrect verbs
	<i>⇒ early syntactic negativities are enhanced by attention</i>	
	<i>⇒ no evidence for different neural networks for agreement and phrase structure</i>	
	<i>⇒ P600 subject to attentional / strategic control</i>	

11.2 On the modularity of syntactic subprocesses

The assumption that phrase structure building and syntactic-relational processing may be correlated with different neurophysiological signatures was based on an expansion of Fodor's modularity principle to the idea that the human syntax processor comprises of several independent subcomponents (see Chapter 1). The invariably early and automatic nature of the syntactic negativities in the present study appears to support the existence of independent (sub-)modules for phrase structure and syntactic-relational processing. However, independent modules according to Fodor (1983) are further supposed to have a fixed neural architecture, that is, they should differ in their neuroanatomical representation (see also Grodzinsky, 2006). Although the agreement and phrase structure MMNs in Experiments 1 and 2 displayed promising topographical tendencies in this respect, statistical confirmations and replications in non-repetitive settings could not be provided by the present data. Strictly speaking, it is therefore not possible to determine whether the word category and subject-verb agreement violations employed in the present setting were processed by the same or by different modules (or rather neuronal mechanisms, as discussed in Section 11.4).

11.3 Implications for serial models of parsing

The concurrence of early ERP effects in response to word category and subject-verb agreement violations questions the seriality of phrase structure building and syntactic-relational processes, as assumed in Friederici's *Neurocognitive Model of Auditory Sentence Comprehension* (see Friederici, 1995, 2002, and Chapter 3). Based on the present data, it rather seems that as long as ERP responses are time-locked to the violation point and violations are implemented at the local level, all types of syntactically mismatching acoustic information are detected as soon as they become available. This notion is corroborated by a recent study by Eckstein and Friederici (2006) who showed that mismatching prosodic information affected ERP responses simultaneously to mismatching word category information when the latter was encoded in the suffix of the critical word, thus indicating an immediate influence of prosody during the initial parsing stage in speech processing.

These considerations show that the linguistically meaningful precedence of phrase structure building over other syntactic processes does not in any circumstance become manifest in

the *temporal* domain. It should however be noted that the current findings do not contradict the assumed *functional* precedence of phrase structure building, as evidenced by Rossi et al. (2005) who showed that the occurrence of a word category error impeded the processing of a simultaneous agreement error. This was indicated by a non-additivity of the two syntactic negativities in response to sentences combining the two violation types, e.g.

(1) Der Junge im **singst** ein Lied. (*The boy in-the **sing** a song.*)

As an impetus for future ERP investigations of syntax processing, the present data send a reminder of the necessity to take all the components of the experimental setting and stimulus material into account when the timing of syntactic ERP effects is interpreted. Besides the point in time at which the syntactically relevant information becomes available, the locality of the syntactic dependency in question and the acoustic characteristics of the stimulus material seem to play an important role for the relative timing of specific syntactic processes. These factors clearly need to be considered more explicitly than it has been the case in the past.

An aspect of the *Neurocognitive Model of Auditory Sentence Comprehension* that is doubtlessly supported by the present findings is that once a syntactic violation has been detected, a final phase of syntactic repair ensues, and that this phase depends on the attentional processing of the stimuli. The P600 effect was only observed in Experiment 4, in which participants judged the correctness of the stimuli. Furthermore, it was restricted to conditions that contained a verb. This may be due to the fact that participants only engaged in syntactic repair when the input resembled minimal sentence requirements, which impressively demonstrates strategic influences on the P600 and clearly distinguishes it from the oddball P300.

11.4 Possible brain mechanisms underlying the early syntactic negativities

As mentioned above, the mostly broad topographical distribution of the early syntactic negativities endorses speculations that the brain mechanisms underlying the analysis of the present two-word utterances may differ from those elicited in larger sentence contexts. Investigations of artificial grammar and sequence learning have yielded similarly broad negativities. For example, Bahlmann et al. (2006) report a broadly distributed negativity for syllable sequences following FSG and PSG rules when the first syllable was violated. They interpret this result

as a reflection of an unfulfilled expectation of a category. Similarly, Rüsseler et al. (2003) observed a broadly distributed negativity with a centroparietal maximum in response to rule violations when these rules had been learned explicitly. The high predictability of possible events in the two-word utterances employed in the present investigation suggests that the mechanism underlying violation detection could be similarly expectation-based as in the above settings. An important difference, however, is that the current violations are based on genuine syntactic rules that can be assumed to be overlearned and automatized during lifelong exposure. This implies a higher degree of automaticity and a greater processing speed in the current setting. The notion of syntactic priming (see Pulvermüller & Shtyrov, 2003, and page 58) appears to give a most appropriate description of the neuronal mechanism that could subserve such a speeded and automatic syntactic analysis. Whether this mechanism is however as effective beyond the processing of two-word utterances, and can therefore be considered as a natural part of sentence comprehension, remains to be shown by further testing. This point will be elaborated in the next and final chapter.

Chapter 12

Perspectives for further research

All experimental investigations of natural language comprehension have to deal with the difficulty to find a balance between experimental control and external validity. The present study was designed to bridge the gap between restrictive and overly controlled syntactic MMN experiments and studies using non-repetitive, more complex sentence material but insufficient control of acoustic parameters and violation points. As such, it still ranges at a considerable distance from language comprehension in the natural environment. This entails a number of restrictions with respect to the generalizability of the present findings that need to be dispelled by future experiments. At the same time, the controlled and concise nature of the material and the sound effects obtained in the experiments are promising with respect to applications in special populations and clinical research. Furthermore, the present results yielded some unexpected findings that deserve further investigation. The first part of this final chapter lists the shortcomings of the present investigation. The second part suggests experimental clarifications of these, and presents possible extensions and applications of the present work.

12.1 Shortcomings of the present study

One of the most apparent pitfalls of the current study is the restricted nature of the syntactic material presented to the participants. While the use of two-word utterances was methodologically necessary to guarantee the acoustic control of the material and to facilitate the applicability within the syntactic MMN paradigm, it negatively affects the external validity of the findings. Furthermore, it raises the question whether the mechanisms triggered in the current

setting are comparable to those triggered by larger sentence contexts as employed by most of the studies that motivated the current investigation.

Another drawback of the current design is the presentation of the two violation types in separate blocks. Although it assured the acoustic balancing of the conditions, this procedure may have artificially promoted fast and automatized processing as it allowed the system to tune in on the detection of a specific type of violation.

And finally, the fact that the current investigation only employed local violations renders it impossible to differentiate between the impact of locality and the impact of unbiased time-locking on the temporal characteristics of the observed ERP responses. The numerous previous studies in which local syntactic-relational violations elicited considerably later ERP effects than those observed in the present study (i.e. LAN; 300 - 500 ms) were largely conducted in the visual modality (e.g. Kutas & Hillyard, 1983; Osterhout & Mobley, 1995; Coulson et al., 1998; Gunter et al., 2000). Here, the exact point in time at which a violation is detected is difficult to determine as it is unclear whether visually presented words and their inflectional morphology are perceived holistically or via grapheme-to-phoneme conversion. In the latter case, the delay in the detection of a violation that is encoded in the suffix can be expected to be similar to that under auditory presentation. Furthermore, it is possible that early effects of syntactic priming are only detectable in the auditory modality, either because auditory violations are more salient, or because their detection is of a stronger automaticity due to a lifelong exposure to speech input. The only auditory study with local inflectional violations time-locked responses to the word onsets of considerably long critical words, thus precluding inferences on this issue (Friederici et al., 1993). A direct manipulation of locality and time-locking in the auditory modality is therefore needed to shed light on this issue.

The above points demonstrate that the present findings should be substantiated by continuative experiments in order to allow more generalizable conclusions. Ways to meet the most urgent experimental issues as well as possible further applications of the present design are outlined in the following, final section of this dissertation.

12.2 Outlook: Future experiments and clinical applications

The above limitations demonstrate that the conclusions drawn in Chapter 11 pend on a replication of the current findings with equivalent stimuli that are embedded into a larger sentence

context. If syntactic priming is effective in natural speech processing, the invariably early latency of the syntactic negativities in response to agreement and word category violations should be retained independently of the sentence context. This would dispel reasonable doubts with respect to the external validity of the current findings. Furthermore, a larger sentence context would allow for a systematic variation of violation locality. This in turn would contribute to the assessment of the role of locality in the temporal characteristics of syntactic ERP components, which is unclear in the current setting due to the confounding of locality and time-locking, as discussed in the previous section.

An ultimate test of the relative timing and automaticity of phrase structure and syntactic-relational processing would be to compare ERP effects in response to word category and agreement violations when these are presented in an interspersed fashion. This was not realized in the present study that rather focused on the acoustic balancing of the conditions. However, it is a necessary precondition to rule out that the system tunes in on the detection of a specific violation type. Now that the acoustic independence of the effects is shown, future experiments could surely combine the well-controlled material of the present study with the argumentational advantages of an interspersed violation paradigm.

In addition to the immediate clarification of the discussed shortcomings, the results of the present study yielded some theoretical implications that could be picked up by further research. First, the assumption that the early syntactic ERP effects are mediated by syntactic priming could be substantiated by means of a genuine syntactic priming experiment including a neutral prime condition. This would allow for the classification of the syntactic priming effect in terms of facilitatory or inhibitory mechanisms (see for example Blumstein et al., 1991; Deutsch & Bentin, 1994). Furthermore, the application of a lexical decision task in such a paradigm would allow for the investigation of agreement and word category priming under implicit processing demands. This may bring to light further differences in the processing and automaticity of the underlying syntactic subprocesses. Second, the Excursus Experiment (Chapter 7) provided first evidence in favour of a word category specific modulation of the MMN. Although a replication with more than a single verb-noun pair is imperative, this finding may foster attempts to differentiate the neuronal representations of the two word categories in the absence of focused attention. And third, the observation of a sustained anterior negativity in response to syntactic violations under passive processing calls for further investigations. In

particular, it should be tested whether the suggested relation to the processing negativity (PN / Nd) and the accordant interpretation in terms of neuronal resource allocation are sustainable.

Moving from basic towards applied research, the controlled design, the conciseness of the stimuli, the independence of attention and task requirements as well as the pronounced effects provided by the present study constitute ideal preconditions for applications in special populations and clinical settings. For example, it could be interesting to study the acquisition of the two investigated syntactic rules in infants, or in adults who are naive to the German language. This approach could complement artificial grammar studies on statistical learning in infants (Gomez & Gerken, 2000) and adults (Pena, Bonatti, Nespor, & Mehler, 2002; Perruchet, Tyler, Galland, & Peere-man, 2004) with real-language data.

Based on the solid grammaticality effects obtained in Experiments 3 and 4 (passive and active processing of variable utterances) there is even a possibility that the early syntactic negativities are robust enough to be evaluated at the single subject level. Should this turn out to be the case, the paradigm employed in these experiments may be of great diagnostic value, for example for the assessment of language disorders and neuronal plasticity following treatment of these. With this concluding idea, it is hoped that the present dissertation did not only contribute to a better understanding of syntax processing in the human brain in general, but also did a small piece of preliminary work on the long way from basic research to clinical application.

Bibliography

- Alain, C., & Woods, D. L. (1997). Attention modulates auditory pattern memory as indexed by event-related brain potentials. *Psychophysiology*, 34, 534-546.
- Alho, K. (1995). Cerebral generators of mismatch negativity (MMN) and its magnetic counterpart (MMNm) elicited by sound changes. *Ear & Hearing*, 16, 38-51.
- Alho, K., Töttölä, K., Reinikainen, K., Sams, M., & Näätänen, R. (1987). Brain mechanism of selective listening reflected by event-related potentials. *Electroencephalography and Clinical Neurophysiology*, 68, 458-470.
- Bahlmann, J. (2007). *Neural correlates of the processing of linear and hierarchical artificial grammar rules: Electrophysiological and neuroimaging studies*. Leipzig: MPI Series.
- Bahlmann, J., Gunter, T. C., & Friederici, A. D. (2006). Hierarchical and linear sequence processing: An electrophysiological exploration of two different grammar types. *Journal of Cognitive Neuroscience*, 18, 1829-1842.
- Ben-Shachar, M., Hendler, T., Kahn, I., Ben-Bashat, D., & Grodzinsky, Y. (2003). The neural reality of syntactic transformations: Evidence from functional magnetic resonance imaging. *Psychological Science*, 14, 433-440.
- Berger, H. (1929). Über das Elektroenkephalogramm des Menschen. *Archiv für Psychiatrie und Nervenkrankheiten*, 87, 527-570.
- Blumstein, S., Milberg, W., Dworetzky, B., Rosen, A., & Gershberg, F. (1991). Syntactic priming effects in aphasia: An investigation of local syntactic dependencies. *Brain and Language*, 40, 393-421.
- Bornkessel, I., & Schlesewsky, M. (2006). The extended argument dependency model: A neurocognitive approach to sentence comprehension across languages. *Psychological Review*, 113, 787-821.
- Chomsky, N. (1957). *Syntactic structures*. The Hague/Paris: Mouton.

- Coles, M. G. H., & Rugg, M. D. (1995). Event-related brain potentials: An introduction. In M. D. Rugg & M. G. H. Coles (Eds.), *Electrophysiology of mind. event-related brain potentials and cognition* (p. 1-26). New York: Oxford University Press.
- Cooper, R., Osselson, J. W., & Shaw, J. C. (1984). *Elektroenzephalographie: Technik und Methoden*. Stuttgart: Gustav Fischer Verlag.
- Coulson, S., King, J. W., & Kutas, M. (1998). Expect the unexpected: Event-related brain response to morphosyntactic violations. *Language and Cognitive Processes*, 13, 21-58.
- Crocker, M. W. (1994). On the nature of the principle-based sentence processor. In C. Clifton, L. Frazier, & K. Rayner (Eds.), *Perspectives on sentence processing* (p. 245-266). Hillsdale: Erlbaum.
- Damasio, A., & Tranel, D. (1993). Nouns and verbs are retrieved with differently distributed neural systems. *Proc. Natl. Acad. Sci. USA*, 90, 4957-4960.
- Daniele, A., Giustolisi, L., Silveri, M. C., Colosimo, C., & Gainotti, G. (1994). Evidence for a possible neuroanatomical basis for lexical processing of nouns and verbs. *Neuropsychologia*, 32, 1325-1341.
- Dawson, G. D. (1954). A summation technique for the detection of small evoked potentials. *Electroencephalography and Clinical Neurophysiology (Suppl.)*, 6, 65-84.
- Deouell, L. Y., Bentin, S., & Giard, M.-H. (1998). Mismatch negativity in dichotic listening: Evidence for interhemispheric differences and multiple generators. *Psychophysiology*, 35, 355-365.
- Deutsch, A., & Bentin, S. (1994). Attention mechanisms mediate the syntactic priming effects in auditory word identification. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 20, 595-607.
- Deutsch, A., & Bentin, S. (2001). Syntactic and semantic factors in processing gender agreement in Hebrew: Evidence from ERPs and eye movements. *Journal of Memory and Language*, 45, 200-224.
- Donchin, E. (1981). Surprise!...surprise? *Psychophysiology*, 18, 493-513.
- Eckstein, K., & Friederici, A. D. (2006). It's early: ERP evidence for initial interaction of syntax and prosody in speech comprehension. *Journal of Cognitive Neuroscience*, 18, 1696-1711.

- Eimer, M. (1999). Attending to quadrants and ring-shaped regions: ERP effects of visual attention in different spatial selection tasks. *Psychophysiology*, 36, 491-503.
- Eimer, M., Goschke, T., Schlaghecken, F., & Stürmer, B. (1996). Explicit and implicit learning of event sequences: Evidence from event-related brain potentials. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 22, 970-987.
- Elbert, T. (1998). Neuromagnetism. In W. Andrä & H. Nowak (Eds.), *Magnetism in medicine: a handbook* (p. 190-262). New York: J. Wiley & Sons.
- Embick, D., Marantz, A., Miyashita, Y., O'Neil, W., & Sakai, K. L. (2000). A syntactic specialization for Broca's area. *Proc Natl Acad Sci U S A*, 97, 6150-4.
- Escera, C., Yago, E., & Alho, K. (2001). Electrical responses reveal the temporal dynamics of brain events during involuntary attention switching. *European Journal of Neuroscience*, 14, 877-883.
- Federmeier, K. D., Segal, J. B., Lombrozo, T., & Kutas, M. (2000). Brain responses to nouns, verbs and class ambiguous words in context. *Brain*, 123, 2552-2566.
- Flores d'Arcais, G. B. (1988). Automatic processes in language comprehension. In B. Denes, C. Semenza, & P. Bisiachi (Eds.), *Perspectives on cognitive neuropsychology* (p. 93-114). LEA.
- Fodor, J. A. (1983). *The modularity of mind. An essay on faculty psychology*. Cambridge, MA; London: MIT Press.
- Forster, K. I. (1979). Levels of processing and the structure of the language processor. In W. E. Cooper & E. C. T. Walker (Eds.), *Sentence Processing* (p. 27-85). Hillsdale, New Jersey: Lawrence Erlbaum Associates.
- Frazier, L. (1987). Sentence processing. In M. Coltheart (Ed.), *Attention and Performance XII: The Psychology of Reading* (p. 559-586). Hove: Erlbaum.
- 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* (p. 265-304). Berlin: Springer.
- Friederici, A. D. (2002). Towards a neural basis of auditory sentence processing. *Trends in Cognitive Sciences*, 6, 78-84.

- Friederici, A. D. (2004). Processing local transitions versus long-distance syntactic hierarchies. *Trends in Cognitive Sciences*, 8, 245-247.
- Friederici, A. D., & Alter, K. (2004). Lateralization of auditory language functions: a dynamic dual pathway model. *Brain and Language*, 89, 267-76.
- Friederici, A. D., Bahlmann, J., Heim, S., Schubotz, R. I., & Anwander, A. (2006). The brain differentiates human and non-human grammars: Functional localization and structural connectivity. *Proc Natl Acad Sci U S A*, 103, 2458-2463.
- Friederici, A. D., Fiebach, C. J., Schlesewsky, M., Bornkessel, I. D., & von Cramon, D. Y. (2006). Processing linguistic complexity and grammaticality in the left frontal cortex. *Cerebral Cortex*, 16, 1709-1717.
- Friederici, A. D., Gunter, T. C., Hahne, A., & Mauth, K. (2004). The relative timing of syntactic and semantic processes in sentence comprehension. *NeuroReport*, 15, 165-169.
- Friederici, A. D., Hahne, A., & Mecklinger, A. (1996). Temporal structure of syntactic parsing: Early and late event-related brain potentials. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 22, 1219-1248.
- Friederici, A. D., Hahne, A., & Saddy, D. (2002). Distinct neurophysiological patterns reflecting aspects of syntactic complexity and syntactic repair. *Journal of Psycholinguistic Research*, 31, 45-63.
- Friederici, A. D., & Kotz, S. A. (2003). The brain basis of syntactic processes: Functional imaging and lesion studies. *NeuroImage*, 20, 8-17.
- Friederici, A. D., & Meyer, M. (2004). The brain knows the difference: Two types of grammatical violations. *Brain Research*, 1000, 72-77.
- 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., Rüschemeyer, S.-A., Hahne, A., & Fiebach, C. (2003). The role of left inferior frontal and superior temporal cortex in sentence comprehension: Localizing syntactic and semantic processes. *Cerebral Cortex*, 13, 170-177.
- Friederici, A. D., Wang, Y., Herrmann, C. S., Maess, B., & Oertel, U. (2000). Localization of early syntactic processes in frontal and temporal cortical areas: A magnetoencephalographic study. *Human Brain Mapping*, 11, 1-11.

- Friederici, A. D., & Weissenborn, J. (2007). Mapping sentence form onto meaning: The syntax-semantic interface. *Brain Research*, 1146, 50-58.
- Friedman, D., Cycowicz, Y. M., & Gaeta, H. (2001). The novelty P3: an event-related brain potential (ERP) sign of the brain's evaluation of novelty. *Neuroscience and Biobehavioral Reviews*, 25, 355-373.
- Frisch, S., Hahne, A., & Friederici, A. D. (2004). Word category and verb-argument structure information in the dynamics of parsing. *Cognition*, 91, 191-219.
- Frisch, S., Kotz, S. A., von Cramon, D. Y., & Friederici, A. D. (2003). Why the P600 is not just a P300: The role of the basal ganglia. *Clinical Neurophysiology*, 114, 336-340.
- Frisch, S., Schlesewsky, M., Saddy, D., & Alpermann, A. (2002). The P600 as an indicator of syntactic ambiguity. *Cognition*, 85, B83-B85.
- Friston, K. (2005). A theory of cortical responses. *Philos. Trans. R. Soc. B.*, 360, 815-836.
- Friston, K., Price, C. J., Fletcher, P., Moore, C., Frackowiak, R. S., & Dolan, R. J. (1996). The trouble with cognitive subtraction. *Neuroimage*, 4, 97-104.
- Fuchs, M., Wagner, M., Köhler, T., & Wischmann, H. A. (1999). Linear and nonlinear current density reconstructions. *Journal of Clinical Neurophysiology*, 16, 267-295.
- Giard, M. H., Perrin, F., Pernier, J., & Bouchet, P. (1990). Brain generators implicated in the processing of auditory stimulus deviance: A topographic event-related potential study. *Psychophysiology*, 27, 627-640.
- Gibson, E. (1998). Linguistic complexity: Locality of syntactic dependencies. *Cognition*, 68, 1-76.
- Gomez, & Gerken. (2000). Infant artificial language learning and language acquisition. *Trends in Cognitive Sciences*, 4, 178-186.
- Goodman, G. O., McClelland, J. L., & Gibbs, R. W. J. (1981). The role of syntactic context in word recognition. *Memory & Cognition*, 9, 580-586.
- Gorrell, P. (1995). *Syntax and parsing*. Cambridge, UK: Cambridge University Press.
- Grodzinsky, Y. (2006). A blueprint for a brain map of syntax. In Y. Grodzinsky & K. Amunts (Eds.), *Broca's region*. Oxford University Press.
- Grodzinsky, Y., & Friederici, A. D. (2006). Neuroimaging of syntax and syntactic processing. *Current Opinion in Neurobiology*, 16, 240-246.

- Gross, I., Ioannides, A. A., Dammers, J., Maess, B., Friederici, A. D., & Müller-Gärtner, H.-W. (1998). Magnetic field tomography analysis of continuous speech. *Brain Topography*, 10, 273-281.
- Gunter, T. C., & Friederici, A. D. (1999). Concerning the automaticity of syntactic processing. *Psychophysiology*, 36, 126-137.
- 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.
- Gunter, T. C., Stowe, L. A., & Mulder, G. (1997). When syntax meets semantics. *Psychophysiology*, 34, 660-676.
- Hackley, S. A., Woldorff, M., & Hillyard, S. A. (1990). Cross-modal selective attention effects on retinal, myogenic, brainstem, and cerebral evoked potentials. *Psychophysiology*, 27, 195-208.
- Hagoort, P., Brown, C., & Groothusen, J. (1993). The syntactic positive shift as an ERP measure of syntactic processing. *Language and Cognitive Processes*, 8, 439-484.
- Hagoort, P., & Brown, C. M. (2000). ERP effects of listening to speech compared to reading: The P600/SPS to syntactic violations in spoken sentences and rapid serial visual presentation. *Neuropsychologia*, 38, 1531-1549.
- Hagoort, P., Wassenaar, M., & Brown, C. M. (2003). Syntax-related ERP-effects in Dutch. *Brain Research: Cognitive Brain Research*, 16, 38-50.
- Hahne, A. (1997). *Charakteristika syntaktischer und semantischer Prozesse bei der auditiven Sprachverarbeitung*. Leipzig: MPI Series.
- Hahne, A., & Friederici, A. (2002). Differential task effects on semantic and syntactic processes as revealed by ERPs. *Brain Research: Cognitive Brain Research*, 13, 339-356.
- 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., Schröger, E., & Friederici, A. D. (2002). Segregating early physical and syntactic processes in auditory sentence comprehension. *NeuroReport*, 13, 305-309.
- Handy, T. C. (Ed.). (2005). *Event-Related Potentials. A Methods Handbook*. Cambridge, MA: MIT Press.
- Hansen, J. C., & Hillyard, S. A. (1983). Selective attention to multidimensional auditory stimuli. *Journal of Experimental Psychology: Human Perception and Performance*, 9, 1-19.
- Hasting, A. S., & Kotz, S. A. (2008). Speeding up syntax: On the relative timing and automaticity of local phrase structure and morphosyntactic processing as reflected in event-related brain potentials. *Journal of Cognitive Neuroscience*, 20.
- Hasting, A. S., Kotz, S. A., & Friederici, A. D. (2007). Setting the stage for automatic syntax processing: The mismatch negativity as an indicator of syntactic priming. *Journal of Cognitive Neuroscience*, 19, 386-400.
- Hasting, A. S., Winkler, I., & Kotz, S. A. (2008). Early differential processing of verbs and nouns in the human brain as indexed by event-related brain potentials. *European Journal of Neuroscience*, 27, 1561-1565.
- Hauk, O., & Pulvermüller, F. (2004). Effects of word length and frequency on the human event-related potential. *Clinical Neurophysiology*, 115, 1090-1103.
- Hillyard, S. A., Hink, R. F., Schwent, V. L., & Picton, T. W. (1973). Electrical signs of selective attention in the human brain. *Science*, 182, 177-180.
- Hillyard, S. A., Teder-Sälejärvi, W. A., & Münte, T. F. (1998, Apr). Temporal dynamics of early perceptual processing. *Current Opinion in Neurobiology*, 8(2), 202-210.
- Hruby, T., & Marsalek, P. (2003). Event-related potentials-the P3 wave. *Acta Neurobiologiae Experimentalis*, 63, 55-63.
- Jaramillo, M., Paavilainen, P., & Näätänen, R. (2000). Mismatch negativity and behavioural discrimination in humans as a function of the magnitude of change in sound duration. *Neuroscience Letters*, 290, 101-104.
- Jasper, H. (1958). The ten twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology*, 10, 371-375.

- Just, M. A., Carpenter, P. A., Keller, T. A., Eddy, W. F., & Thulborn, K. R. (1996). Brain activation modulated by sentence comprehension. *Science*, 274, 114-6.
- Kaan, E., Harris, A., Gibson, E., & Holcomb, P. J. (2000). The P600 as an index of integration difficulty. *Language and Cognitive Processes*, 15, 159-201.
- Kaan, E., & Swaab, T. Y. (2002). The brain circuitry of syntactic comprehension. *TRENDS in Cognitive Sciences*, 6, 350-356.
- Kaan, E., & Swaab, T. Y. (2003). Repair, revision, and complexity in syntactic analysis: An electrophysiological differentiation. *Journal of Cognitive Neuroscience*, 15, 98-110.
- Kahnemann, D., & Treisman, A. (1984). Changing views of attention and automaticity. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of Attention* (p. 29-61). New York: Academic Press.
- Kaiser, J., & Lutzenberger, W. (2003, Dec). Induced gamma-band activity and human brain function. *Neuroscientist*, 9(6), 475-484.
- Keller, T. A., Carpenter, P. A., & Just, M. A. (2001). The neural bases of sentence comprehension: A fMRI examination of syntactic and lexical processing. *Cerebral Cortex*, 11, 223-37.
- Kluender, R., & Kutas, M. (1993). Bridging the gap: Evidence from ERPs on the processing of unbounded dependencies. *Journal of Cognitive Neuroscience*, 5, 196-214.
- Knösche, T. R. (1997). *Solutions of the neuroelectromagnetic inverse problem - an evaluation study*. University of Twente, The Netherlands. (ISBN 9036509734)
- Knösche, T. R. (2002). Transformation of whole-head MEG recordings between different sensor positions. *Forschungsberichte Biomedizinische Technik und Krankenhaustechnik*, 47, 59-62.
- Knösche, T. R., Lattner, S., Maess, B., Schauer, M., & Friederici, A. D. (2002). Early parallel processing of auditory word and voice information. *NeuroImage*, 17, 1493-1503.
- Knösche, T. R., Maess, B., & Friederici, A. D. (1999). Processing of syntactic information monitored by brain surface current density mapping based on MEG. *Brain Topography*, 12, 75-87.
- Kotchoubey, B. (2006). Event-related potentials, cognition, and behavior: A biological approach. *Neuroscience and Biobehavioral Reviews*, 30, 42-65.

- Kubota, M., Ferrari, P., & Roberts, T. P. L. (2003). Magnetoencephalography detection of early syntactic processing in humans: Comparison between L1 speakers and L2 learners of English. *Neuroscience Letters*, 353, 107-110.
- Kubota, M., Ferrari, P., & Roberts, T. P. L. (2004). Human neuronal encoding of English syntactic violations as revealed by both L1 and L2 speakers. *Neuroscience Letters*, 368, 235-240.
- Kuperberg, G. R., Holcomb, P. J., Sitnikova, T., Greve, D., Dale, A. M., & Caplan, D. (2003). Distinct patterns of neural modulation during the processing of conceptual and syntactic anomalies. *Journal of Cognitive Neuroscience*, 15, 272-293.
- Kutas, M., & Federmeier, K. (2000). Electrophysiology reveals semantic memory use in language comprehension. *Trends in Cognitive Sciences*, 4, 463-470.
- 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 & Cognition*, 11, 539-550.
- Kutas, M., Van Petten, C. K., & Kluender, R. (2006). Psycholinguistics electrified II (1994-2005). In M. A. Gernsbacher (Ed.), *Handbook of psycholinguistics* (p. 659-724). San Diego, CA: Academic Press.
- Lancaster, J. L., Summerlin, J. L., Rainey, L., Freitas, C. S., & Fox, P. T. (1997). The Talairach Daemon, a database server for Talairach Atlas Labels. *Neuroimage*, 5, S633.
- Lancaster, J. L., Woldorff, M. G., Parsons, L. M., Liotti, M., Freitas, C. S., Rainey, L., et al. (2000). Automated Talairach atlas labels for functional brain mapping. *Human Brain Mapping*, 10, 120-131.
- Lau, E., Stroud, C., Plesch, S., & Phillips, C. (2006). The role of structural prediction in rapid syntactic analysis. *Brain and Language*, 98, 74-88.
- Logan, G. D. (1992). Attention and preattention in theories of automaticity. *American Journal of Psychology*, 105, 317-339.
- Lohmann, G., Müller, K., Bosch, V., Mentzel, H., Hessler, S., Chen, L., et al. (2001). LIPSIA - a new software system for the evaluation of functional magnetic resonance images of the human brain. *Computerized Medical Imaging and Graphics*, 25, 449-457.

- McGee, T. J., King, C., Tremblay, K., Nicol, T. G., Cunningham, J., & Kraus, N. (2001). Long-term habituation of the speech-elicited mismatch negativity. *Psychophysiology*, 38, 653-658.
- Menning, H., Zwitserlood, P., Schöning, S., Hihn, H., Bölte, J., Dobel, C., et al. (2005). Pre-attentive detection of syntactic and semantic errors. *Neuroreport*, 16, 77-80.
- Meyer, M., Alter, K., & Friederici, A. D. (2003). Functional MR Imaging exposes differential brain responses to syntax and prosody during auditory sentences comprehension. *Journal of Neurolinguistics*, 16, 277-300.
- Meyer, M., Friederici, A. D., & von Cramon, D. Y. (2000). Neurocognition of auditory sentence comprehension: Event related fMRI reveals sensitivity to syntactic violations and task demands. *Brain Research: Cognitive Brain Research*, 9, 19-33.
- Molholm, S., Martinez, A., Ritter, W., Javitt, D., & Foxe, J. (2005). The neural circuitry of pre-attentive auditory change-detection: An fMRI study of pitch and duration mismatch negativity generators. *Cerebral Cortex*, 15, 545-551.
- Moro, A., Tettamanti, M., Perani, D., Donati, C., Cappa, S. F., & Fazio, F. (2001). Syntax and the brain: Disentangling grammar by selective anomalies. *Neuroimage*, 13, 110-118.
- Münte, T. F., Heinze, H.-J., & Mangun, G. R. (1993). Dissociation of brain activity related to syntactic and semantic aspects of language. *Journal of Cognitive Neuroscience*, 5, 335-344.
- Näätänen, R. (1992). *Attention and Brain Function*. Hillsdale, NJ: Lawrence Erlbaum Associates.
- Näätänen, R. (1995). The mismatch negativity: A powerful tool for cognitive neuroscience. *Ear & Hearing*, 16, 6-18.
- Näätänen, R. (2001). The perception of speech sounds by the human brain as reflected by the mismatch negativity (MMN) and its magnetic equivalent (MMNm). *Psychophysiology*, 38, 1-21.
- Näätänen, R., & Alho, K. (1997). Mismatch negativity - the measure for central sound representation accuracy. *Audiology & Neurotology*, 2, 341-353.
- Näätänen, R., Gaillard, A. W., & Mäntysalo, S. (1978). Early selective-attention effect on evoked potential reinterpreted. *Acta Psychologica*, 42, 313-329.

- Näätänen, R., Paavilainen, P., Tiitinen, H., Jiang, D., & Alho, K. (1993). Attention and mismatch negativity. *Psychophysiology*, *30*, 436-450.
- Näätänen, R., & Picton, T. (1987). The N1 wave of the human electric and magnetic response to sound: A review and an analysis of the component structure. *Psychophysiology*, *24*, 375-425.
- Näätänen, R., Simpson, M., & Loveless, N. E. (1982). Stimulus deviance and evoked potentials. *Biological Psychology*, *14*, 53-98.
- Näätänen, R., Tervaniemi, M., Sussman, E., Paavilainen, P., & Winkler, I. (2001). 'Primitive intelligence' in the auditory cortex. *Trends in Neurosciences*, *24*, 283-288.
- Nager, W., Rosenthal, O., Bohrer, I., Teder-Sälejärvi, W. A., & Münte, T. F. (2001). Human event-related potentials and distraction during selective listening. *Neuroscience Letters*, *297*, 1-4.
- Neville, H., Nicol, J. L., Barss, 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.
- Newman, S. D., Just, M. A., Keller, T. A., Roth, J., & Carpenter, P. A. (2003). Differential effects of syntactic and semantic processing on the subregions of Broca's area. *Cognitive Brain Research*, *16*, 297-307.
- Ni, W., Constable, R. T., Mencl, W. E., Pugh, K. R., Fulbright, R. K., Shaywitz, S. E., et al. (2000). An event-related neuroimaging study distinguishing form and content in sentence processing. *Journal of Cognitive Neuroscience*, *12*, 120-133.
- Nicholls, M. E. (1996). Temporal processing asymmetries between the cerebral hemispheres: evidence and implications. *Laterality*, *1*, 97-137.
- Nordby, H., Hammerborg, D., Roth, W. T., & Hugdahl, K. (1994). ERPs for infrequent omissions and inclusions of stimulus elements. *Psychophysiology*, *31*, 544-552.
- Nunez, P. L. (1981). *Electric fields of the brain: The Neurophysics of EEG*. (P. L. Nunez, Ed.). New York: Oxford University Press. (page 484)
- Nunez, P. L. (1990). Physical principles and neurophysiological mechanisms underlying event-related potentials. In J. W. Rohrbaugh, R. Parasuraman, & R. J. Johnson (Eds.), *Event-related brain potentials: Basic issues and applications* (p. 19-36). Oxford University Press.

- Oades, R. D., & Dittmann-Balcar, A. (1995). Mismatch negativity (MMN) is altered by directing attention. *NeuroReport*, 6, 1187-1190.
- Oken, B. S., & Chiappa, K. H. (1986). Statistical issues concerning computerized analysis of brainwave topography. *Annals of Neurology*, 19, 493-497.
- Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia*, 9, 97-113.
- Opitz, B., Mecklinger, A., von Cramon, D. Y., & Kruggel, F. (1999). Combining electrophysiological and hemodynamic measures of the auditory oddball. *Psychophysiology*, 36, 142-147.
- Opitz, B., Rinne, T., Mecklinger, A., von Cramon, D. Y., & Schröger, E. (2002). Differential contribution of frontal and temporal cortices to auditory change detection: fMRI and ERP results. *Neuroimage*, 15, 167-174.
- Orrison, W. W., Lewine, J. D., & Sanders, J. A. (1995). *Functional brain imaging*. St. Louis, MO: Mosby.
- Osterhout, L., & Holcomb, P. J. (1992). Event-related brain potentials elicited by syntactic anomaly. *Journal of Memory and Language*, 31, 785-806.
- Osterhout, L., & Mobley, L. A. (1995). Event-related brain potentials elicited by failure to agree. *Journal of Memory and Language*, 34, 739-773.
- Otten, L. J., & Rugg, M. D. (2005). Interpreting event-related brain potentials. In T. C. Handy (Ed.), *Event-related potentials. A methods handbook*. (p. 3-16). Cambridge, MA: MIT Press.
- Paavilainen, P., Alho, K., Reinikainen, K., Sams, M., & Näätänen, R. (1991). Right hemisphere dominance of different mismatch negativities. *Electroencephalography and Clinical Neurophysiology*, 78, 466-479.
- Paavilainen, P., Simola, J., Jaramillo, M., Näätänen, R., & Winkler, I. (2001). Preattentive extraction of abstract feature conjunctions from auditory stimulation as reflected by the mismatch negativity (MMN). *Psychophysiology*, 38, 359-365.
- Paavilainen, P., Valppu, S., & Näätänen, R. (2001). The additivity of the auditory feature analysis in the human brain as indexed by the mismatch negativity: 1+1 approximately 2 but 1+1+1<3. *Neuroscience Letters*, 301, 179-182.

- Pazo-Alvarez, P., Cadaveira, F., & Amenedo, E. (2003). MMN in the visual modality: A review. *Biological Psychology*, 63, 199-236.
- Pena, M., Bonatti, L. L., Nespor, M., & Mehler, J. (2002). Signal-driven computations in speech processing. *Science*, 298, 604-607.
- Penolazzi, B., Hauk, O., & Pulvermüller, F. (2007). Early semantic context integration and lexical access as revealed by event-related brain potentials. *Biological Psychology*, 74, 374-388.
- Perani, D., Cappa, S. F., Schnur, T., Tettamanti, M., Collina, S., Rosa, M. M., et al. (1999). The neural correlates of verb and noun processing. A PET study. *Brain*, 122, 2337-2344.
- Pereira, F. (2000). Formal grammar and information theory: Together again? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 358, 1239-1253.
- Perrin, F., Pernier, J., Bertrand, O., & Echallier, J. F. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology*, 72, 184-187.
- Perruchet, P., Tyler, M. D., Galland, N., & Peereman, R. (2004). Learning nonadjacent dependencies: no need for algebraic-like computations. *Journal of Experimental Psychology: General*, 133, 573-583.
- Pickering, M. J., Clifton, C., & Crocker, M. W. (2000). Architectures and mechanisms in sentence comprehension. In M. W. Crocker, M. Pickering, & C. Clifton (Eds.), *Architectures and mechanisms for language processing* (p. 1-28). Cambridge, UK: Cambridge University Press.
- Picton, T. W., Alain, C., Otten, L., Ritter, W., & Achim, A. (2000). Mismatch negativity: Different water in the same river. *Audiology & Neurootology*, 5, 111-139.
- Posner, M., & Snyder, C. (1975). Attention and Cognitive Control. In R. L. Solso (Ed.), *Information processing and cognition: The Loyola Symposium* (p. 55-85). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Pulvermüller, F. (1999). Words in the brain's language. *Behavioral and Brain Sciences*, 22, 253-279.
- Pulvermüller, F. (2002). *The neuroscience of language. On brain circuits of words and serial order*. Cambridge, UK: Cambridge University Press.

- Pulvermüller, F., & Assadollahi, R. (2007). Grammar or serial order?: Discrete combinatorial brain mechanisms reflected by the syntactic mismatch negativity. *Journal of Cognitive Neuroscience*, *19*, 971-980.
- Pulvermüller, F., Mohr, B., & Schleicher, H. (1999). Semantic or lexico-syntactic factors: What determines word-class specific activity in the human brain? *Neuroscience Letters*, *275*, 81-84.
- Pulvermüller, F., & Shtyrov, Y. (2003). Automatic processing of grammar in the human brain as revealed by the mismatch negativity. *NeuroImage*, *20*, 159-172.
- Pulvermüller, F., & Shtyrov, Y. (2006). Language outside the focus of attention: The mismatch negativity as a tool for studying higher cognitive processes. *Progress in Neurobiology*, *79*, 49-71.
- Pulvermüller, F., Shtyrov, Y., Hasting, A. S., & Carlyon, R. P. (2008). Syntax as a reflex: Neurophysiological evidence for early automaticity of grammatical processing. *Brain and Language*, *104*, 244-253.
- Pulvermüller, F., Shtyrov, Y., & Ilmoniemi, R. (2005). Brain signatures of meaning access in action word recognition. *Journal of Cognitive Neuroscience*, *17*, 884-892.
- 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.
- Rossi, S., Gugler, M., Hahne, A., & Friederici, A. (2005). When word category information encounters morphosyntax: An ERP study. *Neuroscience Letters*, *384*, 228-233.
- Rugg, M. D., & Coles, M. G. H. (Eds.). (1995). *Electrophysiology of Mind*. New York: Oxford University Press.
- Rüsseler, J., Hennighausen, E., Münte, T. F., & Rösler, F. (2003). Differences in incidental and intentional learning of sensorimotor sequences as revealed by event-related brain potentials. *Brain Research: Cognitive Brain Research*, *15*, 116-126.
- Sabri, M., & Campbell, K. B. (2000). Mismatch negativity to inclusions and omissions of stimulus features. *NeuroReport*, *11*, 1503-1507.
- Sams, M., Paavilainen, P., Alho, K., & Näätänen, R. (1985). Auditory frequency discrimination and event-related potentials. *Electroencephalography and Clinical Neurophysiology*, *62*,

437-448.

- Scherg, M., & Ebersole, J. S. (1993). Models of brain sources. *Brain Topography*, 5, 419-423.
- Scherg, M., & Picton, T. W. (1991). Separation and identification of event-related potential components by brain electric source analysis. *Electroencephalography and Clinical Neurophysiology (Suppl.)*, 42, 24-37.
- Schirmer, A., & Kotz, S. A. (2003). ERP evidence for a sex-specific Stroop effect in emotional speech. *Journal of Cognitive Neuroscience*, 15, 1135-1148.
- Schneider, W., Dumais, S. T., & Shiffrin, R. M. (1984). Automatic and control processing and attention. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of Attention* (p. 1-27). New York: Academic Press.
- Schneider, W., & Shiffrin, R. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological Review*, 84, 1-66.
- Schriefers, H., Friederici, A. D., & Rose, U. (1998). Context effects in visual word recognition: Lexical relatedness and syntactic context. *Memory & Cognition*, 26, 1292-1303.
- Schroeder, C. E., Steinschneider, M., Javitt, D. C., Tenke, C. E., Givre, S. J., Mehta, A. D., et al. (1995). Localization of ERP generators and identification of underlying neural processes. *Electroencephalography and Clinical Neurophysiology. Supplement*, 44, 55-75.
- Schröger, E. (1995). Processing of auditory deviants with changes in one versus two stimulus dimensions. *Psychophysiology*, 32, 55-65.
- Schröger, E. (1996). A neural mechanism for involuntary attention shifts to changes in auditory stimulation. *Journal of Cognitive Neuroscience*, 8, 527-539.
- Schröger, E., & Wolff, C. (1998a). Attentional orienting and reorienting is indicated by human event-related brain potentials. *NeuroReport*, 9, 3355-3358.
- Schröger, E., & Wolff, C. (1998b). Behavioral and electrophysiological effects of task-irrelevant sound change: A new distraction paradigm. *Cognitive Brain Research*, 7, 71-87.
- Shah, A. S., Bressler, S. L., Knuth, K. H., Ding, M., Mehta, A. D., Ulbert, I., et al. (2004). Neural dynamics and the fundamental mechanisms of event-related brain potentials. *Cerebral Cortex*, 14, 476-483.
- Shapiro, K. A., & Caramazza, A. (2003). The representation of grammatical categories in the brain. *Trends in Cognitive Sciences*, 7, 201-206.

- Shapiro, K. A., Pascual-Leone, A., Mottaghy, F. M., Gangitano, M., & Caramazza, A. (2001). Grammatical distinctions in the left frontal cortex. *Journal of Cognitive Neuroscience*, 13, 713-720.
- Sharbrough, F., Chatrian, G., Lesser, R., Lüders, H., Nuwer, M., & Picton, T. (1991). American Electroencephalographic Society guidelines for standard electrode position nomenclature. *Journal of Clinical Neurophysiology*, 8, 200-202.
- Shtyrov, Y., Hauk, O., & Pulvermüller, F. (2004). Distributed neuronal networks for encoding category-specific semantic information: the mismatch negativity to action words. *European Journal of Neuroscience*, 19, 1083-1092.
- Shtyrov, Y., Kujala, T., Lyytinen, H., Kujala, J., Ilmoniemi, R. J., & Näätänen, R. (2000). Lateralization of speech processing in the brain as indicated by mismatch negativity and dichotic listening. *Brain and Cognition*, 43, 392-398.
- Shtyrov, Y., & Pulvermüller, F. (2002). Memory traces for inflectional affixes as shown by mismatch negativity. *European Journal of Neuroscience*, 15, 1085-1091.
- Shtyrov, Y., Pulvermüller, F., Näätänen, R., & Ilmoniemi, R. (2003). Grammar processing outside the focus of attention: An MEG study. *Journal of Cognitive Neuroscience*, 15, 1195-1206.
- Stromswold, K., Caplan, D., Alpert, N., & Rauch, S. (1996). Localization of syntactic comprehension by positron emission tomography. *Brain and Language*, 52, 452-473.
- Sullivan, B. J., & Liu, B. (1984). On the use of singular value decomposition and decimation in discrete-time band-limited signal extrapolation. *IEEE Transactions on Acoustics, Speech & Signal Processing*, ASSP-32(6), 1201-1212.
- Sussman, E., Ritter, W., & Vaughan, H. G. J. (1998). Attention affects the organization of auditory input associated with the mismatch negativity system. *Brain Research*, 789, 130-138.
- Sussman, E., Winkler, I., Huotilainen, M., Ritter, W., & Näätänen, R. (2002). Top-down effects can modify the initially stimulus-driven auditory organization. *Cognitive Brain Research*, 13, 393-405.
- Sutton, S., Braren, M., Zubin, J., & John, E. (1965). Evoked potentials correlates of stimulus uncertainty. *Science*, 150, 1187-1188.

- Talairach, J., & Tournoux, P. (1988). *Co-planar stereotaxis atlas of the human brain*. Stuttgart: Georg Thieme Verlag.
- Tallon-Baudry, C. (2003). Oscillatory synchrony and human visual cognition. *Journal of Physiology, Paris*, 97, 355-363.
- Teder, W., Alho, K., Reinikainen, K., & Näätänen, R. (1993). Interstimulus interval and the selective-attention effect on auditory ERPs: "N1 enhancement" versus processing negativity. *Psychophysiology*, 30, 71-81.
- Teder-Sälejärvi, W. A., Münte, T. F., Sperlich, F., & Hillyard, S. A. (1999). Intra-modal and cross-modal spatial attention to auditory and visual stimuli. an event-related brain potential study. *Brain Research: Cognitive Brain Research*, 8, 327-343.
- Tervaniemi, M., Maury, S., & Näätänen, R. (1994). Neural representations of abstract stimulus features in the human brain as reflected by the mismatch negativity. *Neuroreport*, 5, 844-846.
- Tiitinen, H., May, P., Reinikainen, K., & Näätänen, R. (1994). Attentive novelty detection in humans is governed by pre-attentive sensory memory. *Nature*, 372, 90-92.
- Tyler, L. K., Bright, P., Fletcher, P., & Stamatakis, E. A. (2004). Neural processing of nouns and verbs: The role of inflectional morphology. *Neuropsychologia*, 42, 512-523.
- Uttal, W. R. (2001). *The new phrenology : The limits of localizing cognitive processes in the brain*. Cambridge, MA: MIT Press.
- Vos, S. H., Gunter, T. C., Kolk, H. H., & Mulder, G. (2001). Working memory constraints on syntactic processing: An electrophysiological investigation. *Psychophysiology*, 38, 41-63.
- Wang, J. Z., Williamson, S. J., & Kaufman, L. (1993). Magnetic source imaging based on the minimum-norm least-squares inverse. *Brain Topography*, 5, 365-371.
- Wassenaar, M., Brown, C. M., & Hagoort, P. (2004). ERP effects of subject-verb agreement violations in patients with broca's aphasia. *Journal of Cognitive Neuroscience*, 16, 553-576.
- Winkler, I., Karmos, G., & Näätänen, R. (1996). Adaptive modeling of the unattended acoustic environment reflected in the mismatch negativity event-related potential. *Brain Research*, 742, 239-252.

- Woldorff, M. G., & Hillyard, S. A. (1991). Modulation of early auditory processing during selective listening to rapidly presented tones. *Electroencephalography and Clinical Neurophysiology*, 79, 170-191.
- Wolff, C., & Schröger, E. (2001). Human pre-attentive auditory change-detection with single, double, and triple deviations as revealed by mismatch negativity additivity. *Neuroscience Letters*, 311, 37-40.
- Wright, B., & Garrett, M. (1984). Lexical decision in sentences: Effects of syntactic structure. *Memory & Cognition*, 12, 31-45.

List of Figures

2.1	Methods of cognitive neuroscience: ERP Averaging procedure and typical components	15
5.1	General methods: Splicing procedure	45
5.2	General methods: Array of electrodes used for the EEG recording	46
5.3	General methods: Topographical factors	47
6.1	Experiment 1A: MMN modulation by GRAM	56
6.2	Experiment 1A: MMN modulation by SUF	56
6.3	Experiment 1B: MMN modulation by GRAM	65
6.4	Experiment 1B: MMN modulation by CAT	65
7.1	Excursus: MMN modulation by DEV for isolated syllables	81
7.2	Excursus: MMN modulation by DEV within word context	81
8.1	Experiment 2: ERF time courses and topographic maps	94
8.2	Experiment 2: BSCD ROIs and time courses	95
9.1	Experiment 3A: ERP effect of GRAM	110
9.2	Experiment 3A: ERP effect of SUF	110
9.3	Experiment 3B: ERP effect of GRAM	113
9.4	Experiment 3B: ERP effect of CAT	113
9.5	Experiment 3B: ERP effect of GRAM for verbs	114
9.6	Experiment 3B: ERP effect of GRAM for nouns	114
10.1	Experiment 4: Sequence of events per trial	122

10.2	Experiment 4A: ERP effect of GRAM	124
10.3	Experiment 4A: ERP effect of SUF	124
10.4	Experiment 4B: ERP effect of GRAM	128
10.5	Experiment 4B: ERP effect of CAT	128
10.6	Experiment 4B: ERP effect of GRAM for verbs	129
10.7	Experiment 4B: ERP effect of GRAM for nouns	129

List of Tables

6.1	Experiment 1A: Experimental design AGREEMENT MMN	51
6.2	Experiment 1A: AGREEMENT MMN quantification 100 - 200 ms	54
6.3	Experiment 1B: Experimental design PHRASE STRUCTURE MMN	61
6.4	Experiment 1B: PHRASE STRUCTURE MMN quantification 120 - 220 ms . . .	63
7.1	Excursus: Experimental design ISOLATED SYLLABLE VS. WORD CONTEXT MMN	76
7.2	Excursus: ISOLATED SYLLABLE VS. WORD CONTEXT MMN quantification 120 - 220 ms	78
8.1	Experiment 2: Experimental design agreement vs. phrase structure MMNm . .	90
8.2	Experiment 2: Regions of interest (ROIs) as defined for the BSCD analysis . .	92
8.3	Experiment 2: BSCD peak amplitude analysis of the MMNm	97
8.4	Experiment 2: BSCD peak latency analysis of the MMNm	98
9.1	Experiments 3 and 4: Design for testing the processing of subject-verb agree- ment in variable two-word utterances	107
9.2	Experiments 3 and 4: Design for testing phrase structure processing in vari- able two-word utterances	111
11.1	Summary: Experiments, objectives, main findings and conclusions	139

List of Items

Item	Verb	Noun	DP	Verb (engl.)	Noun (engl.)
1	ackern	Acker	late	<i>to plug away</i>	<i>acre</i>
2	basteln	Bastler	early	<i>to tinker</i>	<i>tinkerer</i>
3	bechern	Becher	late	<i>to cup</i>	<i>mug</i>
4	blinzeln	Blinzler	early	<i>to blink</i>	<i>blink</i>
5	bügeln	Bügel	late	<i>to iron</i>	<i>coat hanger</i>
6	bündeln	Bündel	late	<i>to bundle</i>	<i>bundle</i>
7	drängeln	Drängler	early	<i>to push</i>	<i>so who pushes</i>
8	falten	Falter	early	<i>to fold</i>	<i>butterfly</i>
9	filtern	Filter	late	<i>to filter</i>	<i>filter</i>
10	hobeln	Hobel	late	<i>to plane</i>	<i>planer</i>
11	kaspern	Kasper	late	<i>to clown about</i>	<i>buffoon</i>
12	kegeln	Kegel	late	<i>to bowl</i>	<i>cone</i>
13	kellnern	Kellner	late	<i>to serv</i>	<i>waiter</i>
14	ködern	Köder	late	<i>to bait</i>	<i>bait</i>
15	löffeln	Löffel	late	<i>to spoon</i>	<i>spoon</i>
16	meistern	Meister	late	<i>to master</i>	<i>master</i>
17	mieten	Mieter	early	<i>to rent</i>	<i>tenant</i>
18	mustern	Muster	late	<i>to examine</i>	<i>pattern</i>
19	nageln	Nagel	late	<i>to nail</i>	<i>nail</i>
20	opfern	Opfer	late	<i>to sacrifice</i>	<i>victim</i>
21	paddeln	Paddel	late	<i>to paddle</i>	<i>paddle</i>
22	pflastern	Pflaster	late	<i>to pave</i>	<i>pavement</i>

Item	Verb	Noun	DP	Verb (engl.)	Noun (engl.)
23	rätseln	Rätsel	late	<i>to puzzle</i>	<i>puzzle</i>
24	rudern	Ruder	late	<i>to row</i>	<i>oar</i>
25	satteln	Sattel	late	<i>to saddle</i>	<i>saddle</i>
26	schlachten	Schlachter	early	<i>to butcher</i>	<i>butcher</i>
27	schlichten	Schlichter	early	<i>to conciliate</i>	<i>conciliator</i>
28	schnorcheln	Schnorchel	late	<i>to snorkel</i>	<i>snorkel</i>
29	schulden	Schuldner	early	<i>to owe</i>	<i>debitor</i>
30	schustern	Schuster	late	<i>to cobble</i>	<i>cobbler</i>
31	segeln	Segel	late	<i>to sail</i>	<i>sail</i>
32	speichern	Speicher	late	<i>to store</i>	<i>store</i>
33	spitzeln	Spitzel	late	<i>to spy</i>	<i>snitch</i>
34	sprinten	Sprinter	early	<i>to sprint</i>	<i>sprinter</i>
35	stapeln	Stapel	late	<i>to stack</i>	<i>stack</i>
36	stempeln	Stempel	late	<i>to stamp</i>	<i>stamp</i>
37	stiefeln	Stiefel	late	<i>to stride</i>	<i>boot</i>
38	tadeln	Tadel	late	<i>to reprove</i>	<i>reproval</i>
39	testen	Tester	early	<i>to test</i>	<i>tester</i>
40	toasten	Toaster	early	<i>to toast</i>	<i>Toaster</i>
41	trampeln	Trampel	late	<i>to trample</i>	<i>so who tramples</i>
42	trödeln	Trödler	early	<i>to loiter</i>	<i>loiterer</i>
43	trommeln	Trommler	early	<i>to drum</i>	<i>drummer</i>
44	wirbeln	Wirbel	late	<i>to whirl</i>	<i>whirl</i>
45	würfeln	Würfel	late	<i>to dice</i>	<i>dice</i>
46	zaubern	Zauber	late	<i>to conjure</i>	<i>spell</i>
47	zimmern	Zimmer	late	<i>to carpenter</i>	<i>room</i>
48	züchten	Züchter	early	<i>to breed</i>	<i>breeder</i>
49	zügeln	Zügel	late	<i>to rein</i>	<i>rein</i>
50	zweifeln	Zweifel	late	<i>to doubt</i>	<i>doubt</i>

List of Abbreviations

Δ	Delta = amplitude difference in μV
μV	microVolt
Ag/AgCl	silver/silverchlorid
ANOVA	Analysis of Variance
BA	Brodmann Area
BSCD	brain surface current density
DP	divergence point
EEG	electroencephalogram
ELAN	early left anterior negativity
EOG	electrooculogramm
ERP	event related (brain) potential
fMRI	functional Magnetic Resonance Imaging
FSG	final state grammar
fT	femto Tesla
IFG	inferior frontal gyrus
kΩ	kiloOhm

kHz	kiloHertz
LAN	left anterior negativity
LQ	laterality quotient
MEG	magnetoencephalography
MMN	mismatch negativity
MMNm	magnetic mismatch negativity
MNLS	minimum norm least squares
ms	milliseconds
MTG	middle temporal gyrus
nAm	nano-Ampere-meter
NP	noun phrase
PET	Positron Emission Tomography
PSG	phrase structure grammar
rCBF	regional cerebral blood flow
ROI	region of interest
SD	standard deviation
SNR	signal-to-noise ratio
SOA	stimulus onset asynchrony
STG	superior temporal gyrus

Curriculum Vitae

Anna Sophie Hasting

Date of Birth	26/02/1978
Place of Birth	Bremen, Germany
Marital Status	married; one son

Education

1997	Abitur (A-Levels) Altes Gymnasium Bremen, Germany
1998 - 2004	Study of Psychology (Diplom) University of Konstanz, Germany
2004 - 2008	PhD student, IPP "From Signal Processing to Behaviour" University of Leipzig, Germany

Professional Experience

1999 - 2001	Student research assistant Dept. of Clinical Psychology, University of Konstanz, Germany
2001 - 2002	Scientific internship MRC Cognition and Brain Sciences Unit, Cambridge, UK
2003	Scientific internship MPI for Human Cognitive and Brain Sciences, Leipzig, Germany
2004 - 2008	PhD student MPI for Human Cognitive and Brain Sciences, Leipzig, Germany

Awards

2004	Award of the "Verein der Ehemaligen der Universität Konstanz" (VEUK) for outstanding study achievements
------	---

Bibliographic Details

Hasting, Anna S.

SYNTAX IN A BLINK: EARLY AND AUTOMATIC PROCESSING OF SYNTACTIC RULES AS
REVEALED BY EVENT-RELATED BRAIN POTENTIALS

Universität Leipzig, Dissertation

184 pages, 211 references, 25 figures, 13 tables

Paper The present dissertation investigates the timing and automaticity of two syntactic sub-processes, namely phrase structure building and the syntactic-relational processing of agreement, by means of event-related brain potentials (ERPs). Consistent with linguistically based serial models of parsing, most previous ERP studies on syntax processing reported automatic effects of initial phrase structure building in the time range of 150 to 200 ms, whereas less automatic effects of agreement were hardly ever observed before 300 ms. However, an extension of the mismatch negativity (MMN) paradigm recently showed that this early automatic ERP component is reliably modulated by agreement manipulations. Although this observation challenges the previous findings, it is difficult to put into perspective due to methodological differences in the experimental approaches.

Therefore, a set of experiments was conducted in which the two syntactic subprocesses were investigated under strictly comparable conditions. Experiment 1 replicated the syntactic MMN effect for agreement violations and extended it to word category violations that disrupt phrase structure building. Experiment 2 tested whether the agreement and the phrase structure MMN are subserved by different cortical areas. Experiment 3 loosened the restrictive and repetitive MMN paradigm by greatly increasing the variability of the speech stimuli and by replacing the oddball sequences with a randomized presentation. And finally, Experiment 4 compared the two syntactic subprocesses under focused attention.

In all experiments, syntactic violations elicited a negative ERP component with an onset latency of about 100 ms. This negativity occurred independently of the violation type, the experimental paradigm and the participants' attention. It is concluded that the human brain

grasps syntactic rules invariably early and automatically as long as they are realized at a local level. This rapid syntactic processing capacity is assumed to be based on syntactic priming.

Referat Die vorliegende Dissertation untersucht die zeitliche Abfolge und Automatizität zweier syntaktischer Subprozesse, nämlich Phrasenstrukturaufbau und syntaktisch-relationale Verarbeitung von Kongruenz, anhand von Ereigniskorrelierten Potentialen (EKPs). In Übereinstimmung mit linguistisch begründeten seriellen Parsing-Modellen berichten die meisten bisherigen EKP Studien zur Syntaxverarbeitung automatische Effekte des initialen Phrasenstrukturaufbaus im Zeitbereich um 150 bis 200 ms, während weniger automatische Kongruenzeffekte kaum vor 300 ms beobachtet wurden. Allerdings zeigte kürzlich eine Ausweitung des Mismatch Negativity (MMN) Paradigmas, dass diese frühe automatische EKP-Komponente zuverlässig durch Kongruenzmanipulationen moduliert wird. Obwohl diese Beobachtung die bisherigen Befunde in Frage stellt, ist sie aufgrund von methodischen Unterschieden in den experimentellen Herangehensweisen schwierig einzuordnen.

Daher wurde eine Reihe von Experimenten durchgeführt, in denen die zwei syntaktischen Subprozesse unter streng vergleichbaren Bedingungen untersucht wurden. Experiment 1 replizierte den syntaktischen MMN Effekt für Kongruenzverletzungen und weitete ihn auf Wortkategorieverletzungen (die den Phrasenstrukturaufbau unterbrechen) aus. Experiment 2 untersuchte, ob die Kongruenz- und die Phrasenstruktur MMN von unterschiedlichen kortikalen Arealen bedient werden. Experiment 3 lockerte das restriktive und repetitive MMN Paradigma durch eine stark erhöhte Variabilität der Sprachreize und durch deren randomisierte Darbietung anstelle der Oddball-Sequenzen auf. Abschliessend verglich Experiment 4 die beiden syntaktischen Subprozesse unter fokussierter Aufmerksamkeit.

In allen Experimenten lösten syntaktische Verletzungen eine negative EKP Komponente mit einer Anfangslatenz um 100 ms aus. Diese Negativierung erschien unabhängig von dem Verletzungstyp, dem experimentellen Paradigma und der Aufmerksamkeit der Teilnehmer. Daraus wird geschlossen, dass das menschliche Gehirn syntaktische Regeln beständig früh und automatisch erfassen kann, solange diese lokal realisiert sind. Es wird angenommen, dass diese schnelle syntaktische Verarbeitungskapazität auf syntaktischem Priming basiert.

Selbständigkeitserklärung

Hiermit erkläre ich, dass die vorliegende Arbeit ohne unzulässige Hilfe und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt wurde und dass die aus fremden Quellen direkt oder indirekt übernommenen Gedanken in der Arbeit als solche kenntlich gemacht worden sind.

Anna S. Hasting

Leipzig, 26. Oktober 2007

MPI Series in Human Cognitive and Brain Sciences:

- 1 Anja Hahne
Charakteristika syntaktischer und semantischer Prozesse bei der auditiv Sprachverarbeitung: Evidenz aus ereigniskorrelierten Potentialstudien
- 2 Ricarda Schubotz
Erinnern kurzer Zeitdauern: Behaviorale und neurophysiologische Korrelate einer Arbeitsgedächtnisfunktion
- 3 Volker Bosch
Das Halten von Information im Arbeitsgedächtnis: Dissoziationen langsamer corticaler Potentiale
- 4 Jorge Jovicich
An investigation of the use of Gradient- and Spin-Echo (GRASE) imaging for functional MRI of the human brain
- 5 Rosemary C. Dymond
Spatial Specificity and Temporal Accuracy in Functional Magnetic Resonance Investigations
- 6 Stefan Zysset
Eine experimentalpsychologische Studie zu Gedächtnisabrufprozessen unter Verwendung der funktionellen Magnetresonanztomographie
- 7 Ulrich Hartmann
Ein mechanisches Finite-Elemente-Modell des menschlichen Kopfes
- 8 Bertram Opitz
Funktionelle Neuroanatomie der Verarbeitung einfacher und komplexer akustischer Reize: Integration haemodynamischer und elektrophysiologischer Maße
- 9 Gisela Müller-Plath
Formale Modellierung visueller Suchstrategien mit Anwendungen bei der Lokalisation von Hirnfunktionen und in der Diagnostik von Aufmerksamkeitsstörungen
- 10 Thomas Jacobsen
Characteristics of processing morphological structural and inherent case in language comprehension
- 11 Stefan Kölsch
Brain and Music
A contribution to the investigation of central auditory processing with a new electrophysiological approach
- 12 Stefan Frisch
Verb-Argument-Struktur, Kasus und thematische Interpretation beim Sprachverstehen
- 13 Markus Ullsperger
The role of retrieval inhibition in directed forgetting – an event-related brain potential analysis
- 14 Martin Koch
Measurement of the Self-Diffusion Tensor of Water in the Human Brain
- 15 Axel Hutt
Methoden zur Untersuchung der Dynamik raumzeitlicher Signale

- 16 Frithjof Kruggel
Detektion und Quantifizierung von Hirnaktivität mit der funktionellen Magnetresonanztomographie
- 17 Anja Dove
Lokalisierung an internen Kontrollprozessen beteiligter Hirngebiete mithilfe des Aufgabenwechselparadigmas und der ereigniskorrelierten funktionellen Magnetresonanztomographie
- 18 Karsten Steinhauer
Hirnphysiologische Korrelate prosodischer Satzverarbeitung bei gesprochener und geschriebener Sprache
- 19 Silke Urban
Verbinformationen im Satzverstehen
- 20 Katja Werheid
Implizites Sequenzlernen bei Morbus Parkinson
- 21 Doreen Nessler
Is it Memory or Illusion? Electrophysiological Characteristics of True and False Recognition
- 22 Christoph Herrmann
Die Bedeutung von 40-Hz-Oszillationen für kognitive Prozesse
- 23 Christian Fiebach
Working Memory and Syntax during Sentence Processing. A neurocognitive investigation with event-related brain potentials and functional magnetic resonance imaging
- 24 Grit Hein
Lokalisation von Doppelaufgabendefiziten bei gesunden älteren Personen und neurologischen Patienten
- 25 Monica de Filippis
Die visuelle Verarbeitung unbeachteter Wörter. Ein elektrophysiologischer Ansatz
- 26 Ulrich Müller
Die catecholaminerge Modulation präfrontaler kognitiver Funktionen beim Menschen
- 27 Kristina Uhl
Kontrollfunktion des Arbeitsgedächtnisses über interferierende Information
- 28 Ina Bornkessel
The Argument Dependency Model: A Neurocognitive Approach to Incremental Interpretation
- 29 Sonja Lattner
Neurophysiologische Untersuchungen zur auditorischen Verarbeitung von Stimminformationen
- 30 Christin Grünewald
Die Rolle motorischer Schemata bei der Objektrepräsentation: Untersuchungen mit funktioneller Magnetresonanztomographie
- 31 Annett Schirmer
Emotional Speech Perception: Electrophysiological Insights into the Processing of Emotional Prosody and Word Valence in Men and Women

- 32 André J. Szameitat
Die Funktionalität des lateral-präfrontalen Cortex für die Verarbeitung von Doppelaufgaben
- 33 Susanne Wagner
Verbales Arbeitsgedächtnis und die Verarbeitung ambiger Wörter in Wort- und Satzkontexten
- 34 Sophie Manthey
Hirn und Handlung: Untersuchung der Handlungsrepräsentation im ventralen prämotorischen Cortex mit Hilfe der funktionellen Magnet-Resonanz-Tomographie
- 35 Stefan Heim
Towards a Common Neural Network Model of Language Production and Comprehension: fMRI Evidence for the Processing of Phonological and Syntactic Information in Single Words
- 36 Claudia Friedrich
Prosody and spoken word recognition: Behavioral and ERP correlates
- 37 Ulrike Lex
Sprachlateralisierung bei Rechts- und Linkshändern mit funktioneller Magnetresonanztomographie
- 38 Thomas Arnold
Computergestützte Befundung klinischer Elektroenzephalogramme
- 39 Carsten H. Wolters
Influence of Tissue Conductivity Inhomogeneity and Anisotropy on EEG/MEG based Source Localization in the Human Brain
- 40 Ansgar Hantsch
Fisch oder Karpfen? Lexikale Aktivierung von Benennungsalternative bei der Objektbenennung
- 41 Peggy Bungert
*Zentralnervöse Verarbeitung akustischer Informationen
Signalidentifikation, Signallateralisation und zeitgebundene Informationsverarbeitung bei Patienten mit erworbenen Hirnschädigungen*
- 42 Daniel Senkowski
Neuronal correlates of selective attention: An investigation of electro-physiological brain responses in the EEG and MEG
- 43 Gert Wollny
Analysis of Changes in Temporal Series of Medical Images
- 44 Angelika Wolf
Sprachverstehen mit Cochlea-Implantat: EKP-Studien mit postlingual ertaubten erwachsenen CI-Trägern
- 45 Kirsten G. Volz
Brain correlates of uncertain decisions: Types and degrees of uncertainty
- 46 Hagen Huttner
Magnetresonanztomographische Untersuchungen über die anatomische Variabilität des Frontallappens des menschlichen Großhirns
- 47 Dirk Köster
Morphology and Spoken Word Comprehension: Electrophysiological Investigations of Internal Compound Structure

- 48 Claudia A. Hruska
Einflüsse kontextueller und prosodischer Informationen in der auditorischen Satzverarbeitung: Untersuchungen mit ereigniskorrelierten Hirnpotentialen
- 49 Hannes Ruge
Eine Analyse des raum-zeitlichen Musters neuronaler Aktivierung im Aufgabenwechselparadigma zur Untersuchung handlungssteuernder Prozesse
- 50 Ricarda I. Schubotz
Human premotor cortex: Beyond motor performance
- 51 Clemens von Zerssen
Bewusstes Erinnern und falsches Wiedererkennen: Eine funktionelle MRT Studie neuroanatomischer Gedächtniskorrelate
- 52 Christiane Weber
Rhythm is gonna get you. Electrophysiological markers of rhythmic processing in infants with and without risk for Specific Language Impairment (SLI)
- 53 Marc Schönwiesner
Functional Mapping of Basic Acoustic Parameters in the Human Central Auditory System
- 54 Katja Fiehler
Temporospatial characteristics of error correction
- 55 Britta Stolterfoht
Processing Word Order Variations and Ellipses: The Interplay of Syntax and Information Structure during Sentence Comprehension
- 56 Claudia Danielmeier
Neuronale Grundlagen der Interferenz zwischen Handlung und visueller Wahrnehmung
- 57 Margret Hund-Georgiadis
Die Organisation von Sprache und ihre Reorganisation bei ausgewählten, neurologischen Erkrankungen gemessen mit funktioneller Magnetresonanztomographie – Einflüsse von Händigkeit, Läsion, Performanz und Perfusion
- 58 Jutta L. Mueller
Mechanisms of auditory sentence comprehension in first and second language: An electrophysiological miniature grammar study
- 59 Franziska Biedermann
Auditorische Diskriminationsleistungen nach unilateralen Läsionen im Di- und Telenzephalon
- 60 Shirley-Ann Rüchemeyer
The Processing of Lexical Semantic and Syntactic Information in Spoken Sentences: Neuroimaging and Behavioral Studies of Native and Non-Native Speakers
- 61 Kerstin Leuckefeld
The Development of Argument Processing Mechanisms in German. An Electrophysiological Investigation with School-Aged Children and Adults
- 62 Axel Christian Kühn
Bestimmung der Lateralisierung von Sprachprozessen unter besondere Berücksichtigung des temporalen Cortex, gemessen mit fMRT

- 63 Ann Pannekamp
Prosodische Informationsverarbeitung bei normalsprachlichem und deviantem Satzmaterial: Untersuchungen mit ereigniskorrelierten Hirnpotentialen
- 64 Jan Derrfuß
Functional specialization in the lateral frontal cortex: The role of the inferior frontal junction in cognitive control
- 65 Andrea Mona Philipp
*The cognitive representation of tasks
Exploring the role of response modalities using the task-switching paradigm*
- 66 Ulrike Toepel
Contrastive Topic and Focus Information in Discourse – Prosodic Realisation and Electrophysiological Brain Correlates
- 67 Karsten Müller
Die Anwendung von Spektral- und Waveletanalyse zur Untersuchung der Dynamik von BOLD-Zeitreihen verschiedener Hirnareale
- 68 Sonja A.Kotz
The role of the basal ganglia in auditory language processing: Evidence from ERP lesion studies and functional neuroimaging
- 69 Sonja Rossi
The role of proficiency in syntactic second language processing: Evidence from event-related brain potentials in German and Italian
- 70 Birte U. Forstmann
Behavioral and neural correlates of endogenous control processes in task switching
- 71 Silke Paulmann
Electrophysiological Evidence on the Processing of Emotional Prosody: Insights from Healthy and Patient Populations
- 72 Matthias L. Schroeter
Enlightening the Brain – Optical Imaging in Cognitive Neuroscience
- 73 Julia Reinholz
Interhemispheric interaction in object- and word-related visual areas
- 74 Evelyn C. Ferstl
The Functional Neuroanatomy of Text Comprehension
- 75 Miriam Gade
Aufgabeneinhibition als Mechanismus der Konfliktreduktion zwischen Aufgabenrepräsentationen
- 76 Juliane Hofmann
Phonological, Morphological, and Semantic Aspects of Grammatical Gender Processing in German
- 77 Petra Augurzky
Attaching Relative Clauses in German – The Role of Implicit and Explicit Prosody in Sentence Processing
- 78 Uta Wolfensteller
Habituelle und arbiträre sensomotorische Verknüpfungen im lateralen prämotorischen Kortex des Menschen

- 79 Päivi Sivonen
Event-related brain activation in speech perception: From sensory to cognitive processes
- 80 Yun Nan
Music phrase structure perception: the neural basis, the effects of acculturation and musical training
- 81 Katrin Schulze
Neural Correlates of Working Memory for Verbal and Tonal Stimuli in Nonmusicians and Musicians With and Without Absolute Pitch
- 82 Korinna Eckstein
Interaktion von Syntax und Prosodie beim Sprachverstehen: Untersuchungen anhand ereignis-korrelierter Hirnpotentiale
- 83 Florian Th. Siebörger
Funktionelle Neuroanatomie des Textverstehens: Kohärenzbildung bei Witzen und anderen ungewöhnlichen Texten
- 84 Diana Böttger
Aktivität im Gamma-Frequenzbereich des EEG: Einfluss demographischer Faktoren und kognitiver Korrelate
- 85 Jörg Bahlmann
Neural correlates of the processing of linear and hierarchical artificial grammar rules: Electrophysiological and neuroimaging studies
- 86 Jan Zwickel
Specific Interference Effects Between Temporally Overlapping Action and Perception
- 87 Markus Ullsperger
Functional Neuroanatomy of Performance Monitoring: fMRI, ERP, and Patient Studies
- 88 Susanne Dietrich
Vom Brüllen zum Wort – MRT-Studien zur kognitiven Verarbeitung emotionaler Vokalisationen
- 89 Maren Schmidt-Kassow
What's Beat got to do with it? The Influence of Meter on Syntactic Processing: ERP Evidence from Healthy and Patient populations
- 90 Monika Lück
Die Verarbeitung morphologisch komplexer Wörter bei Kindern im Schulalter: Neurophysiologische Korrelate der Entwicklung
- 91 Diana P. Szameitat
Perzeption und akustische Eigenschaften von Emotionen in menschlichem Lachen
- 92 Beate Sabisch
Mechanisms of auditory sentence comprehension in children with specific language impairment and children with developmental dyslexia: A neurophysiological investigation
- 93 Regine Oberecker
Grammatikverarbeitung im Kindesalter: EKP-Studien zum auditorischen Satzverstehen
- 94 Şükrü Barış Demiral
Incremental Argument Interpretation in Turkish Sentence Comprehension
- 95 Henning Holle
The Comprehension of Co-Speech Iconic Gestures: Behavioral, Electrophysiological and Neuroimaging Studies

96 Marcel Braß

Das inferior frontale Kreuzungsareal und seine Rolle bei der kognitiven Kontrolle unseres Verhaltens