

Claudia Männel: Prosodic Processing during Language Acquisition.
Electrophysiological Studies on Intonational Phrase Processing. Leipzig:
Max Planck Institute for Human Cognitive and Brain Sciences, 2009
(MPI Series in Human Cognitive and Brain Sciences; 115)

Impressum

Max Planck Institute for Human Cognitive and Brain Sciences, 2009



Diese Arbeit ist unter folgender Creative Commons-Lizenz lizenziert:
<http://creativecommons.org/licenses/by-nc/3.0/de>

Titelbild: EEG-Ableitung bei einem Säugling – mit freundlicher Genehmigung der Eltern
Coverpicture: Infant-EEG recording – with friendly permission of the parents

Druck: Sächsisches Druck- und Verlagshaus Direct World, Dresden

ISBN 978 3-936816-89-1

Prosodic processing during language acquisition:
Electrophysiological studies on intonational phrase processing

DISSERTATION

zur Erlangung des akademischen Grades

doctor rerum naturalium (Dr. rer. nat.)

im Fach Psychologie

eingereicht an der

Mathematisch-Naturwissenschaftlichen Fakultät II

der Humboldt-Universität zu Berlin

von

Diplom-Psychologin Claudia Männel

geboren am 26. Oktober 1973 in Schlema

Präsident der Humboldt-Universität zu Berlin:

Prof. Dr. Dr. h.c. Christoph Marksches

Dekan der Mathematisch-Naturwissenschaftlichen Fakultät II:

Prof. Dr. Wolfgang Coy

Gutachterinnen:

Prof. Dr. Angela D. Friederici

Prof. Dr. Elke van der Meer

Prof. Dr. Isabell Wartenburger

Tag der Verteidigung: 27. Mai 2009

Acknowledgements

Diese Arbeit entstand im Rahmen meiner Doktorandenzeit am Max-Planck-Institut für Kognitions- und Neurowissenschaften Leipzig und wurde durch die Unterstützung vieler Kollegen und Freunde ermöglicht. Allen diesen Personen möchte ich an dieser Stelle herzlich danken.

Für die hervorragende Betreuung und die exzellenten Arbeitsmöglichkeiten am Max-Planck-Institut danke ich Prof. Dr. Angela D. Friederici. Für die Annahme der Begutachtung dieser Arbeit gilt mein Dank Prof. Dr. Angela D. Friederici, Prof. Dr. Elke van der Meer und Prof. Dr. Isabell Wartenburger.

Großer Dank gilt meinen Arbeitskollegen im Berliner Lindenhof und den Leipziger Arbeitskollegen für anregende Diskussionen – fachlicher und privater Natur – und fortwährende Unterstützung unterschiedlicher Art.

Kristiane Werrmann, Sylvia Stasch und Cornelia Schmidt gilt mein Dank für die Datenerhebung bei Erwachsenen. Christina Rügen, Jödis Haselow, Tina Radtke und Kristiane Werrmann danke ich für die Erhebung der Kinderdaten – die nicht nur technisches Wissen, sondern den einfühlsamen Umgang mit Kindern unterschiedlichen Alters, einschließlich deren Eltern, beinhaltet.

Bei Andrea Gast-Sandmann und Kerstin Flake bedanke ich mich für die schnelle und professionelle Anfertigung von Abbildungen – mit bewundernswerter Freundlichkeit und Ruhe bei ständigen Änderungswünschen. Dr. Maren Grigutsch danke ich für die vielen interessanten methodischen Diskussionen sowie die geduldige Hilfe bei Fragen zur Datenanalyse und der Erstellung von Skripten. Bei Dr. Burkhard Maess bedanke ich mich für die lehrreichen Einblicke in die Methode der PCA und die Unterstützung bei der entsprechenden Datenanalyse.

Thea Kumsteller danke ich für die freundliche und schnelle Bereitstellung von Literatur und die ständige Fristverlängerung für diese.

Bei Nicole Harkin und Brian Corrigan bedanke ich mich für das geduldige und konstruktive Korrekturlesen. Dr. Jelena Krivokapic danke ich für die hilfreichen inhaltlichen Kommentare.

Mein besonderer Dank gebührt meiner Familie und meinen Freunden für ihre rückhaltlose Unterstützung in allen Phasen dieser Arbeit – dieser Dank gilt auch Meinolf.

Preface

The wonder of language acquisition, with its remarkable speed and high levels of success, remains a mystery. At birth, infants are able to communicate their basic needs by different ways of crying. Also, from birth on, infants show a preference for the sound of their native language. Following these first language-related steps, there is a fast progression in the development of perceptive and expressive language skills. At around four months, babies start to babble, the earliest stages of language production. A mere twelve months after birth most babies start to speak their first words, and about half a year later they even speak in short sentences. Finally, at the end of most children's third year, they have acquired at least 500 words and know how to combine them into complex utterances.

Although a detailed outline of the language acquisition process exists (e.g., Clark, 2003; Szagun, 2006), crucial questions remain. One puzzling issue is how children get started on this impressive learning process. How do infants know what sound patterns to pay attention to, so that they eventually detect phrases and words in the ongoing speech stream and later acquire the meaning and syntactic features associated with these linguistic units? For example, before learning what the word *car* means (lexical-semantic information) and that this word is a noun, which can serve as subject or object of a sentence (syntactic information), infants need to segment the according linguistic unit *car* from the sounds they hear. Thus, the most challenging task is to initially identify relevant linguistic units in the speech stream before further learning can take place. The fact that infants are typically not presented with single words but connected speech, where only a few reliable cues mark linguistic units, shows that this task is by no means trivial (Cutler, 1994). However, prosodic cues, such as pauses and pitch changes, signal boundaries that are particularly prominent for larger units, e.g., phrases (Cooper & Paccia-Cooper, 1980). As proposed by the *prosodic bootstrapping* hypothesis (Gleitman & Wanner, 1982), infants can ultimately arrive at the syntactic units (e.g., clauses) of their native language by discovering those prosodically marked units (e.g., intonational phrases). Thus, the initial processing of phrase-level prosodic information seems to be essential to later language learning.

The so-called segmentation problem has been a prominent topic in developmental behavioral research. However, studying children's first steps in language acquisition is not easily accomplished because a good deal of learning takes place before children are able to speak and show overt responses

to what they actually perceive. Children's perceptive language skills develop much earlier than their expressive skills, but are for the most part beyond the scope of observation. The method of event-related brain potentials (ERP) allows to virtually look into the brain, where the acquisition of language is taking place. The use of the ERP method to investigate online processing has been successfully proven in adults and particular ERP components have been identified that are specific to various aspects of language processing (e.g., Friederici, 2004). In the current thesis, ERPs are the method of choice to investigate phrase-level prosodic processing during early infancy and preschool age. More specifically, the present ERP studies examine the neurophysiological basis of intonational phrase (IP) processing across different developmental stages and, in addition, aim to 1) specify the role of particular prosodic boundary cues in IP processing and 2) evaluate the interaction between prosodic processing abilities and syntactic knowledge acquired at different age levels.

Part I of this thesis provides an introduction into the topic of prosody, covering both theoretical considerations and empirical evidence. In Chapter 1, prosody is described as an inherent feature of spoken language and its role in language comprehension is reviewed. In Chapter 2, the role of prosodic information in language acquisition is discussed and an overview of developmental behavioral research on prosodic processing given. Chapter 3 summarizes results of neuroimaging studies on phrase-level prosodic processing that have been incorporated into neurocognitive models of language comprehension. In Chapter 4, a brief summary of the introduction is provided. In *Part II*, the method at hand is explained, with an introduction to ERP components that have been observed in language studies and the ERP method's advantages for research in Developmental Cognitive Neuroscience (Chapter 5).¹ In the empirical part (*Part III*), the outline of general research questions (Chapter 6) is followed by a description of the experimental methods applied in the current experiments (Chapter 7).² Study I investigates IP processing in infants and adults, specifying the role of the pause as prosodic boundary cue (Chapter 8).³ Study II examines IP processing in toddlers and preschool children, thus evaluating prosodic processing at different levels of syntax acquisition (Chapter 9). In Chapter 10, the current findings are summarized and discussed in light of previous behavioral and neurophysiological studies on phrase-level prosodic processing.

¹Chapter 5 is a modified version of Männel (2008) and Männel and Friederici (2008).

²Sections of Chapter 7 have been published in Männel and Friederici (in press).

³Chapter 8 is a modified version of Männel and Friederici (in press).

Contents

I	Introduction	1
1	The role of prosody in language processing	3
1.1	The prosodic organization of language	4
1.1.1	Prosodic information in spoken language	4
1.1.2	The prosodic hierarchy	8
1.2	Prosody in auditory sentence comprehension	11
1.2.1	Prosodic information in lexical segmentation	12
1.2.2	Prosodic information in syntactic processing	14
2	The role of prosody in language acquisition	19
2.1	Acquisition mechanisms: Learning by bootstrapping	20
2.2	The processing of prosodic information in infancy and childhood	23
3	The neuroscience of prosody	27
3.1	Patient studies and neuroimaging studies on phrase-level prosodic processing	28
3.2	Electrophysiological studies on phrase-level prosodic processing: The Closure Positive Shift	32
3.3	Neurocognitive models of language comprehension	36
4	Summary of introduction	39

II Methodology	41
5 The ERP method in developmental cognitive neuroscience	43
5.1 Electroencephalography and Event-related brain potentials	44
5.1.1 From EEG to ERP	44
5.1.2 ERP components and their interpretation	45
5.1.3 Advantages and disadvantages of the ERP method	50
5.2 ERP components associated with language processing	52
5.3 The ERP method in developmental research: Some considerations	56
III Empirical Investigations	59
6 Research questions	61
7 General methods	63
7.1 Subjects	63
7.1.1 Adults	63
7.1.2 Children	63
7.2 Stimulus material	64
7.2.1 Naturally spoken sentences	65
7.2.2 Sentences with neutralized pause	69
7.3 Experimental procedure	70
7.4 EEG recordings	71
7.5 Data processing and analysis	71
8 Study I – Pauses and intonational phrasing: ERP studies in 5-month-old German infants and adults	73
8.1 Introduction	73
8.2 Methods	77
8.2.1 Subjects	77
8.2.2 Stimuli	77

8.2.3	Data analysis	77
8.3	Results	78
8.3.1	Naturally spoken sentences	78
8.3.2	Sentences with neutralized pause	81
8.3.3	Positive shift in the infant ERP: CPS or obligatory onset response	85
8.3.4	The role of the pause in obligatory onset responses: Infant and adult ERPs	88
8.4	Discussion and interim conclusions	93
9	Study II – The emergence of the CPS during childhood: ERP studies on intonational phrase processing in 2-, 3-, and 6-year-old children	99
9.1	Introduction	99
9.2	Methods	103
9.2.1	Subjects	103
9.2.2	Stimuli	103
9.2.3	Data analysis	104
9.3	Results	104
9.3.1	ERP data of 21-month-olds	104
9.3.2	ERP data of 3-year-olds	105
9.3.3	ERP data of 3-year-olds and 21-month-olds: A developmental comparison	107
9.3.4	ERP data of 6-year-olds	111
9.3.5	PCA on the ERP data of 6-year-olds	115
9.4	Discussion and interim conclusions	121
10	General discussion and future directions	127
10.1	Summary of Study I	127
10.2	Pauses and intonational phrasing: When infants learn German	129
10.3	Summary of Study II	135
10.4	Prosody and syntax in language acquisition: An interactive relationship	136
10.5	Conclusion	141
	References	143

List of Figures	169
List of Tables	171
Appendices	173

Part I

Introduction

Chapter 1

The role of prosody in language processing

Language is a complex multi-faceted system that comprises the levels *pragmatics* (the mechanisms of language use and speech acts), *semantics* (the meaning of language units), *syntax* (the rules of sentence form), *morphology* (the rules of word form), and *phonology* (the sound system of language units). The study of *prosody*, as a specific area of phonology, has gained increasing interest within the last decades, attracting not only linguists and phonologists but also psycholinguists and psychologists in the field of adult language processing and, most importantly, language development.

As its translation from Greek suggests (*pros* = thereto, *ode* = song and *prosadein* = to sing thereto), prosody refers to the rhythmic and melodic properties of spoken language.⁴ Since these are sound features that usually span across several phonemes or segments, prosody is the particular subpart of phonology that deals with linguistic units at the suprasegmental level, e.g., words and sentences. Accordingly, synonyms of prosody are *suprasegmental phonology* and *prosodic phonology*.

Importantly, prosody stands for those sound phenomena that serve linguistic functions (see Crystal, 1997), such as coding of sentence modi (i.e., statement, question, or request), defining information structure (e.g., accentuation of new or important information in a sentence), and marking of syntactic structure. While some authors additionally subsume para- and extralinguistic phenomena⁵ under the term prosody (e.g., Kohler, 1995; Clark & Yallop, 1995), in the current thesis, this term is exclusively used to refer to linguistic phenomena (*linguistic prosody*).

⁴The other common meaning of the term prosody, referring to poetic meter and versification, is disregarded here.

⁵Para- and extralinguistic features are, for example, information about the communication situation (e.g., whispering signaling confidentiality), general information about the speaker (e.g., pitch signaling gender and age) and information about the speaker's emotional state (e.g., loudness signaling anger; see *emotional* or *affective prosody*).

The current thesis investigates the neurophysiological correlates of phrase-level prosodic processing in infants and preschool children, thus addressing the role of prosody during language acquisition.

The following chapter illustrates prosody as an integral feature of spoken language, by first describing the acoustic and phonological properties of speech that reveal the prosodic structure of language. Then, the role of prosody in the comprehension of spoken utterances is discussed, focusing on lexical segmentation and syntactic processing.

1.1 The prosodic organization of language

1.1.1 Prosodic information in spoken language

Prosodic information of a given language can be described in its acoustic and phonological characteristics. The former reflect the physical properties of the speech signal, the latter address phonological categories that reflect the listener's mental representation of the speech signal (see, e.g., Warren, 1999). More specifically, spoken language is modulated by three main physical parameters that result in listeners' cognitively driven perceptions, which in turn serve linguistic functions (see Figure 1.1): 1) the fundamental frequency of sounds (perceived as pitch), 2) the duration or extension of sounds in time (perceived as length of segments and pauses), and 3) the amplitude of sounds (perceived as loudness/intensity).

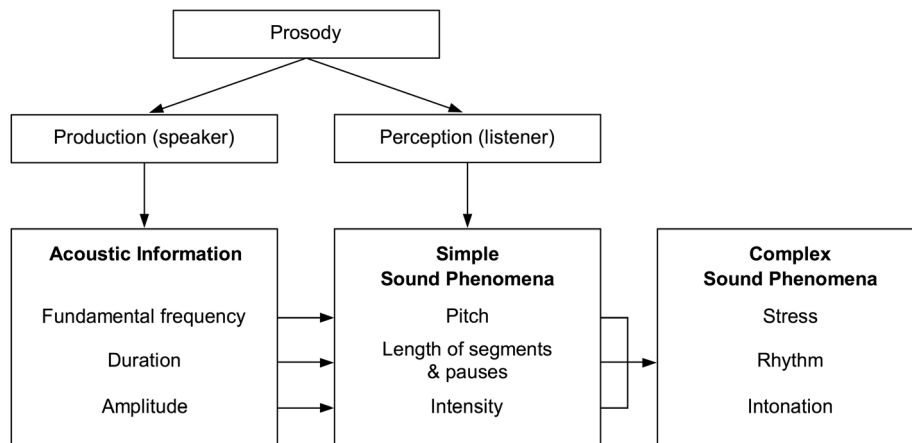


Figure 1.1: Prosody with acoustic information on the production side and phonetic-phonological information on the perception side.

In this context, Ladd and Cutler (1983) distinguish between a concrete approach to prosody, addressing the physical properties (*form*) and an abstract approach, dealing with the respective phonological structure (*function*). Accordingly, Nooteboom (1997) terms phoneticians as proponents of the concrete approach, since they quantify acoustic features and study perceptual processes at an empirical level. Phonologists, as proponents of the abstract approach, describe prosodic structure and its relation to other language phenomena at a theoretical level (see also Kohler, 1995). However, as Cutler, Dahan, and van Donselaar (1997) discuss in their later work, this strict dichotomy does not relate to discrete fields in prosody research but rather reflects different starting points, since observed sound features require to be classified and theoretically explained, while phonological theories need to be empirically grounded.

The transition from the production level on the speaker's side to the perception level on the listener's side (see Figure 1.1) is not a trivial process. First, there is no linear function between acoustic cues and their phonological relevance (e.g., Lehiste, 1970). For example, a pitch value of 200 Hz is perceived as high pitch in the voice of men but as low pitch in children. Furthermore, the perceived duration of a word does not only depend on its actual length but also on its position within the sentence and the general speech rate. Thus, the evaluation of acoustic cues by the human perceptual system is determined by several factors, such as the stimulus context and the interaction among several acoustic cues. Second, the described sound characteristics typically combine to more complex phonologically relevant phenomena, i.e., stress, rhythm, and intonation (see Figure 1.1). For example, to accentuate information within a sentence (i.e., phrasal stress), a speaker's voice does not only turn louder but also higher. Here, the same acoustic cue can subserve several phonological phenomena. For instance, changes in pitch play a crucial role in the accentuation of information, but also contribute to the overall intonational sentence contour. Importantly, the role of a particular acoustic cue is not universal, since certain prosodic phenomena are realized differently across languages (see Hirst & Di Cristo, 1998; for a contrastive comparison of English and German, see Markus, 2006).

In the following paragraphs, the prosodic phenomena stress, rhythm, and intonation are described in more detail (for a discussion of their linguistic functions, see also 1.2 and 1.3).

From an acoustic-phonetic view, *stress* is realized by changes in intensity and pitch, combined with concurrent changes of length (see, e.g., Kochanski, Grabe, Coleman, & Rosner, 2005). All of

these cues variably contribute to what defines the perception of stress, i.e., the relative prominence of syllables. More specifically, stressed syllables are in most cases marked by greater intensity and longer duration than unstressed syllables. Furthermore, stressed syllables often exhibit higher pitch and stronger pitch movement relative to unstressed ones. The term *stress* generally relates to the relative prominence of a syllable, while the term *accent* additionally involves pitch for prominence marking, i.e., pitch accent⁶ (see Cruttenden, 1997). Differences in stress can be realized at various levels, applying to words or phrases. Accordingly, *word* or *lexical stress* defines stressed and unstressed syllables within words and thus, for instance, differentiates between homographic words, such as IM-port (noun) and im-PORT (verb).⁷ Languages differ with respect to the particular acoustic realization of word stress. For example, in German word stress is mainly modulated by vowel duration (Jessen, Marasek, Schneider, & Clahssen, 1995), while in French it relies more on pitch characteristics (Meisenburg & Selig, 1998). Furthermore, languages differ in their rules how stress patterns typically apply to words (see Cruttenden, 1997). In German and English, word stress is applied on the initial syllables in most cases, although both languages allow for variable stress placement (see example above). In contrast, Polish has a fixed stress position, with word stress on the penultimate syllable. These cross-linguistic differences have important implications for the role of stress information in access to word forms and word recognition (see 1.2.1). Similar to word stress, *phrasal stress* or *sentence stress*⁸ refers to the prominence of one word within a phrase or a sentence, in being longer, louder or higher than the other words. Just as word stress can mark different word categories or word interpretations, phrases or sentences may have different structures or meanings dependent on the type and location of pitch accents. Specifically, accented words typically carry new or corrective/contrastive information (i.e., *focus*), thus defining the *information structure* of a sentence. Furthermore, pitch accents play an important role in defining the intonation contour of utterances (see *intonation*, below).

Closely related to prosodic modulations by variations in stress, the prosodic phenomenon *rhythm* or *meter* describes regular patterns of changes in length, loudness, and pitch. For example, in so-called

⁶In tonal languages, such as Mandarin, pitch accent, which then is called *tone*, encodes lexical information. For example, in Mandarin, tone changes the meaning of *ma* dependent on whether it is realized with high-level tone (*mother*), high rising tone (*hemp*), low-level tone (*horse*), or falling tone (*to scold*).

⁷Stress is indicated by upper case letters.

⁸Some authors use the term *accent* for phrasal or sentence stress, while they use the term *stress* to refer to word stress.

stress-timed languages,⁹ words and phrases exhibit regular patterns of stressed and unstressed syllables (see Hogg & McCully, 1987). According to the level of application, meter can be distinguished in lexical and phrasal meter. Regarding *lexical meter*, words in English and German, for example, show typical alternating patterns of strong (i.e., stressed) and weak (i.e., unstressed) syllables, as is evident in E-lec-TRI-ci-TY and PO-ssi-BI-li-TY. With respect to *phrasal meter*, grammatical morphemes can be arranged such that no more than two unstressed syllables occur in sequence, followed by a stressed syllable. As pointed out, the rhythmic properties of a given language are relevant in lexical segmentation and lexical recognition (see 1.2.1).

Phonetically spoken, *intonation* refers to pitch and loudness patterns modified in their temporal extension across utterances. Thus, utterances are typically structured in intonational phrases, also called intonation groups, tone groups, tone units, etc. (see 1.1.2). Here, cross-linguistic differences come into play regarding the role of particular acoustic cues in marking those intonational units (see, e.g., Markus, 2006). Following Cruttenden (1997), internal and external criteria are used to determine these units based on intonational characteristics. Internal criteria relate to the judgement of intonational phrases as complete units in that they exhibit an acceptable complete intonation pattern. The overall intonation pattern within one unit forms the *pitch contour* or *tune*. Pitch contours may contribute to the meaning of an utterance, e.g., a rising contour marks the sentence as question, which is, in turn, not universal. Furthermore, pitch contours relate to syntactic structure by indicating the continuation or completion of phrases and sentences, with rising pitch, for example, signaling continuation (e.g., Warren, Grabe, & Nolan, 1995). As has been highlighted with respect to pitch accents in phrasal stress, the intonational sentence contour relates to the sentence's information structure and serves semantic-pragmatic functions. External criteria, according to Cruttenden (1997), address the marking of intonational boundaries by acoustic markers, such as pauses. Numerous psycholinguistic studies have addressed the role of prosodic phrasing, based on these boundaries, in relation to syntactic structure, for example in syntactic ambiguity resolution (e.g., Kjelgaard & Speer, 1999; Marslen-Wilson, Tyler, Warren, Grenier, & Lee, 1992; Schafer, Speer, Warren, & White, 2000; Warren, Grabe, & Nolan, 1995).

⁹See Abercrombie (1967) for more detail on the typological differentiation between stress-timed languages (e.g., English), syllable-timed languages (e.g., French), and pitch accent languages (e.g., Japanese).

1.1.2 The prosodic hierarchy

When studying the organization of spoken language, phonologists in the late 1970s (e.g., Goldsmith, 1976; Liberman & Prince, 1977) found that the rules of syntax are not sufficient to account for the structure of speech. Although prosodic structure is highly determined by and often matches syntactic structure, there is no isomorphism between both linguistic structures (for discussion, see Hirst, 1993; Inkelas & Zec, 1990; Steedman, 1990). As shown in the example sentence in Table 1.1, there are several ways to realize the prosodic structure of one particular sentence (example from Selkirk, 1984, p. 293). Prosodic boundaries can occur at different positions within a syntactic unit, matching or non-matching syntactic boundaries. As is evident in the example, prosodic phrasing is highly dependent on the information structure of a sentence (e.g., focus on the giver *Jane* or the recipient of the given object *Mary*), and matches in the example the syntactic structure only in the second sentence.¹⁰

Table 1.1: Different prosodic realization of an example sentence (example from Selkirk, 1984). Prosodic boundaries are indicated by brackets.

1) [Jane gave the book to Mary.]
2) [Jane] [gave the book to Mary.]
3) [Jane gave the book] [to Mary.]
4) [Jane gave] [the book] [to Mary.]
5) [Jane] [gave the book] [to Mary.]
6) [Jane] [gave] [the book] [to Mary.]

Just as the prosodic realization of utterances cannot generally be predicted from their syntactic structure, some syntactic distinctions are not reflected in prosody. For instance, the sentence *John shot the man with the gun* offers two critically different interpretations (i.e., *the man was shot with the gun* or *the man with the gun was shot*), determined by the respective syntactic structure. In contrast, the prosodic realization may be the same in both versions. Even if the sentence is pronounced differently, prosodic cues are, in this particular case, not sufficient to resolve the syntactic ambiguity.

Given the non-isomorphic relationship between prosody and syntax, the prosodic organization of spoken language requires its own theoretical formalization. Most phonological theories of prosodic

¹⁰Only sentence 2) follows the syntactic structure with a prosodic boundary between the noun phrase *Jane* and the verb phrase *gave the book to Mary*.

structure are based on the *strict layering hypothesis*, first suggested by Pierrehumbert (1980) and employed by many theorists, e.g., Hayes (1989), Nespor and Vogel (1986), and Selkirk (1984). According to this hypothesis, prosodic categories or domains are hierarchically organized in layers, with higher-level domains being exhaustively parsed by domains at the next lower level. Following the hierarchy, less phonological rules apply at each level down, so that higher-level constituents dominate lower-level constituents. Furthermore, prosodic units at one level are all of the same type and stand in a linear, nonrecursive relation. This nonrecursivity rule contrasts syntactic structure, where a higher-level unit may be parsed into constituents of its own type.

Based on the strict layering hypothesis, one influential model of prosodic hierarchy for English has been suggested by Selkirk (1984) and can likewise be applied to German (see Fery, 1993; Wiese, 1996). Similar models have been proposed by Beckman and Pierrehumbert (1986), Hayes (1989), and Nespor and Vogel (1986) (see Shattuck-Hufnagel & Turk, 1996 for an overview). As Selkirk (1996) remarks, the strict layering hypothesis should not be viewed as exceptionless principle but rather formulated in four violable constraints, regarding the above mentioned characteristics dominance, layeredness, exhaustivity, and nonrecursivity. In this context, violations of exhaustivity and nonrecursivity have been discussed by Ladd (1986, 1996) and Selkirk (1996).

As shown in Figure 1.2, the proposed model of prosodic hierarchy (Selkirk, 1984) contains as top-level constituent an *utterance*. Utterances essentially comprise a stretch of speech bounded by silent pauses and are the largest units to which phonological rules apply. In many cases, utterances relate to single syntactic sentences but may cover two or more sentences joined into a single higher-level sentence. Each utterance can be divided into one or more *intonational phrases*. As their name suggests, these prosodic constituents are intonationally defined but also to a great extent determined by syntactic constraints (for more detail, see paragraph below).

The next level down concerns *phonological phrases*, also called intermediate phrases. These phrases are to a much higher degree constrained by syntactic rules and often defined in syntactic terms. Each phonological phrase is parsed into one or more *prosodic words*. Prosodic words are specified as lexical words (noun, verb, adjective) together with their adjacent grammatical morphemes (e.g., *my uncle* or *the man*). Prosodic words are parsed into *feet* and *syllables*, where a foot consists of a sequence of one strong syllable and a number of adjacent weak syllables. Since this thesis deals with the processing of intonational phrases, the defining characteristics of this prosodic unit are described in detail below (for more detail on the other constituents see Fery, 1993; Nespor & Vogel, 1986; Selkirk, 1984; Shattuck-Hufnagel & Turk, 1996; Wiese, 1996).

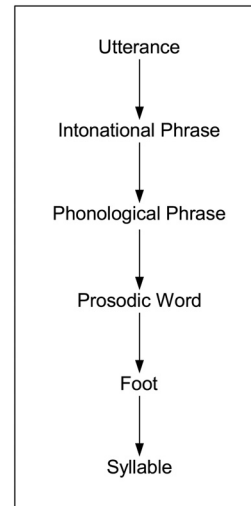


Figure 1.2: Hierarchy of prosodic constituents (Selkirk, 1984).

Intonational phrases (IPs) IPs are the largest prosodic constituents of an utterance, defined by several acoustic-phonetic features. IPs contain at least one nuclear accent and are characterized by the course of their pitch contour, i.e., the lowering or rising of the contour towards the end of the phrase, followed by a resetting of the pitch level at the beginning of the next phrase. Moreover, IPs are marked by intonational phrase boundaries (IPBs), which are defined by certain boundary features (Selkirk, 1984). First, resulting from the mentioned phrase-final pitch change, IPBs are marked by a low or high boundary tone (Pierrehumbert, 1980). Second, IPBs are characterized by a phrase-final lengthening, i.e., syllables preceding the boundary are lengthened as compared to syllables in non-phrase final positions. Third, IPBs are in most cases followed by a linguistically relevant pause.

As discussed, IPs follow the criterion of acceptable complete intonation patterns. The formation of those perceptually coherent IPs through the placement of boundaries is determined by both syntactic and non-syntactic factors. Non-syntactic factors are, for example, length of utterances, speech rate and semantic-pragmatic issues (Gee & Grosjean, 1983; Jun, 1993; Nespor & Vogel, 1986; Selkirk,

1984). Semantic-pragmatic considerations deserve special mention with respect to the production of utterances, since particularly focus and information structure influence prosodic phrasing (see also Table 1.1). Regarding syntactic factors, it has been pointed out that while syntactic structure does not fully determine prosodic structure, it does to a large extent. Accordingly, there is ample evidence for cases where IPs refer to syntactic clauses or interruptions of the main sentence (e.g., Ferreira, 1988; Gee & Grosjean, 1983; Selkirk, 2000). In terms of information structure, this holds true for cases of neutral focus. Furthermore, certain syntactic structures have been shown to form their own IPs, for example tag questions and unrestrictive relative clauses (e.g., Nespor and Vogel, 1986).

Supporting the notion of a syntax-prosody-mapping, analyses of continuous speech have demonstrated the existence of prosodic boundary cues in relation to clause and phrase boundaries. More specifically, at the right edge of syntactic phrases, in syllables which precede the syntactic boundary, an increase in vowel length can be observed (e.g., Beckman & Edwards, 1990; Cooper & Paccia-Cooper, 1980; Wightman, Shattuck-Hufnagel, Ostendorf, & Price, 1992). In addition, the pitch contour signals the presence of clause boundaries by changes in pitch level (e.g., Ladd, 1988; Pierrehumbert, 1980). Finally, pauses at word boundaries that coincide with clause boundaries tend to be longer than pauses at word boundaries occurring elsewhere in an utterance (e.g., Cooper & Paccia-Cooper, 1980; Scott, 1982). In conclusion, although IPs are to some degree subject to non-syntactic constraints, prosodic structure tends to coincide with syntactic structure. While not all syntactic boundaries are marked by prosodic boundaries, most prosodic boundaries are also syntactic boundaries. Here, syllable lengthening, pitch change, and pause often combine to mark the edges of syntactic units, promoting, for example, the parsing of clauses and syntactic phrases (see 1.2.2).

1.2 Prosody in auditory sentence comprehension

As outlined in 1.1, spoken language contains systematic prosodic variations based on a number of acoustic-phonetic cues. For example, stress cues mark prominent syllables in words and prosodic boundary cues relate to syntactic structure. In this context, the question arises to what degree those prosodic cues in fact aid lexical-semantic and syntactic processing in the perception of spoken utter-

ances. Here, prior research has mainly covered the areas of word segmentation and syntactic structure. The following paragraphs give an overview of the main results of these two lines of research.¹¹

1.2.1 Prosodic information in lexical segmentation

In language comprehension, continuous speech has to be segmented into smaller linguistic units to allow for lexical and syntactic parsing. For example, given the notion of lexicon entries being isolated word forms (see Lively, Pisoni, & Goldinger, 1994), discrete units have to be extracted from the speech input before processes of lexical access can be initiated. Although full segmentation of utterances is not a prerequisite for successful word recognition, the rapid detection of word onsets likely supports the efficiency of word recognition processes. Numerous studies have investigated the influence of stress and rhythmic patterns on the identification of word boundaries (see work by Cutler and colleagues, below).

The role of prosodic cues has not only been studied in lexical segmentation but also in relation to *word recognition*, i.e., the identification of words by activating lexicon entries. Lexical prosody (i.e., stress, tone, pitch accent) may support lexical access, particularly in cases, when it provides the only information in which word forms differ. Most studies investigating the influence of prosodic information on word recognition have been carried out for English and Dutch, and accordingly deal with lexical stress (e.g., Cooper, Cutler, & Wales 2002; Cutler & van Donselaar, 2001; Slowiaczek, 2000; Van Donselaar, Koster, & Cutler, 2005; Wingfield, Lindfield, & Goodglass, 2000; for reviews see Cutler, 2008; Cutler, Dahan, & van Donselaar, 1997).

With respect to *lexical segmentation*, Cutler and colleagues propose that English listeners make a first pass at speech segmentation by assuming word boundaries at the onset of each strong syllable, using the so-called *metrical segmentation strategy* (Cutler & Norris, 1988). The proposal that English listeners focus on stress in lexical segmentation is justified by analyses of distributional patterns in the speech input. These analyses revealed that strong syllables are highly likely to signal word onsets, since about 90% of all English content words feature initial stress (Cutler & Carter, 1987). Similar distributional patterns have been found for Dutch (Schreuder & Baayen, 1994), and Dutch speakers

¹¹For more detail on semantic-pragmatic aspects of prosodic functions, the reader is referred to overviews of the linguistic functions of prosody (Cutler, Dahan, & van Donselaar, 1997, Hirst & DiCristo, 1998) as well as to recent neurolinguistic studies on sentence modality (Astesano, Besson, & Alter, 2004) and information structure (e.g., Magne, Astesano, Lacheret-Dujour, Morel, & Besson, 2005).

were shown to use a similar strategy as English speakers (Vroomen, van Zon, & van Gelder, 1996). For these so-called stress-timed languages (see Abercrombie, 1967), it was suggested that rather than stress per se, the alternation of strong and weak syllables, i.e., rhythm, yields boundary detection (see, e.g., Cutler, Dahan, & van Donselaar, 1997). Accordingly, studies with English and Dutch speakers revealed no general segmentation preference for syllables over non-syllable sequences. However, boundaries at stressed syllables seemed to be a relevant segmentation point, alluding to the foot as rhythmic unit (e.g., Zwitserlood, Schriefers, Lahiri, & Donselaar, 1993; Finney, Protopapas, & Eimas, 1996; Cutler, Mehler, Norris, & Segui, 1986). Similarly, for syllable-timed languages (e.g., French and Spanish) and mora-timed languages (e.g., Japanese) native listeners showed segmentation preferences dependent on the respective linguistic rhythm. Specifically, Spanish listeners preferred syllables over non-syllable sequences in segmentation (e.g., Bradley, Sanches-Casas, & Garcia-Albea, 1993; Sebastián-Gallés, Dupoux, Segui, & Mehler, 1992), while Japanese listeners relied more on boundaries between moras than between syllables (Otake, Hatano, Cutler, & Mehler, 1993; Cutler & Otake, 1994). Thus, strategies for word boundary detection seem to be generally driven by the rhythmic patterns of a particular language. However, segmentation strategies are not triggered by the rhythmic structure of the speech input but are dependent on the listener's native language-specific experience. For example, neither English nor French listeners showed evidence of a mora-based segmentation when presented with Japanese input (Otake et al., 1993). Importantly, as Cutler and colleagues point out, linguistic rhythm does not directly index boundary locations but rather provides information as to where most-probable boundary locations are (for more detail, see Cutler & Carter, 1987). Further studies have demonstrated that word segmentation is not solely based on rhythmic cues but is also influenced by lexical information, e.g., resulting in shorter reaction times for the detection of syllables embedded in words than in nonwords (McQueen, Norris, & Cutler, 1994; Norris, McQueen, & Cutler, 1995). In this context, Mattys, White, and Melhorn (2005) have suggested a hierarchical model, taking into account various cues to word segmentation, with lexical information on the top, followed by statistical regularities, and again followed by metrical stress.¹² In summary, the reported studies on lexical segmentation indicate that listeners possess native language-specific segmentation

¹²Interestingly, the authors found this hierarchy to be reversed in a noisy environment, with metrical stress then being the most important cue (Mattys, White, & Melhorn, 2005).

strategies. Further studies need to specify when and to what degree rhythmic information is applied by listeners in everyday communication.

1.2.2 Prosodic information in syntactic processing

In syntactic processing, the role of prosodic cues has mainly been discussed in relation to syntactic categorization and the processing of syntactic structure. Regarding *syntactic categorization*, lexical units may be classified based on the prosodic differences between elements of different syntactic classes. Here, lexical stress may support the differentiation between content words (stressed) and function words (unstressed) (Gleitman & Wanner, 1982) as well as different content words, such as nouns and verbs (Kelly, 1996). For example, in English lexical stress differentiates between verbs, which are in most cases realized with iambic stress (e.g., re-CALL) and nouns, which mostly feature trochaic stress (e.g., RE-call) (Kelly, 1992; Kelly & Bock, 1988). As the example illustrates, stress patterns become particularly relevant in the lexical and syntactic distinction of homographic forms. Since the focus of this thesis is IP processing, the following paragraph covers, in more detail, the interaction of prosodic phrasing and *syntactic structure*.

The influence of prosodic cues on syntactic parsing has been subject to a controversial debate for several decades (see Cutler, Dahan, & van Donselaar, 1997). While a number of behavioral studies reported an impact of prosodic cues on syntactic parsing strategies (e.g., Marslen-Wilson et al., 1992; Warren, Grabe, & Nolan, 1995), other studies disproved an early influence of prosody on syntactic processing (e.g., Stirling & Wales, 1996; Watt & Murray, 1996). In recent years, however, studies using online behavioral paradigms and electrophysiological measures have delivered increasing evidence of the close interaction between prosody and syntax, focusing on the temporal dynamics of these processes.

The first studies on how prosody may aid sentence processing were carried out more than 30 years ago and examined the processing of global syntactic structure ambiguities¹³ (e.g., Cooper & Paccia-Cooper, 1980; Lehisté, 1973; Streeter, 1978). In general, in sentence parsing, listeners incrementally

¹³Global or standing syntactic ambiguities of sentences generally admit more than one sentence interpretation and are not resolved by further upcoming linguistic information within the sentence, e.g., *I read about the payment with interest*. In contrast, local or temporary syntactic ambiguities refer to the way lexical units are attached to preceding ones and experience resolution while the sentence unfolds. Sentences of this type are also called *gardenpath* sentences, e.g., *As you know Mike is not feeling well* versus *As you know Mike the game is not over*.

reconstruct the syntactic structure as they hear a sentence. In the case of ambiguous sentences, which allow to build multiple syntactic structures, listeners encounter problems in assigning the appropriate structure. Here, the referenced studies revealed that acoustic parameters (duration, fundamental frequency, and amplitude) can reliably constrain syntactic analysis by signaling prosodic breaks. For example, in an early study, Lehiste (1973) investigated the processing of sentences with global syntactic ambiguities, such as in the example in Table 1.2. Dependent on the respective prosodic realization, with prosodic boundaries at different sentence positions, listeners were able to chose the adequate answer to the question *Who will come?*.

Table 1.2: Prosodic disambiguation of an example sentence with global syntactic structure ambiguity (example from Lehiste, 1973). Prosodic boundaries are indicated by brackets.

Steve or Sam and Bob will come.
1) [Steve] [or Sam and Bob] [will come.]
2) [Steve or Sam] [and Bob] [will come.]

Regarding the role of single acoustic parameters in syntactic analysis, Beach (1991) investigated to what degree duration and fundamental frequency contribute to local syntactic ambiguity resolution. The author varied both parameters in the word at the critical ambiguous point of the sentence. Subjects were presented with sentence fragments up to this word and asked to decide which sentence type a fragment was excised from. Given the listeners' judgement, the author concluded that prosodic cues influence syntactic parsing strategies (but see Stirling & Wales, 1996)¹⁴ and that in this matter duration and fundamental frequency stand in a *cue trading* relation. In other words, the importance of one cue for the identification of a particular syntactic structure depends on the relative informativeness of the other cue, indicating interactive processes in prosodic boundary perception.

Although these studies revealed that listeners are able to exploit prosodic cues in ambiguity resolution, these studies only used offline tasks (e.g., end-of-sentence comprehension tasks) for the verification of a prosodic influence. Thus, the results delivered no information about at what point during syntactic parsing prosodic information becomes relevant, i.e., initial influence or post-initial evaluation. The first online study investigating the temporal dynamics of the prosody-syntax interaction

¹⁴Stirling and Wales (1986) only partially replicated the findings by Beach (1991). The authors found an influence of prosodic cues on the listeners' judgement only for short but not for long sentence fragments.

in local syntactic ambiguity resolution was carried out by Marslen-Wilson et al. (1992). In a *cross-modal naming paradigm*,¹⁵ the authors presented syntactically preferred and non-preferred sentences, which were spoken such that prosodic cues clearly marked the respective syntactic structure (see Table 1.3 for example sentences). As a result, naming latencies did not differ between the two sentence conditions, in spite of the fact that structurally non-preferred sentences typically evoke *gardenpath* effects, indicating parsing difficulties for sentences that do not match general parsing preferences (see Frazier, 1987). Thus, prosody seemed to have an influence on syntactic parsing at early processing stages so that parsing preferences were overridden.

Table 1.3: Example sentences with local syntactic ambiguities (example from Marslen-Wilson et al., 1992). The non-preference in sentence 2) can be overridden with the according prosodic realization, marking an IPB between *considered* and *the last offer*.

1) Syntactically preferred structure

The workers considered the last offer of the management – of the factory.

2) Syntactically non-preferred structure

The workers considered the last offer of the management – was a real insult.

The seminal study by Marslen-Wilson et al. (1992) has been followed by numerous similar on-line studies, demonstrating that adults use phrasal prosody to resolve syntactic structure ambiguities (e.g., Blasko & Hall, 1998; Kjelgaard & Speer, 1999; Nagel, Shapiro, Tuller, & Nawy, 1996; Schafer et al., 2000; Warren, Grabe, & Nolan, 1995). Importantly, most of these studies (e.g., Blasko & Hall, 1998; Kjelgaard & Speer, 1999) investigated not only cases of matching prosodic and syntactic structure but also cases of mismatch. Here, prosodically incongruent sentences, in which the prosodic structure violated the syntactic structure, evoked slower reaction times and higher error rates. These results were interpreted as a prosodically induced *gardenpath* effect, indicating not only a close interaction of prosody and syntax but also the existence of prosodic processes that are independent of syntactic processes. Further research has shown that even boundaries of smaller prosodic units, i.e., phonological phrase boundaries, can constrain syntactic analysis (Millotte, Rene, Wales, & Christophe, 2008) and not only boundaries of IPs, as has been for example suggested by Price,

¹⁵In the cross-modal naming paradigm, a sentence is presented up to a disambiguating word, followed by a visually presented test word, which has to be named. The rationale of this paradigm is that the test word is named the faster, the easier it can be integrated in the previously presented sentence context. Thus, naming latencies give information about the particular syntactic parsing strategies.

Ostendorf, Shattuck-Hufnagel, and Fong (1991). Thus, it seems that the relative size of a boundary in relation to other boundaries within the sentence (Clifton, Carlson, & Frazier, 2002) and the felicity of these boundaries (Millotte, Wales, & Christophe, 2007), rather than the absolute boundary size (Price et al., 1991), are relevant factors for the potential role of prosodic phrasing in syntactic processing.

Another line of research targeting the prosody-syntax interface deals with the anticipation of syntactic structure based on prosodic information. In this context, Grosjean (1983) postulates a predictive function of prosody that reduces the number of parsing possibilities, making sentence processing more efficient and possibly even faster. In the study by Grosjean (1983), subjects were presented with sentences with optional prepositional phrases of different lengths (see example sentences in Table 1.4). Importantly, dependent on the length of the prepositional phrases, sentences differed in their intonational characteristics. When presented with the different sentence versions up to the last obligatory word *cake* (see Table 1.4), subjects were able to accurately predict the original sentence length. These results suggest that prosodic information reliably triggers the anticipation of syntactic structure (see also Grosjean & Hirt, 1996, for a replication of this study in English and French).

Table 1.4: Example sentences without (1) and with (2-4) optional prepositional phrases of different lengths (example from Grosjean, 1993). Dependent on the length of the prepositional phrase, sentences differed in their prosodic realization.

1) Yesterday my sister made a cake.
2) Yesterday my sister made a cake for the fair.
3) Yesterday my sister made a cake for the fair at the school.
4) Yesterday my sister made a cake for the fair at the school at the hill.

Taken together, the reported studies all suggest a close interaction of prosodic and syntactic structure during sentence processing. However, even so-called online experiments, applying mostly the cross-modal naming paradigm, cannot provide a precise picture of the temporal characteristics of this interaction. Moreover, the cross-modal naming paradigm suffers from the often unnatural disruption of the sentences during auditory presentation and the abrupt change from the auditory to the visual modality. Therefore, new online paradigms and methods with higher temporal resolution are required that capture indirect (e.g., eye-tracking) or direct (e.g., electrophysiology) indicators of the brain mechanisms involved in sentence processing. Several studies have demonstrated the advantage

of those new methods for the temporal specification of the prosody-syntax interaction. For example, Weber, Grice, and Grocker (2006) applied the eye-tracking technique to study the influence of prosody on syntactic parsing. The authors showed by means of anticipatory eye-movements that prosodic cues trigger structural ambiguity resolution even in the absence of clear morphological information. Furthermore, Eckstein and colleagues used the ERP method and found that prosodic cues influence both initial and later steps of syntactic structure building (Eckstein & Friederici, 2005, 2006; for more detail see 5.2).

Interim summary This chapter aimed to demonstrate that prosody is an integral feature of spoken language. More specifically, whenever speakers produce utterances, they use acoustic-phonetic cues to mark lexical-semantic units and syntactic structure. Thus, prosodic cues serve linguistic functions in that they evoke the perception of phonological phenomena, such as the listener's perception of lexical stress and phrase boundaries. It was outlined that the prosodic structure of speech cannot be sufficiently explained in syntactic terms but requires its own theoretical formalization. In this context, one prominent model of prosodic hierarchy has been described (Selkirk, 1984). Essential for the purpose of the current thesis, it was shown that prosody plays a crucial role in sentence comprehension. It was argued that lexical stress can influence word segmentation and word recognition. Regarding the prosody-syntax interface, it was shown that prosody can influence syntactic parsing preferences and initiate the anticipation of syntactic structure. Importantly, new online methods enable the specification of the exact relationship between prosody and syntax. In this regard, the ERP method (see 5.1), which is also applied in the current studies, allows for examining the time course and the neurophysiological basis of language processing.

Chapter 2

The role of prosody in language acquisition

Language acquisition is characterized by a remarkable speed and high levels of success. In acquiring their native language, children accomplish learning at a rate and with such efficiency, which in second language learning, adults barely achieve after years of training. Most children, however, have mastered the entry into their native language at the end of their third year of life. More specifically, they have acquired 1) a complex system with the typical sounds of a language, 2) how these sounds are combined in different ways to make up a large vocabulary, and 3) how the vocabulary entries are related together by means of syntactic rules.

The puzzle of how children accomplish this learning task has been subject to a longstanding discussion between proponents of different theoretical views, emphasizing innate (*nature*) or environmental (*nurture*) prerequisites of language acquisition. Independent of the respective theoretical view, it is beyond question that infants must possess some efficient processing and analysis mechanisms that allow for extracting the relevant information from the speech input within a short period of time. In this regard, prosodic information has been suggested as a likely candidate for an initial acquisition point (see *prosodic bootstrapping*, below). The universal use of infant-directed speech (across languages, gender, etc.), with pronounced prosodic features, supports the potential key role of prosody in the language acquisition process (e.g., Fernald et al., 1989).

For successful language learning, the language input infants are presented with must contain the relevant linguistic information (see 1.1) and, in addition, children must be sensitive to this kind of information. The following chapter describes a potentially powerful acquisition mechanism, called *bootstrapping*. Here, the account of *prosodic bootstrapping* is described in more detail, while other

bootstrapping models are only briefly introduced. The second part of the chapter provides an overview of empirical evidence showing at what age infants process prosodic information, with a focus on prosodic boundary information.

2.1 Acquisition mechanisms: Learning by bootstrapping

The question of how children initially start to identify and extract essential information for language learning from the speech input has been explicitly formulated as the *bootstrapping problem* (e.g., Pinker, 1984, 1987). Various solutions to the bootstrapping problem have been suggested within the framework of different bootstrapping accounts. These accounts all postulate some domain-specific innate knowledge and constraints on learning. Given these conditions, it is further suggested that children make use of correlations between different linguistic levels in language learning, thus bootstrapping from existent linguistic information of some kind into new information at a correlated level. The derived knowledge can in turn serve for the acquisition of further linguistic information. Depending on the kind of information that children rely on in building up new linguistic knowledge, there are different accounts of bootstrapping.

Prosodic bootstrapping Prosodic bootstrapping accounts, also referred to as *bootstrapping from the signal*,¹⁶ state that language learners can derive information about the syntactic organization of a given language by relying on the prosodic information in the speech signal. Gleitman and Wanner (1982) first put forward the idea that acoustic cues in the speech input provide infants with cues to syntactic boundaries i.e., the infant can bootstrap from the acoustic cues in the speech signal into the syntactic units defining the sentence structure and thus derive the basic syntactic rules governing the language input (see also Gleitman, Gleitman, Landau, & Wanner, 1988; Morgan, Meier, & Newport, 1987; Peters, 1983). In addition to prosodic boundary cues relevant for the identification of larger syntactic units, children rely on information about the rhythmic organization of a given language (Nazzi & Ramus, 2003). Stress patterns are relevant in language learning in that they aid the initial segmentation of words from continuous speech (e.g., Mattys, Jusczyk, Luce, & Morgan, 1999) and

¹⁶This term more adequately accounts for the notion that learners make use of various kinds of information in the speech signal that extend beyond prosody, such as distributional and phonotactic cues, i.e., information regarding the permissible sound sequences of a given language.

also provide some information about the syntactic category of a word (see 1.2). As outlined, the latter may lead to a discrimination between content words (stressed) and function words (unstressed) (Gleitman & Wanner, 1982) as well as different content words, such as nouns (stress on the first syllable) and verbs (stress on the second syllable) (Kelly, 1996). Furthermore, prosodic information has been suggested to play a role in the acquisition of word order regularities (Höhle, Weissenborn, Schmitz, & Ischebeck, 2001; Mazuka, 1996; Nespor, Guasti, & Christophe, 1996; Nespor et al., submitted). In this context, Nespor and colleagues have shown that in German the realization of prosodic prominence changes as a function of word order. While object-verb orders in subordinate clauses are correlated with an increase of pitch and intensity at the left edge of the phrase, verb-object orders are correlated with a lengthening at the right edge (Nespor et al., submitted).

Bootstrapping from the signal crucially depends on the presence of prosodic cues in the speech input and children's sensitivity to them. A large number of studies have focused on identifying the acoustic cues provided in a given language and determining at what developmental stages infants encode and utilize those cues, for example, in speech segmentation. Ramus, Nespor, and Mehler (1999) found in their analysis of eight languages that linguistic rhythm is reflected in the acoustic/phonetic properties of the speech input, with syllable structure being the most reliable predictor of rhythmic class. With respect to prosodic boundary cues, acoustic analyses of continuous speech show that syntactic boundaries often coincide with prosodic boundaries. More specifically, vowel lengthening, pitch change and pause conjointly mark the edges of syntactic units, facilitating, for example, the detection of clauses and phrases (e.g., Beckman & Edwards, 1990; Cooper & Paccia-Cooper, 1980; Ladd, 1988; Pierrehumbert, 1980; Scott, 1982; Wightman et al., 1992). While not all syntactic boundaries are marked by prosodic boundaries, nearly every prosodic boundary is also a syntactic boundary. From this it follows that prosodic boundaries deliver, although not exhaustively (Gerken, Jusczyk, & Mandel, 1994), a first good guess for infants as to where syntactic boundaries occur in the speech stream (Gerken, 1996; Saffran, Newport, & Aslin, 1996).

In speech directed to infants and children, prosodic cues are typically enhanced, as has been observed in mothers' and fathers' speech to infants across languages (Fernald et al., 1989; Fisher & Tokura, 1996a). More specifically, *infant-directed speech*, also called *motherese* or *baby-talk*, is characterized by a simplified structure, slow speech rate, and exaggerated prosodic features, such as

greater pitch variability, higher mean pitch level, and longer pauses. Infant-directed speech seems to serve at least two functions: 1) the attraction of infants' attention and 2) the provision of potential cues for speech segmentation. In fact, infants as young as one month have been shown to discriminate low-pass filtered infant-directed speech from adult-directed speech (Cooper & Aslin, 1990) and at 4 months, they prefer to listen to infant-directed speech over adult-directed speech (Fernald, 1985). Furthermore, Thiessen, Hill, and Saffran (2005) found that infants aged 6.5-7.5 months were able to segment words from continuous speech when presented with infant-directed speech but failed to do so for adult-directed speech. These studies indicate that in addition to infants' general preference for infant-directed speech, these particular speech characteristics in fact facilitate language learning.

With respect to infants' early ability to perceive prosodic cues in the speech signal, both innate linguistic capacities and more general perceptual capacities (possibly even active during prenatal periods) are conceivable (for a discussion see, e.g., Jusczyk, 1997). A brief developmental sketch of empirical evidence of infants' prosodic processing abilities, particularly processing of prosodic boundary information, is provided in 2.2.

Other bootstrapping accounts Various approaches to bootstrapping have applied the same acquisition principles to other linguistic areas to explain further steps in language acquisition. In the *semantic bootstrapping* approach (e.g., Pinker, 1984, 1987), children are suggested to initially solve the problem of identifying syntactic categories and syntactic relations by relying on knowledge about correlations between semantic and syntactic categories. More specifically, children must, in a first step, successfully map meaning onto lexical entries and derive a rough semantic representation of an utterance. In a second step, they utilize their knowledge about certain correlations between those semantic elements and syntactic categories, for example, relating names of objects and persons to the syntactic category of *nouns* and names of actions or changes of state to the category *verb*. In this way, children can induce the respective syntactic category from the semantic input. Similarly, syntactic rules are semantically-inferred by relating the semantic role of an *agent* to the syntactic role of a *subject*. Given some basic innate configurative knowledge, children derive new knowledge about syntactic-semantic relations, which they in turn use to acquire more advanced rules, such as phrase structure knowledge.

According to the *distributional bootstrapping* hypothesis, also called correlational bootstrapping, children are sensitive to distributional information in the language input and utilize these cues for accessing syntactic categories (e.g., Maratsos & Chalkley, 1980). Distributional features comprise co-occurrences between words of different classes (e.g., positional relations between words of different syntactic categories) and co-occurrences between certain types of inflections and syntactic categories. The recognition of these distributions in the analysis of a word's properties may aid children's identification of syntactic categories. For example, if children discover that several words are preceded by an article, they may infer that these words are all members of the same syntactic category, i.e., nouns.

In the *syntactic bootstrapping* approach, Gleitman (1990) has suggested that children use syntactic information to acquire verb meaning. More specifically, information about previously learned nouns and their structural positions, i.e., defining the syntactic context a verb is embedded in, can deliver information about the verb's argument structure. For example, if children identify a transitive verb, given that it occurs with subject and object, the interpretation of the verb is restricted to a lower number of possible meanings. Here, some innate knowledge of the correlation between the syntactic structure of an utterance and the argument structure of verbs is assumed.

2.2 The processing of prosodic information in infancy and childhood

There is considerable behavioral evidence to suggest that very young infants are sensitive to the prosodic features of their native language. The fact that infants show this sensitivity even during their first days of life suggests that they start prenatally to lay foundations for language acquisition. More specifically, research using the *high amplitude sucking paradigm* (for more detail on this method, see Jusczyk, 1985) revealed that newborns show recognition of maternal voice (DeCasper & Fifer, 1980) and stories they heard before birth (DeCasper & Spence, 1986). Furthermore, infants prefer to listen to their native language over other languages, even if the speaker is unknown. However, they do not show any preference when presented with two foreign languages (Mehler et al., 1988; Nazzi, Bertoncini, & Mehler, 1998). Interestingly, these studies gained the same results, when infants were presented with low-pass filtered versions of the original speech samples, which only contained prosodic information, while all segmental information was removed. These results on infants' early native-language preference are best explained as an effect of prenatal exposure. This approach finds

support through studies indicating that the uterine wall acts as low-pass filter, thus transferring language characteristics into the uterus typically associated with prosody, i.e., intonational and rhythmic features (Armitage, Baldwin, & Vince, 1980; Griffiths, Brown Jr., & Gerhardt, 1994). For infants older than 2 months, behavioral methods have been developed that measure mean orientation or listening times, such as the *conditioned head-turn procedure* or the *head-turn preference procedure* (for more detail on these methods, see Kemler Nelson et al., 1995; Werker, Polka, & Pegg, 1997). Using these methods, several studies have demonstrated older infants' preference for their native language. Infants at 2 months have been shown to distinguish their native language from a foreign language of a different rhythmic class (Dehaene-Lambertz & Houston, 1998; Mehler et al., 1988), but not yet from a foreign language of the same rhythmic class (Christophe & Morton, 1998). At the age of 4-5 months, infants are even able to discriminate between their native language and a rhythmically similar language, e.g., Catalan and Spanish (Bosch & Sebastián-Gallés, 1997), and between different dialects of their native language, e.g., American English and British English (Nazzi, Jusczyk, & Johnson, 2000). Thus, continuing native language experience results in infants' progress from a rather general perception of global rhythmic features to a more fine-grained perception of the specific sound organization of their native language.

In addition to rhythm perception, infants are from birth able to process some prosodic boundary information and can discriminate between identical syllable sequences that contain an intervening phrase boundary from those that do not (Christophe, Dupoux, Bertoncini, & Mehler, 1994; Christophe, Mehler, & Sebastián-Gallés, 2001). At around 4.5 months, infants begin to show sensitivity to specific prosodic markers in the continuous speech stream and prefer to listen to passages with artificial pauses inserted at clause boundaries (conincident version) over pauses inserted at other sentence positions (non-coincident version) (Jusczyk, Hohne, & Mandel, 1995; see also Hirsh-Pasek et al., 1987). Interestingly, Jusczyk, Hohne, and Mandel (1995) found that English-learning 4.5-month-olds show a preference for coincident versions of both English and Polish speech samples, while English-learning infants at 6 months show this preference only for English samples. This suggests a developmental trend from global discrimination abilities to a greater attention to language-specific characteristics. For the phrasal level, the preference for pauses at phrasal over non-phrasal boundaries has been shown at the age of 9 months; including a preference even for low-pass filtered speech,

which adds support to the notion that infants place a special emphasis on suprasegmental over segmental cues (Jusczyk et al., 1992). Further studies have demonstrated infants' developing ability to recognize larger linguistic units in continuous speech based on prosodic boundary cues at both clause level (Nazzi, Kemler Nelson, Jusczyk, & Jusczyk, 2000; Seidl, 2007; Soderstrom, Nelson, & Jusczyk, 2005) and phrase level (Soderstrom, Seidl, Nelson, & Jusczyk, 2003).¹⁷ Infants at 6 months perceive clauses, but not yet reliably phrases, in continuous speech (Nazzi, Kemler Nelson, et al., 2000; Seidl, 2007; Soderstrom, Nelson, & Jusczyk, 2005; Soderstrom et al., 2003). In contrast, infants at 9 months prefer prosodically well-formed syntactic units over non-units even at phrase level (Soderstrom et al., 2003). Thus, the existing data suggest that infants perceive larger linguistic units, such as clauses, earlier in continuous speech than smaller unit, such as syntactic phrases.

The recognition of prosodic phrase boundary cues may also facilitate the detection of words, since phrase boundaries and word boundaries coincide, at least at the right edge of the phrase boundary. It seems that infants do not start to segment words from fluent speech until they can recognize larger units in the speech stream, since they do not start to extract monosyllabic words from fluent speech before 6-7.5 months (Jusczyk & Aslin, 1995) and bisyllabic words before 7.5 months (Johnson & Jusczyk, 2001; Jusczyk, Houston, & Newsome, 1999; Morgan & Saffran, 1995; Nazzi, Dilley, Jusczyk, Shattuck-Hufnagel, & Jusczyk, 2005). Accordingly, Gout, Christophe, and Morgan (2004) demonstrated for 10-month-old infants that word detection was facilitated when words occurred at phrase boundary positions (see also Seidl & Johnson, 2007). Interestingly, the arising ability of word segmentation from continuous speech falls within a developmental period, when infants start to show a preference for the predominant word stress patterns of their native language. Jusczyk, Cutler, and Redanz (1993) found that English-learning infants at 9 months, but not at 6 months, listened longer to word lists that followed the typical strong-weak pattern than to word lists featuring the weak-strong pattern (see also Turk, Jusczyk, & Gerken, 1995). Infants' ability to segment words also follows the typical native language rhythm. English-learning infants begin at 7 months to segment bisyllabic words that exhibit the typical strong-weak pattern, but do not extract words featuring the

¹⁷In these studies, infants were familiarized with identical word sequences as well-formed syntactic units (within prosodic boundaries) and ill-formed non-syntactic units (across prosodic boundaries). After familiarization, infants listened to speech passages that contained the familiarized strings and other passages with non-familiarized strings. Since infants were shown to discriminate familiarized units when they either occurred as syntactic unit or syntactic non-unit in larger test passages (by means of orientation or listening times), the authors concluded that infants utilize prosodic boundary cues to detect syntactic units in continuous speech.

weak-strong pattern before the age of 10 months, when they most likely use additional information, such as phonotactic cues (Jusczyk, Houston, & Newsome, 1999). Taken together, the analysis and segmentation of smaller, syntactically and lexically relevant units occurs later during an infant's language development and is likely to be facilitated by reliance on rhythmic patterns and bootstrapping from acoustically marked larger units in the speech signal.

In summary, this brief review of prosodic processing during infancy has provided ample evidence of infants' early perceptual abilities. These initial, rather global perceptions are shaped by the emergent properties of the native language input, so that infants are more and more tuned to the typical sound patterns of their native language. In support of the prosodic bootstrapping account, it seems that the early perception of prosodic features aids the detection of syntactic units in continuous speech, thus providing the basis for the acquisition of lexicon and syntax.

Interim summary Various bootstrapping accounts of language acquisition have suggested solutions to the learnability puzzle, such that learners, equipped with some initial knowledge, draw on one type of linguistic information in the language input to provide clues about other levels of linguistic organization. Here, it seems plausible that several of the suggested accounts all work in concert or become differently relevant during various stages of language acquisition. The perceptual mechanisms subsumed under the prosodic bootstrapping account seem to be particularly relevant during first stages of language learning. Ample behavioral evidence of infants' and toddlers' ability to encode and utilize prosodic boundary information and rhythmic patterns delivers further support for this account. As a prerequisite for later lexical and structural learning, infants first have to segment linguistically relevant units from the speech input. Given the potential significance of these units in the initial stages of language acquisition, the principles underlying infants' early perception of prosodic cues that signal prosodic phrases, particularly IPs as the largest units in phrasal prosody, require further investigation. Although a number of behavioral studies have contributed to the description of the developmental course of infants' sensitivity to prosodically marked units, the underlying neurophysiological basis remains widely unknown. The ERP method provides an online measure of the ongoing information processing in the brain and thus is a suitable tool to study the neurophysiology of early language acquisition (see Chapter 5).

Chapter 3

The neuroscience of prosody

For over half a century, there has been an increasing effort to uncover the brain mechanisms underlying cognitive processing – in addition to investigating the corresponding behavioral consequences. Various methods in the field of cognitive neuroscience capture 1) the spatial resolution of these processes – lesion studies, functional magnetic resonance imaging (fMRI), positron emission tomography (PET), optical imaging or near-infrared spectroscopy (NIRS), 2) the temporal resolution of these processes – electroencephalography (EEG), or 3) both the spatial and temporal resolution of these processes – magnetoencephalography (MEG).

With respect to language processing, different linguistic aspects (i.e., prosody, phonology, semantics, syntax) have been shown to be processed differently in the brain (for review, see Friederici, 2002, 2004; Friederici & Alter, 2004; Scott & Johnsrude, 2003). For a more comprehensive understanding of prosodic processing, the following chapter deals with the neuroanatomical and neurophysiological bases of phrase-level prosody by first introducing patient studies and functional brain imaging studies that examine hemispheric lateralization and the involvement of particular brain regions. Second, evidence drawn from electrophysiological studies are described in more detail, as EEG/ERP is the method of choice for the current studies in infants and children. Here, the focus is placed on studies investigating the processing of sentence-level prosody that report a specific electrophysiological component for prosodic phrase processing, the Closure Positive Shift. As far as available, infant studies are discussed. However, both lines of research provide only sparse evidence of infants' and children's prosodic processing. Both ethical concerns (regarding e.g., high magnetic fields in fMRI) and methodological restrictions may be causal for this lack of developmental data.

3.1 Patient studies and neuroimaging studies on phrase-level prosodic processing

In language processing, studies of the functional localization of phonological, semantic, and syntactic processing have mainly revealed the involvement of left hemisphere regions (see, e.g., Friederici, 2002). Studies of the functional localization of linguistic prosody, however, have not yet provided a clear picture of lateralization to one hemisphere (for review, see e.g., Baum & Pell, 1999).

Clinical studies describe patients' particular processing difficulties that result from their specific brain lesions and thus allow for conclusions about the functional significance of the damaged areas. Several patient studies have suggested that right hemisphere (RH) regions play a crucial role in the processing of prosody, since these patients are impaired in the discrimination of different intonation contours of otherwise identical sentences (e.g., Bradvik et al., 1991; Weintraub, Mesulam, & Kramer, 1981). Other studies, however, have described similar processing difficulties for left hemisphere (LH) patients (e.g., Emmorey, 1987; Pell & Baum, 1997; Van Lancker, 1980). For example, Bryan (1989) tested RH and LH patients and found both groups impaired in discriminating words with different stress patterns and sentences with different intonation contours. Interestingly, when both patient groups were tested with filtered versions of the experimental material (i.e., only preserving suprasegmental information), RH patients' performance was generally more impaired, while LH patients performed only slightly worse than controls. Similarly, Perkins, Baran, and Gandour (1996) first found that LH patients, but not RH patients, experienced problems when asked to identify sentence modi based on intonational information. The reverse pattern of impairment occurred, when segmental information was removed from the sentences. When only prosodic information was available, RH patients, but not LH patients, demonstrated problems in solving the task. Thus, it seems that LH regions are engaged in intonation processing when segmental information is involved but that RH regions are superior when only suprasegmental information is present.

The results of clinical studies in children, although very limited in number, also deliver a heterogeneous picture. For example, Cohen, Branch, and Hynd (1994) found for 6- to 16-year-old children with LH or RH dysfunction, that only children with RH damage experienced problems in intonation perception. In contrast, Trauner, Ballantyne, Friedland, and Chase (1996) observed for both lesion

groups difficulties in the identification of sentence modi (intonation contour) and discrimination of information structure (sentence stress).

In explanation of the different results gained from various patient studies, it has been suggested that the lateralization of prosodic processing may vary as a function of the tested acoustic parameters. In this regard, the *cue-dependent lateralization theory* proposes that spectral properties are preferentially processed in the RH, while duration properties are primarily processed in the LH (e.g., Robin, Tranel, & Damasio, 1990; Van Lancker & Sidtis, 1992; Zatorre, Belin, & Penhune, 2002). However, studies that tested the processing of temporal parameters in boundary perception found that both LH patients and RH patients experienced problems in the identification of phrasal groupings (Aasland & Baum, 2003; see also Baum & Dwivedi, 2003). LH patients were only able to solve the phrase perception task, when durational boundary cues were exaggerated, while RH patients showed general problems with boundary perception independent of the duration manipulation.

Generally, for the interpretation of the inconsistent clinical data on prosodic processing, both the actual functional hemispheric differences and the impact of particular experimental manipulations and task requirements should be considered (see, e.g., Plante, Creusere, & Sabin, 2002). Furthermore, in the study of patient populations, the variability in size and area of the brain lesions most likely contributes to a heterogeneous pattern of results.

In contrast to patient studies, neuroimaging studies (e.g., fMRI, PET, MEG studies) deliver a more precise picture of the brain areas involved in particular processes. One approach to investigating the neural correlates of prosodic processing is to present suprasegmental information isolated from natural speech. This can be achieved 1) by removing segmental information from natural speech by filtering, as in low-pass filtered sentences, which contain only the intonational sentence contour (Meyer, Alter, & Friederici, 2003; Meyer, Alter, Friederici, Lohmann, & von Cramon, 2002; Meyer, Steinhauer, Alter, Friederici, & von Cramon, 2004; Plante, Creusere, & Sabin, 2002) or 2) by presenting only suprasegmental information *ab initio*, as in hummed sentences (Ischebeck, Friederici, & Alter, 2008). More specifically, Meyer and colleagues compared in fMRI studies brain activation patterns evoked by low-pass filtered versus normal speech and obtained activation differences in a frontotemporal network with a RH dominance (Meyer, Alter, & Friederici, 2003; Meyer et al., 2002, 2004). Similarly, Plante, Creusere, and Sabin (2002) observed stronger right frontal brain activations

for low-pass filtered as compared to normal sentences. Interestingly, this difference only occurred under task solving and not passive listening conditions, suggesting lateralization differences dependent on response demands (regarding working memory and decision processes). In contrast to the results with low-pass filtered sentences, Ischebeck, Friederici, and Alter (2008) found no additional activation, when comparing response patterns of hummed speech to normal speech. The bilateral activation pattern (strongest in the superior temporal gyrus) observed for hummed sentences pitted against baseline most likely resulted from the particular task demands, since the probe detection task involved processing of segmental information.

Another approach to study prosodic processing is to remove intonational information 1) by high-pass filtering, which reveals so-called *flattened* sentences without intonational contour (Herrmann et al., 2003; Meyer et al., 2004) or 2) by reducing the amount of prosodic information when using speech with low prosodic expressiveness (Hesling, Clement, Bordessoules, & Allard, 2005). The contrast of low-prosodic speech with normal speech should reveal brain areas that are typically involved in prosodic processing. Meyer and colleagues found stronger RH involvement, particularly in the superior temporal gyrus, when contrasting activation patterns of flattened versus normal speech, however, there were no additional activations for the reverse contrast (Meyer et al., 2004). Hesling et al. (2005) reported stronger involvement of RH regions for high-prosodic versus low-prosodic speech, specifically in the right inferior prefrontal cortex, but only for normal sentences and not for low-pass filtered ones. Thus, the results reported here are somewhat mixed and need to be interpreted in light of the different task requirements and specific prosodic manipulations.

The processing of prosodic boundaries has only been addressed by two neuroimaging studies. Strelnikov, Vorobyev, Chernigovskaya, and Medvedev (2006) compared the processing of segmented (with IPB) versus unsegmented phrases (without IPB) and found stronger activations for the boundary condition in right prefrontal regions and the right cerebellum. Ischebeck, Friederici, and Alter (2008) studied activation patterns evoked by sentences with one IPB and sentences with two IPBs, in normal and hummed speech. The authors observed for both speech types stronger activations in left temporal regions for the two IPBs condition than the one IPB condition. Only in normal sentences did they also find right temporal regions more activated. It follows that, although reflected in differential

activation patterns, sentences that contain a higher degree of prosodic boundary information evoke more pronounced responses.

Cross-linguistic neuroimaging studies have demonstrated that the lateralization of prosodic processing is dependent on the particular linguistic function of prosody in a given language. For example, in tonal languages, such as Mandarin Chinese, lexical-semantic processing is highly determined by prosodic information. Accordingly, in native speakers of Mandarin, a LH dominance for the processing of sentence-level prosody was observed, in contrast to English speakers presented with the same stimulus material (Gandour et al., 2004; Tong et al., 2005).

Of the few neuroimaging studies on language processing in infants and pre-school children (e.g., Dehaene-Lambertz, Dehaene, & Hertz-Pannier, 2002), only three have directly addressed the processing of prosodic information. In an optical imaging study with 3-month-old sleeping infants, Homae, Watanabe, Nakano, Asakawa, and Taga (2006) observed stronger right temporoparietal brain responses to normal than to flattened sentences. Wartenburger et al. (2007) reported in a NIRS study with 4-year-old children a differential hemispheric involvement dependent on the presence of segmental and suprasegmental information in the sentence material. While the authors observed stronger right frontotemporal activation patterns in response to hummed sentences, normal sentence processing revealed additional LH activation patterns. Recently, Sambeth and colleagues utilized MEG to investigate sleeping newborns' brain responses to varying degrees of prosodic information (Sambeth, Ruohio, Alku, Fellman, & Huotilainen, 2008). For normal continuous speech and singing, infants showed pronounced brain responses, which however, dramatically decreased when infants were presented with filtered low-prosody speech.

In conclusion, the combined findings of patient studies and neuroimaging studies suggest that the processing of linguistic prosody is supported by a widespread neural network, which does not only involve RH but also LH regions. Although several studies have reported a RH processing dominance when prosodic information is presented in isolation, processing seems to shift to or additionally require LH regions when prosodic information is combined with segmental cues, such as lexico-semantic and syntactic information (see 3.3). Variations in the involvement of LH regions seem to be particularly influenced by the specific task requirements (see, e.g., Meyer et al., 2004; Plante, Creusere, & Sabin, 2002; Tong et al., 2005).

3.2 Electrophysiological studies on phrase-level prosodic processing: The Closure Positive Shift

Electrophysiological studies deliver online measures of voltage changes at the surface of the scalp over time, thus providing an exact temporal resolution of the ongoing cognitive processing in the brain (see Chapter 5). In a seminal study, Steinhauer, Alter, and Friederici (1999) investigated the processing of prosodic units at the sentence level by means of ERPs. In this study, adults were presented with sentences of two different prosodic realizations, determined by the sentences' particular syntactic structure: 1) sentences containing one IPB and 2) sentences featuring two IPBs (for examples, see Figure 3.1). As can be seen from Figure 3.1, listening to the different sentence types evoked different ERP patterns dependent on the respective boundary manipulation. More specifically, the ERP average for each sentence type showed in correspondence to each boundary a positive shift that occurred with a centroparietal scalp distribution. Accordingly, ERP responses to sentences with one IPB obtained one positive shift, while responses to sentences with two IPBs revealed two corresponding positive shifts.

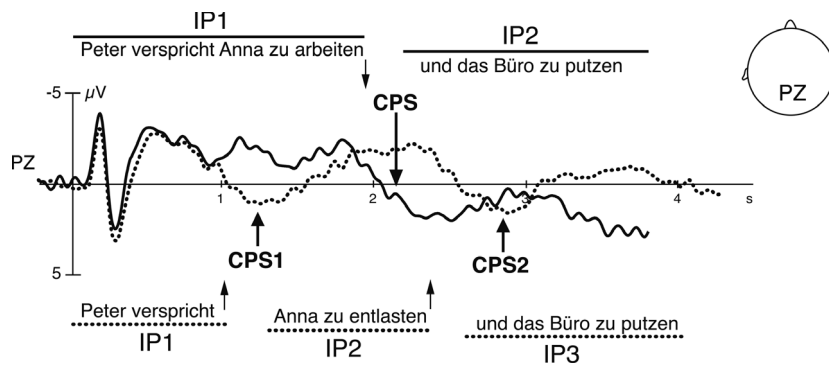


Figure 3.1: Closure Positive Shift (CPS). Positive shifts in the ERP in correlation to sentences with one IPB (solid line) [Peter verspricht Anna zu arbeiten und das Büro zu putzen/Peter promises Anna to work and to clean the office] and with two IPBs (dotted line) [Peter verspricht Anna zu entlasten und das Büro zu putzen/Peter promises to help Anna and to clean the office]. Small arrows indicate the IPB in the sentence. Large arrows indicate the CPSs that follow the IPBs. Figure is modified from Steinhauer, Alter, and Friederici (1999).

In verification of the observed effect reflecting the processing of prosodic units, subjects were tested under different task conditions, i.e., comprehension task or prosodic judgement in addition to a comprehension task. Independent of the respective tasks, ERP responses to both sentence types

obtained the same patterns as reported before. Moreover, to ascertain that the positive shift reflects prosodic phrasing, instead of indicating the processing of specific acoustic properties that define IPBs (e.g., pauses), the authors included an additional experiment, for which the pause at the boundary was deleted, while the other boundary cues were preserved. Assuming that the positive shift in fact signals the recognition of a prosodic boundary, this perception should be independent of whether the boundary is acoustically realized by lengthening, boundary tones, or pausing (as long as the remaining boundary information is sufficient; see cue trading, Beach, 1991 and Streeter, 1978). Since after the pause deletion, the ERP patterns still showed a positive shift at the boundary, the authors concluded that the observed ERP effect is not driven by speech interruptions (i.e., pauses) per se but reflects the perception of prosodic cues that in concert define prosodic breaks.

In conclusion, Steinhauer and colleagues interpreted the observed positive-going ERP component as an indicator of the closure of prosodic phrases by IPBs and accordingly named it *Closure Positive Shift (CPS)*. The CPS marks task-independent processing of phrase-level prosodic cues that in combination define IPBs, i.e. pitch change, syllable lengthening, and pausing (see Selkirk, 1984). The perception of those cues is essential for structuring the incoming speech signal and enables further speech analyses.

The described ERP experiments on the perception of phrasal prosody all address the auditory processing domain. However, most readers are known to automatically experience an *inner voice* when, for example, reading a text (Chafe, 1988). Here, written words activate their phonological representations, a process called phonological recoding (e.g., Share, 1999). It follows that intonational patterns are not only perceived during listening but also during reading, where the subvocal activation of prosodic phrasing enables the structuring and segmentation of the visual speech input. Given that the CPS generally indicates prosodic phrase processing, it may also occur for visual presentations of speech. Steinhauer and Friederici (2001) investigated the role of implicit prosody during reading, where prosodic phrasing was triggered by commas (see also Steinhauer, 2003). In a replication of the original study in the visual domain, the authors observed a similar, although smaller and shorter, CPS component in correspondence to the comma-induced boundaries. Interestingly, the results revealed interindividual differences dependent on subjects' knowledge of comma rules. Only subjects with strict punctuation habits showed a CPS, while subjects with inconsistent punctuation habits did not.

In a second experiment, the authors found the same comma-induced CPS when subjects replicated sentence melodies (of previously heard low-pass filtered sentences) during silent reading. The similarities between the ERP effects of both experiments support the notion of commas as triggers for subvocal prosodic phrasing during reading.

As a result of the reported studies, the CPS has been interpreted as an indicator for the perception of prosodic breaks in the speech input and accordingly, the segmentation of continuous speech into prosodic units. However, as Steinhauer and Friederici (2001) point out, these data cannot completely resolve the issue whether the CPS is related to prosodic structuring per se or the consequences of prosodic structure for syntactic processing.¹⁸ Further support for the interpretation of the CPS as an indicator for the processing of prosodic structure was provided through studies by Pannekamp and colleagues that systematically varied the linguistic content of the presented sentence material (Pannekamp, 2005; Pannekamp, Toepel, Alter, Hahne, & Friederici, 2005). In these studies, the authors recorded brain responses to sentences with one IPB and sentences with two IPBs that were constructed from normal speech, speech without content words, pseudospeech (without content and function words), and hummed speech. Thus, while the degree of segmental information (lexico-semantic and syntactic) was varied, all sentences contained suprasegmental information, with prosodic boundary cues marking IPBs. Independent of the degree of segmental content, ERPs to all sentence types revealed a CPS in response to the respective boundary. This result let the authors conclude that the CPS component in fact reflects the processing of prosodic phrasing, as it even occurred in the absence of segmental information. Interestingly, while the CPS was broadly distributed over both hemispheres for all conditions involving segmental information, it showed a RH dominance when only prosodic information was present (i.e., in hummed sentences). This is in line with the lateralization results for discrete prosodic processing in patient and imaging studies (see 3.1).

Furthermore, a CPS in adult Dutch natives was reported by Kerkhofs, Vonk, Schriefers, and Chwilla (2007), who investigated the processing of prosodic phrasing in discourse by creating matches and mismatches of syntactic and prosodic boundaries. This was realized by setting up expectations of the occurrence or absence of a syntactic break, which was either met or not met by the occurrence of a prosodic break. The authors found that the CPS at the prosodic break was smaller in amplitude, when

¹⁸As outlined in 1.1.2 and 1.2.2, prosodic boundaries are in most cases also syntactic boundaries. Thus, at most speech breaks both prosodic and syntactic boundary information is available and either one can trigger segmentation.

it was aligned with a syntactic break than when it was not aligned with a syntactic break. These data suggest an immediate interaction between prosody and syntax in discourse comprehension. However, given the experimental design, crucial comparisons regarding the CPS were made across match and mismatch conditions, which demands some caution in the interpretation of the effects.

As the characteristics assigned to prosody are often called the *melody* of language, a comparative investigation of the mechanisms of phrase structure processing in music is of particular interest. In an ERP study, Knösche et al. (2005) first examined musical phrase perception by using similar experimental material as in the reported language studies, comprising 1) melodies with two phrases divided by a pause and 2) melodies with one phrase without pause, both melodies being otherwise identical. In response to the musical phrase boundary, the authors observed a positive shift that resembled the CPS in latency and distribution and was therefore labeled *music CPS*. Interestingly, Neuhaus, Knösche, and Friederici (2006) found differential ERP effects for the perception of musical phrases dependent on the subjects' musical expertise, with only musicians showing a music CPS, while non-musicians displayed a negative ERP component. Furthermore, Nan, Knösche, and Friederici (2006) studied cross-cultural differences in musical phrase perception in Chinese and Western music. The authors reported ERP effects that reflect cultural-specific and universal aspects of musical phrase processing.

Important in the context of the current thesis on developmental aspects of prosodic processing, the CPS has not only been reported for adults but also for 8-month-old infants (Pannekamp, Weber, & Friederici, 2006). The study by Pannekamp and colleagues was the first to investigate IP processing in infancy by means of ERPs. The authors used the same sentence constructions as in the adult studies (e.g., Pannekamp et al., 2005), but sentences were spoken in an infant-directed manner. Since infants' attention decreased towards the end of the sentences, the authors only analyzed the first critical part of both sentence types, contrasting conditions with IPB and without IPB. For the condition containing the IPB, the ERP results revealed a positive shift, which, however, occurred delayed as compared to the adult data. The authors concluded that infants as young as 8 months show electrophysiological correlates of IPB perception that are similar to the CPS observed in adults.

In summary, the CPS has been observed across different modalities – the auditory domain, the visual domain, and in music – and can be taken as an indicator for the structuring of the respective input based on prosodic/melodic cues.

3.3 Neurocognitive models of language comprehension

Research in the field of cognitive neuroscience delivers online brain measures that can be used to formulate models of the underlying cognitive processing mechanisms. Based on evidence from patient studies, functional imaging studies, and electrophysiological studies, Friederici (2002) proposed a *Neurocognitive Model of Auditory Sentence Comprehension*. The model describes (Figure 3.2), how in sentence comprehension, after an initial acoustic and phonological analysis of the auditory input (*Phase 0*), three processing phases take place, each of which is reflected in particular ERP components (for more detail on language-related ERP components, see 5.2).¹⁹ In *Phase 1* (100-300 ms), words are assigned to their according syntactic categories, thus allowing their subsequent integration into the sentence's syntactic structure. In the case of a mismatch between the actual word category and what is predicted from the preceding word, an *Early left anterior negativity* (ELAN) is elicited. When the process of phrase structure building is completed, *Phase 2* (300-500 ms) is initiated. During this phase, lexical information associated with the processed word is accessed from two independently and parallel working pathways: the one functional, and the other one interpretative in nature. Here, lexical and morpho-syntactic information is analyzed to enable the integration of each word into the thematic-semantic structure of the sentence. At this stage, an N400 is observed for lexical-semantic violations, while a *Left anterior negativity* (LAN) occurs for morpho-syntactic violations. During *Phase 3* (500-1000 ms), processes of reanalysis and/or repair are initiated, when different kinds of information cannot be mapped onto another, reflected in a P600. In this context, it is assumed that phrase structure building processes are independent of semantic processing, while the processing of other syntactic information may interact with semantic processing.

The Neurocognitive Model of Language Comprehension has been extended to the *Dynamic Dual-Pathway Model* (Friederici & Alter, 2004). Here, the authors describe the underlying neuronal network of syntactic, semantic, and phonological processes in auditory sentence comprehension. Importantly, this model addresses both the processing of segmental and suprasegmental information. As the model's name suggests, the existence of two temporo-frontal pathways is proposed for language comprehension. One pathway is located in the LH and is devoted to the processing of segmental information. This pathway comprises two distinct circuits for syntactic and semantic information. The

¹⁹The reported brain regions, suggested to be involved in the different processing stages, are not discussed here.

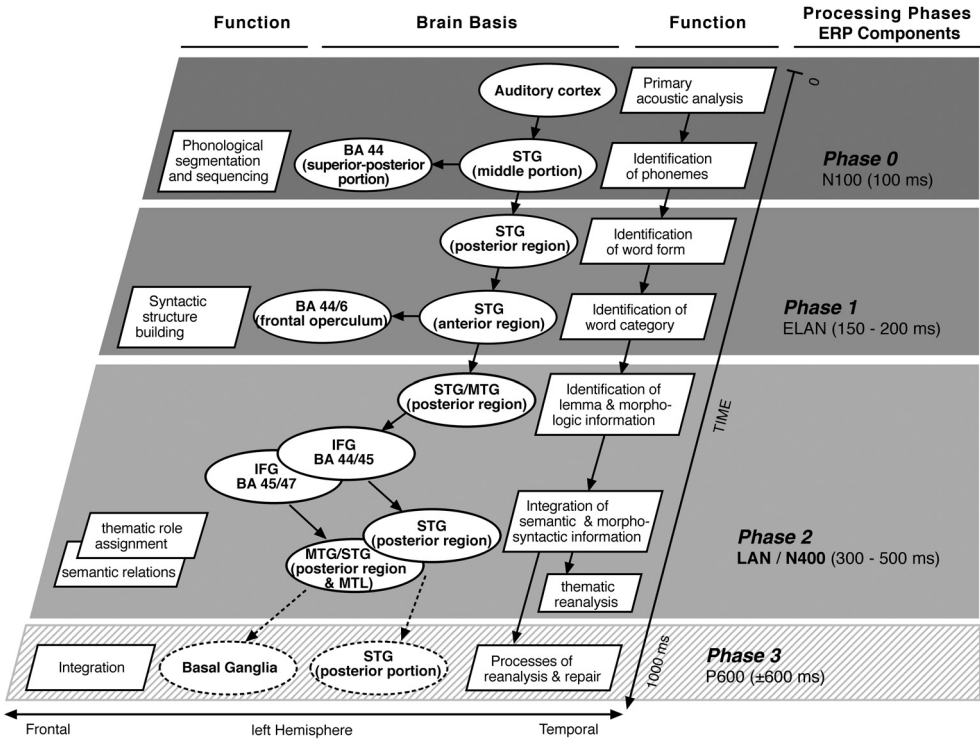


Figure 3.2: Neurocognitive Model of Sentence Processing (Friederici, 2002). In sentence comprehension, each processing phase is associated with particular ERP components (Figure from Friederici, 2006b).

second pathway is located in the RH and is devoted to the processing of suprasegmental information, i.e., sentence-level prosody. Importantly, the model incorporates the dynamic interaction between syntactic and prosodic information mediated by the corpus callosum (see Friederici, von Cramon, & Kotz, 2007). According to the model, the activation of the respective pathway depends on the particular features of the language stimuli and the experimental task. More specifically, the model proposes that semantics and syntax are predominately processed in the LH, while prosody recruits a more dynamic network. When the auditory speech signal contains (mainly) prosodic information, it is processed in the RH. However, the LH becomes engaged the more linguistic the task or the stimulus content, i.e., (additionally) comprising lexico-semantic and syntactic information.

Interim summary The present chapter aimed to describe the spatial and temporal characteristics of the brain mechanisms underlying phrase-level prosodic processing. Patient studies, imaging studies, and electrophysiological studies all contribute to a better understanding of the neuroanatomical and neurophysiological bases of prosody. The study of phrase-level prosody in isolation has revealed a functional lateralization to the RH, which, however, seems to involve or shift to the LH when prosody is bound to segmental information, as in natural speech. Electrophysiological research on prosodic boundary processing has revealed a particular ERP component, the CPS that indicates the perception of IPBs. Although prosodic information plays an essential role in language learning, there is still a lack of neuroscience research on infants' prosodic processing. The results of electrophysiological and brain imaging studies on language processing in adults have been integrated in the proposal of a Dynamic Dual-Pathway Model (Friederici & Alter, 2004). The model accounts for the differential processing of different linguistic aspects in the brain and, most importantly, incorporates the processing of phrase-level prosodic information.

Chapter 4

Summary of introduction

Part I of this thesis aimed to provide a comprehensive introduction to the defining features of prosody and the crucial role of prosodic information in both adult language comprehension and language acquisition. In this context, theoretical considerations and empirical evidence from studies using behavioral and neuroscience techniques have been provided.

More specifically, it was shown that prosody, as an integral feature of spoken language, is closely related to syntactic structure. Importantly, in auditory sentence comprehension, there is a close interaction between prosodic and syntactic information, such that prosodic boundary information signals syntactic constituents and the intonation contour of a sentence can influence syntactic parsing preferences and initiate the anticipation of syntactic structure. *From this, it can be concluded that the prosody-syntax interface is particularly important in adults' comprehension of spoken language.*

Numerous behavioral studies have provided evidence of infants' and toddlers' early ability to encode and utilize prosodic boundary information and rhythmic patterns. These prosodic cues signal linguistically relevant units in the speech stream, so that the detection of those cues constitutes a likely starting point for later lexical and syntactic learning. *It follows that, for infants in acquiring their native language, prosody may provide an entrance into the discovery of syntactic structure during the acquisition process.*

In recent years, neuroscience research has delivered increasing evidence of the spatial and temporal characteristics of the brain mechanisms underlying phrase-level prosodic processing. In this context, electrophysiological studies of adults' prosodic boundary processing have revealed a partic-

ular ERP component, the CPS that occurs in correspondence to IPBs. *As is evident in adult ERP studies, the CPS constitutes an electrophysiological measure for the perception of IPBs.*

Despite the advancement of developmental language research by behavioral studies, virtually nothing is known about the exact time course and the neurophysiological basis of phrase-level prosodic processing. In this regard, the ERP method provides a suitable research tool to study the brain characteristics of early language processing. The current studies aim to investigate, by means of ERP components (i.e., the adult CPS), the principles underlying infants' and children's IP processing, evaluating both acoustic and phonological aspects of IPBs.

Part II

Methodology

Chapter 5

The ERP method in developmental cognitive neuroscience

Research in the field of developmental cognitive neuroscience focuses on the relationship between brain development and cognitive development. For example, in language acquisition, the age at which infants perceive single words in the continuous speech stream is subject to research (i.e., when the underlying brain mechanisms become functional), especially when infants are not yet able to show an according verbal response. In developmental studies, the most frequently applied measures are ERPs, derived from EEG recordings. The use of NIRS and fMRI has only recently become more prominent (for example studies, see Anderson et al., 2001; Csibra et al., 2004; Dehaene-Lambertz, Dehaene, & Hertz-Pannier, 2002; Pena et al., 2003).

The following chapter provides a brief introduction to ERPs as a powerful research tool for the study of cognitive processes as they occur in the brain. First, the method at hand is explained, sketching the way from the EEG to the ERP signal. Further, it is illustrated how to look at and interpret the derived ERPs. Most importantly, the use of the ERP method for language studies is demonstrated by introducing ERP components observed in language processing, which in turn have been utilized in ERP studies of language acquisition. Finally, some characteristics of the ERP method are highlighted that become especially relevant when working with developmental populations.

5.1 Electroencephalography and Event-related brain potentials

5.1.1 From EEG to ERP

The human brain constantly produces electrical activity. This activity is associated with a wide range of brain states, such as states of activation, relaxation, tiredness, and engagement in cognitive tasks. Electrical brain activity originates from both neurons' action potentials and their postsynaptic potentials (for more detail, see Creutzfeldt & Houchin, 1974; Lopes da Silva, 1991; Speckmann & Elger, 1993). These electrical signals are minute and only recordable at the scalp when large populations of spatially aligned neurons are simultaneously active, so that in sum such signals are large enough to be measured. The timing characteristics of action potentials (lasting only 1-2 ms), *inter alia*, restrict the effect of summation, so that resulting currents are not measurable at larger distances (only within a few μm). In contrast, the slower postsynaptic potentials tend to sum up in neighboring neurons and produce macrocellular currents that are able to reach the surface of the scalp. The conductance characteristics of the brain tissue, skull, and scalp enable the current flow and summed postsynaptic potentials to be registered by electrodes placed on the scalp. The EEG continuously records electrical brain activity by measuring the voltage changes that arise from the difference in potentials between the recording electrodes and the reference electrodes (see Figure 5.2).

EEG recordings deliver a global picture of the brain's electrical activity. However, in cognitive neuroscience, researchers are interested in voltage fluctuations that are time-locked to specific sensory or motor events. The detection of those evoked responses in the global EEG signal is complicated, since they are relatively small (1-30 μV ; Regan, 1989) and masked by the ongoing background EEG activity (up to 100 μV ; Regan, 1989), unrelated to specific events. To study the processing of events of interest, these events have to be repeatedly presented and the EEG signal in response to these events subsequently averaged, so that brain activity unrelated to processing the stimulus cancels out across a sufficient number of repetitions. In this way, an average electrical brain response to a specific stimulus can be obtained.

The following example illustrates the derivation of ERPs from the continuous EEG signal. In an experimental procedure, subjects listen to tones of different pitch (Figure 5.1, A1), while an EEG is recorded. The brain signal generated by the subject is recorded over the course of the experiment and

amplified before being stored on a hard drive (Figure 5.1, B). Importantly, while the experimental computer is delivering the acoustic stimuli, it is simultaneously sending a trigger to the recording computer, marking the onset of each tone in the ongoing EEG (Figure 5.1, A2). After the EEG recording (Figure 5.1, C), filtering and artifact rejection/correction can be applied to the EEG raw data to remove artifacts caused by eye movement, perspiration, etc. (Figure 5.1, D). Filtering describes the removal of certain frequencies from the EEG signal that are sufficiently different from the frequencies that contribute to the ERP waveform (for more detail on filtering techniques, see Edgar, Stewart, & Miller, 2005). To increase the signal-to-noise-ratio, artifacts are often eliminated by simply rejecting contaminated trials. Alternatively, especially for artifacts stemming from eye movement, the artifact portion that contributes to the EEG signal is calculated and subtracted without losing the affected trials (for an overview of artifact estimation and removal, see Talsma & Woldorff, 2005 and Brunia et al., 1989). Following the preprocessing of the EEG data, time-locked epochs triggered by the onset of each tone (i.e., EEG data in a defined time window) are extracted (Figure 5.1, E). These temporally aligned EEG epochs are averaged following the assumption that the effect of random noise distributed by each of the single trials is reduced, while the event-related brain response remains (Figure 5.1, F). Consequently, a sufficient number of artifact-free trials, usually between 50-100, is required for averaging to gain a high signal-to-noise-ratio. Data processing and subsequent trial averaging ideally produce a smooth curve of changes in electrical activity that represents the average processing of a stimulus over time, i.e., the event-related brain potential (Figure 5.1, G).

In summary, the EEG method represents a non-invasive measurement of summed post-synaptic electric potentials at the scalp that are generated by similarly aligned and simultaneously firing pyramidal cells in the neocortex. The subsequent averaging of stimulus-triggered EEG epochs delivers a direct measure of the temporal course of changes in electrical activity, so-called ERPs that correspond to neuronal information processing.

5.1.2 ERP components and their interpretation

The schematic ERP waveform in Figure 5.1 (G) displays a sequence of positive-going and negative-going voltage changes. The designation of these changes as waves, deflections, peaks, or positivity/negativity primarily refers to their physical appearance, while the term component additionally ac-

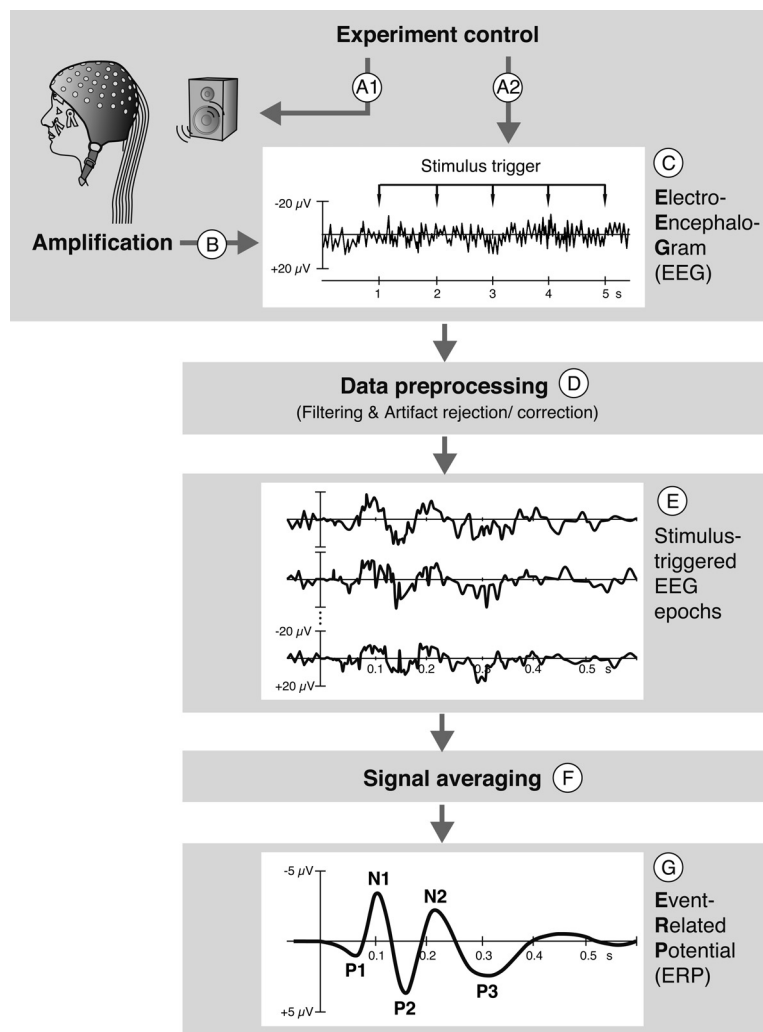


Figure 5.1: From EEG to ERP. Electroencephalographic recordings and subsequent data processing reveal event-related brain potentials. A1) The experiment computer generates acoustic stimuli. A2) At the same time, the experiment computer sends stimulus trigger to the ongoing EEG recording. B) Amplification of the scalp-measured EEG signal. C) Ongoing EEG recording. D) Optional preprocessing of EEG raw data. E) Extraction of time-locked epochs from the EEG signal. F) Averaging of time-locked EEG epochs. G) Resulting event-related brain potentials in response to the acoustic stimuli. (Figure from Männel, 2008).

counts for their functional significance. In other words, ERP components are considered to be indicators of various sensory, motor, and cognitive processes, reflecting covert and overt information processing. The components of ERPs can be described and defined by four parameters: amplitude/polarity, latency, scalp distribution/topography, and functional significance.

Amplitude (plotted on the y-axis in μV ; see Figure 5.1, G) specifies the extent to which neural activity is generated in response to an experimental stimulus. Dependent on the pole orientation of the measured electric field, the polarity of this response varies, resulting in positive or negative deflections.²⁰ Regarding the experimental value of amplitude measures, a decrease of the amplitude of a certain ERP component across experimental conditions may be related to a reduction in the processing demands or efficiency.

Latency (timecourse plotted on the x-axis in ms, see Figure 5.1, G) indicates the point in time at which ERP components occur relative to stimulus onset. Both the amplitude/polarity parameter and the latency parameter contribute to an ERP component's particular name. Waves with a negative-going deflection are labeled with N, waves with a positive-going deflection with P. The time (in ms) from stimulus onset to certain wave peaks is indicated by a number. The N100 component, for example, refers to a negativity that can be observed around 100 ms after stimulus onset. However, components are often labeled according to the order of their appearance during stimulus processing (e.g., P1, N1, P2, N2), rather than just denoting the actual time of their occurrence. This holds true for the so-called early components (from 100 ms to about 200 ms), which usually have a fixed latency. So-called late components (from about 300 ms on) are subject to the specific experimental conditions to a much greater degree. For example, the latency of the P300 component varies between 300 ms and 700 ms post-stimulus, depending on the degree of discrimination difficulty, stimulus complexity, and task demands (e.g., Katayama & Polich, 1998; Daffner et al., 2000). Generally, a latency increase of a specific ERP component across experimental conditions can be attributed to a slowing down of a specific cognitive process.

Scalp distribution or topography (denoted by electrode positions or according to anatomical descriptions, see Figure 5.2) describes a component's voltage gradient over the scalp at any point during stimulus processing. An ERP component's label can include topographical information, referring to

²⁰Negativity is plotted upward in most figures by convention, but some laboratories plot negativity downward.

a defining feature of this component, e.g., ELAN for Early Left Anterior Negativity (see later in this chapter). As can be seen from Figure 5.2, the longitudinal line between nasion (NZ) and inion (IZ) divides the schematic two-dimensional scalp into the left and right hemispheres, while the latitudinal line between the left and right pre-auricular points separates the anterior and posterior brain regions. Thus, the ELAN refers to a negative ERP component that occurs relatively early, at around 200 ms post-stimulus onset, and can be primarily observed at left anterior regions. Furthermore, some ERP components occur with a central focus in their scalp distribution (e.g., N400; see 5.2), while others exhibit a more posterior distribution (e.g., P600; see 5.2). The evaluation of the ERP signal across electrode sites delivers some restricted spatial information about the underlying neurophysiological mechanisms and allows conclusions about the lateralization to one hemisphere or the distribution over posterior brain regions. Topographic maps display the voltage difference between two conditions distributed over the scalp (e.g., negativities or positivities over particular regions). However, conclusions about the exact location of the neural generators of ERP components cannot be drawn by relying on topographic information only. To achieve valid localization statements, source localization methods should be applied that estimate the location of the neural generators based on the scalp-recorded potential.²¹

The recording positions of electrodes are standardized and defined by international conventions. The most common electrode naming and placing system is the *10-20 system* (Jasper, 1958; Sharbrough et al., 1991), where electrodes are located at distances of 10% or 20% along the longitudinal line and the latitudinal line across the head (see Figure 5.2). Electrode positions are denoted by letters that refer to anatomical terms, such as F for frontal, C for central, T for temporal, P for parietal, and O for occipital. In addition, numbers indicate the distance of lateral positions from the midline as the zero point (z), with larger numbers indicating greater distance. Even numbers refer to right hemisphere positions, while odd numbers name left hemisphere positions. It follows that the ERP signal, plotted for single electrodes, can be easily allocated by following these naming conventions. The original placement system can be extended to the *10-10 system*, according to the 10% distance rule (Chatrian, Lettich, & Nelson, 1988). Thus, an EEG is recorded with lower or higher density, dependent on the number of recording electrodes (for an example configuration, see Figure 5.2).

²¹For more detail, see Pascual-Marqui, 2002; Pascual-Marqui, Michel, & Lehmann, 1994, on the minimum norm-based technique *LORETA* and Scherg, Vajsar, & Picton, 1989; Scherg & von Cramon, 1986, on the *BESA* technique.

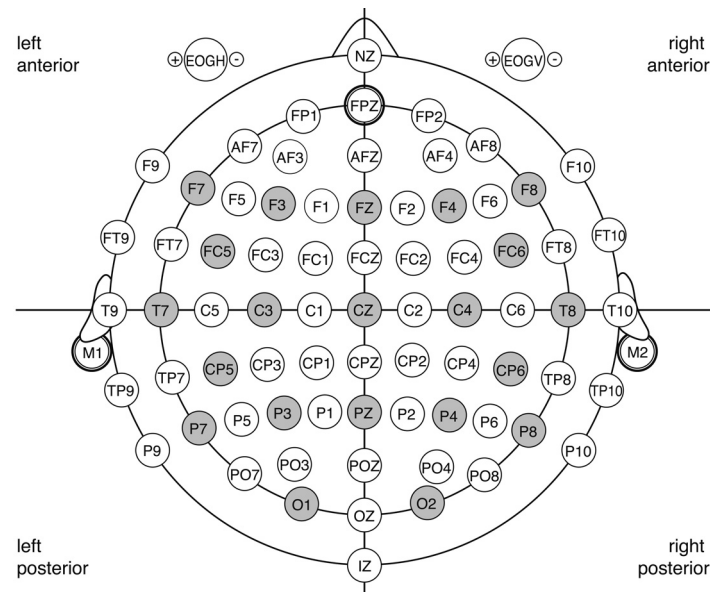


Figure 5.2: International 10-10 System of Electrode Placement (Chatrian, Lettich, & Nelson, 1988). Electrode positions are defined by letters and numbers: Letters depict anatomical terms; F=frontal, C=central, T=temporal, P=parietal, O=occipital, FP=fronto-polar, AF=anterior frontal, FC=fronto-central, CP=centro-parietal, TP= temporo-parietal, PO=parieto-occipital. Even numbers refer to right hemisphere electrode locations, odd numbers to left hemisphere electrode locations. Additionally, numbers indicate the distance from the midline as zero point (Z), with larger numbers indicating greater distance. Gray electrode positions mark an example recording configuration. Framed electrode positions indicate reference electrodes (M=mastoid). In addition to the EEG signal, typically an Electrooculogram (EOG) is recorded to monitor horizontal (EOGH) and vertical eye movement (EOGV).

Regarding their *functional significance*, specific ERP components are known to be elicited under certain experimental conditions or paradigms. For instance, the P300 component has been observed in various oddball paradigms in response to deviant (infrequent) stimuli presented in a series of standard (frequent) stimuli. This component reflects memory- and context-updating processes after stimulus evaluation (Donchin & Coles, 1988). The label of an ERP component can depict the particular experimental paradigm in which the component is evoked, e.g., MMN for Mismatch Negativity (see 5.2). As pointed out, ERP components are considered to be indicators of the progression of information processing over time.²² Early components (up to 100-200 ms after stimulus onset) are thought to reflect essentially automatic processes that are modulated by the physical properties of a stimulus, such as the loudness and pitch of a spoken word. Late components (300 ms and beyond) are regarded as indicators of higher-order cognitive processing, influenced by a person's intentions and actions, for example present during a discrimination task between words and non-words. Importantly, sensory ERP components of different modalities (e.g., the visual N1 and P2 and the auditory N1 and P2), typically do not refer to the same underlying mechanisms, but are specific to the input modality, whereas late components (e.g., the P300) are more modality-independent. For more detail and a discussion of the functional significance of particular ERP components, see 5.2 and reviews by Donchin, Karis, Bashore, Coles, and Gratton (1986); Regan (1989); and Rugg and Coles (1996).

5.1.3 Advantages and disadvantages of the ERP method

The evaluation of a method's advantages and disadvantages allows the selection of research questions that can be answered by applying this particular method. The following paragraphs discuss the benefits and shortcomings of the ERP method, as compared to other methods, thus pointing to the preferential area of application.

Behavioral methods measure overt responses by evaluating response speed and accuracy. These parameters permit conclusions about the direct effect of experimental manipulations on the resulting behavior, for instance, task difficulty resulting in slowed responses. The obvious functional significance of a behavioral response is a definite advantage of these methods. However, since behavioral

²²The idea of sequentially occurring ERP components as indicators of successive processing stages is certainly a simplification, as it takes neither parallel processing nor the possible temporal overlap of activation from different neuronal generators into account. Nevertheless, this highly simplified model has proven itself in practice.

techniques only capture the end product of the processing of a given stimulus, they do not deliver any information about the involved cognitive processes. This leads to a distinct advantage of the ERP method for monitoring the actual online cognitive processing that yields the observed behavior. The continuous ERP measure between stimulus input and response output enables the investigation of each processing step. This allows to determine whether a slow down due to task difficulty stems from slowed perceptual processes or slowed response processes. Here, eye-tracking methods likewise deliver online parameters of the ongoing information processing. Nonetheless, these measures are only indirect indicators of the underlying brain mechanisms. In contrast, electrophysiological and hemodynamic measures directly reflect the online stages of information processing in the brain.

In the realm of neuroscience methods, the ERP method features excellent temporal resolution, as it provides information about the time course of brain responses in millisecond accuracy. In this way, ERPs deliver a mental chronometry, i.e., an exact temporal sequencing of information processing (see Coles et al., 1996). In comparison to neuroimaging techniques, such as fMRI and PET, the spatial resolution for the identification of the neural generators of the obtained signal is relatively poor, since maximal amplitude measures at certain electrode sites only provide information about where neural activity, evoked by certain stimuli, arrives at the scalp's surface. As pointed out, source localization techniques calculate the location of the neural generators of the ERP signal by either postulating distributed current sources as neural origins (e.g., the minimum norm-based technique LORETA; Pascual-Marqui, 2002; Pascual-Marqui, Michel, & Lehmann, 1994) or equivalent current dipoles (e.g., the BESA technique; Scherg, Vajsar, & Picton, 1989; Scherg & von Cramon, 1986). Nonetheless, these measures deliver only estimations of the location of neural generators, even if highly probable, and cannot compete with the actual spatial marking of hemodynamic changes in the brain with millimeter accuracy.

In summary, the decision to use a specific method should be based on the kind of question to be answered and, thus, the kind of information sought: the neuronal correlates of information processing in their spatial and/or temporal resolution or the behavioral consequences that follow from these processes. With respect to the ERPs, it can be stated that this method provides an online brain measure of sensory, motor, and cognitive processes that features an excellent temporal resolution, while the spatial resolution is comparably poor.

5.2 ERP components associated with language processing

The most important cognitive phenomenon, the human ability to process and produce language, has been a prominent object of research throughout the centuries. Language comprehension requires the analysis and integration of various aspects of linguistic information, all within a very short time frame. The investigation of these processes and their underlying brain mechanisms thus requires highly time-sensitive online measures. Over the last decades, numerous adult ERP studies have revealed that the processing of different aspects of linguistic information can be clearly distinguished by means of different ERP components. These studies have described functionally different components that are associated with low-level acoustic processing (the N1-P2 complex), phonetic and phonological processing (the MMN), prosodic processing (the RAN and the CPS), semantic processing (the N400) and syntactic processing (the E/LAN and the P600). In the following paragraphs, these ERP components are briefly introduced (see also reviews by Friederici, 2002; 2004; Kutas & Federmeier, 2000).

The *N1-P2-complex* describes an early automatic response in the ERP, which is composed of the N1 component, a negative deflection at approximately 100 ms post-stimulus onset, and the P2 component, a positive deflection at around 200 ms. These ERP components are also called *obligatory components*, since they are invariably elicited whenever input reaches the sensory systems. Accordingly, the N1-P2 complex is not specific to language but is automatically evoked in any kind of stimulus processing. The N1-P2 complex is modulated by the properties of the eliciting stimuli (e.g., loudness and fundamental frequency) and only partially determined by cognitive parameters, such as selective attention (see Crowley & Colrain, 2004; Hall, 1992; Näätänen & Picton, 1987). In infants, obligatory components are composed of the P150, N250, and P350 (Kushnerenko et al., 2002). This pattern changes across the development, where some obligatory components do not reach an adult-like appearance until far into adolescence (Pang & Taylor, 2000; Pasman, Rotteveel, Maassen, & Visco, 1999; Ponton, Eggermont, Kwong, & Don, 2000).

The *Mismatch negativity (MMN)* refers to a negative deflection in the ERP that occurs at around 100-250 ms post-stimulus onset and is largest at frontal and central midline electrode sites. Functionally, the MMN can be described as pre-attentive electrophysiological response to any discriminable change in repetitive auditory stimulation (Näätänen, 1990). This discrimination response is typically

studied in a so-called mismatch paradigm or passive oddball paradigm, where two classes of stimuli are repeatedly presented with one stimulus occurring relatively frequently (standard) and the other one relatively rarely (deviant or oddball). The mismatch response in the ERP is the result of the brain's automatic detection of the deviant among the standards and, thus, becomes especially apparent in the ERP subtraction wave, i.e., the ERP response to deviant stimuli minus the ERP response to standard stimuli. In language processing, the MMN has been, for example, observed during the discrimination of phonetically different stimuli (e.g., Opitz, von Cramon, & Kruggel, 1999) and was found to be modulated by language experience (Winkler et al., 1999). In infants, the *mismatch response* (*MMR*) has either been observed as negativity or positivity in the ERP. There are several reasons that may contribute to this differential outcome: 1) differences in the infants' alertness state (Friederici, Friedrich, & Weber, 2002), 2) methodological differences, e.g., use of different filters (Trainor et al., 2003), and 3) the coexistence/overlap of two types of mismatch responses (He, Hotson, & Trainor, 2007; Morr, Shafer, Kreuzer, & Kurtzberg, 2002). In general, there is a developmental transition in the infants' MMR from a positivity to an MMN-like negativity. This transition may be dependent upon the maturation of the human brain (Paus et al., 2001).

The *Right Anterior Negativity* (*RAN*) designates a negativity in the ERP at around 300-500 ms post-stimulus onset that can primarily be observed at right anterior electrode sites. The RAN was first reported by Eckstein and Friederici (2005) and is associated with the processing of prosodic incongruencies, caused by a mismatch between the syntactic structure and the expected prosody for that particular syntactic structure. In a follow-up study, Eckstein and Friederici (2006) observed a broadly distributed negativity (300-500 ms post-stimulus onset) in response to prosodic violations, rather than a right lateralized negativity. The variation in distribution can be attributed to differences in prosodic manipulation. In the earlier study, the prosodic violation was realized as an omission of the critical word, signaling sentence continuation that can simply be detected by auditory analyses. In the later study, sentence prosody was manipulated so that the prosody on the critical word (in penultimate sentence position) signaled either that the sentence would continue (prosodically correct) or that it was finished (prosodically incorrect). In the incorrect condition, this substitution delivers additional linguistic information, which might have superseded the auditory features. In all experiments, the

RAN was followed by a P600, which in this case was interpreted as reflecting integration difficulties due to the violation of the intonation contour.

The *Closure Positive Shift (CPS)* is a positive-going shift in the ERP with a centro-parietal distribution. As the component's name indicates, it is associated with the closure of prosodic phrases by IPBs (Pannekamp et al., 2005; Steinhauer & Friederici, 2001). Thus, the CPS marks the processing of phrase-level prosodic cues, since IPBs are defined by particular parameters, such as pitch change, syllable lengthening, and pause. The CPS was first reported by Steinhauer and Friederici (2001), who presented subjects with two sentences conditions: sentences with one IPB and sentences with two IPBs. The ERP response to each sentence type showed positive shifts in correspondence to each of the IPBs. Since the positive shift even occurred after deleting the pause at the IPB, the authors concluded that the observed ERP effect is not merely driven by speech interruptions (i.e., pauses), but reflects the perception of prosodic cues that in concert define prosodic breaks. The interpretation of the CPS as indicator of prosodic structure rather than syntactic structure processing found support in a study by Pannekamp et al. (2005). In this study, Pannekamp and colleagues systematically varied the linguistic information of the sentence material and found a CPS in response to IPBs even for hummed sentences, containing only prosodic information, while all segmental (lexico-semantic and syntactic) information was removed. Furthermore, the CPS has not only been observed in auditory sentence comprehension, but also in the visual domain, where prosodic breaks were triggered by commas during silent reading (Steinhauer & Friederici, 2001). In addition, a CPS has been described the processing of musical phrase structure, where musical phrase boundaries were defined by similar parameters as in phrase-level prosody (Knösche et al., 2005; Nan, Knösche, & Friederici, 2006; Neuhaus, Knösche, & Friederici, 2006). For more detail on the CPS, see 3.2.

The *N400* describes a centro-parietally distributed negativity that occurs at around 400 ms post-stimulus onset. The N400 has been intensely studied and is known to indicate lexical-semantic processes at both word level (Holcomb & Neville, 1990) and sentence level (Kutas & Hillyard, 1980; 1983). The N400 marks the effort to integrate an event into the semantic context and is more pronounced the more semantically unfamiliar, unexpected, or non-matching an event is, given the current semantic context or the semantic knowledge in long-term memory (for more detail see Holcomb, 1993). This implies that the N400 amplitude is inversely related to the expectation triggered by the

semantic context, a process called semantic priming, resulting in a reduction of semantic integration efforts. The N400 has been studied in various semantic priming paradigms and was observed in response to both words and pictures that do not match the semantic expectation built up by previously presented words, sentences, pictures and picture stories (Friederici, Pfeifer, & Hahne, 1993; West & Holcomb, 2002). In lexical processing, ERP studies have shown that the N400 amplitude is larger for pseudowords than for real words, whereas nonwords do not evoke an N400 response (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Holcomb, 1993; Nobre & McCarthy, 1994). Thus, pseudowords, but not nonwords, are treated as likely lexicon entries as they follow the phonotactic regularities, i.e., the rules that define how phonemes are legally combined to words in a given language. In studies on sentence processing, the semantic violation paradigm revealed N400 responses for sentences with semantically unexpected sentence endings versus semantically expected endings (Friederici, Pfeifer, & Hahne, 1993; Hahne & Friederici, 2002).

The *Early Left Anterior Negativity (ELAN)* designates a negativity in the ERP at around 150-350 ms post-stimulus onset that can primarily be observed at left anterior electrode sites. The ELAN is associated with highly automatic phrase structure building processes (Friederici, Pfeifer, & Hahne, 1993; Hahne & Friederici, 1999). Thus, when syntactically correct and incorrect sentences (containing phrase structure violations) are presented in a syntactic violation paradigm, the ELAN occurs together with the P600 component in response to the incorrect sentences. This ERP pattern has been observed for both passive as well as active sentence constructions (Friederici, Pfeifer, & Hahne, 1993; Hahne & Friederici, 1999; Hahne, Eckstein, & Friederici, 2004; Rossi, Gugler, Hahne, & Friederici, 2005). A *left anterior negativity (LAN)* that occurs between 300-500 ms post-stimulus onset has been reported for morphosyntactic violations in a language with inflectional morphology (i.e., German) (see Friederici & Weissenborn, 2007). The LAN is followed by a P600 as well.

The *P600* refers to a centro-parietal positivity in the ERP between 600-1000 ms post-stimulus onset, also called *Syntactic Positive Shift (SPS)* (Hagoort, Brown, & Groothusen, 1993). As pointed out, the P600 occurs together with the ELAN or the LAN in response to syntactic violations (Friederici, Pfeifer, & Hahne, 1993; Hahne & Friederici, 1999; Osterhout & Mobley, 1995). The P600 is interpreted to reflect controlled processes of syntactic reanalysis and integration that are initiated after the detection of syntactic errors (ELAN/LAN). The P600 has not only been observed for the processing

of syntactic violations, but also for syntactically complex sentences and syntactically non-preferred gardenpath sentences. The processing of those sentences requires a high degree of syntactic integration as well as syntactic reanalysis and repair (Friederici, Hahne, & Mecklinger, 1996; Hagoort, Brown, & Groothusen, 1993; Kaan, Harris, Gibson, & Holcomb, 2000; Osterhout & Holcomb, 1992; 1993; Osterhout, Holcomb, & Swinney, 1994).

5.3 The ERP method in developmental research: Some considerations

In working with infants and young children, researchers are confronted with certain limitations that make the experimental procedure much more challenging than in adults. More specifically, an abbreviated attention span, limited verbal and motor skills, frequently occurring hunger and tiredness necessitate short experiments that work without instructions and do not require motor responses. Given these restrictions, one immense benefit of the ERP method becomes readily apparent. For EEG recordings, no overt responses are necessary, since an EEG directly measures brain activity evoked by specific stimuli, thus considerably facilitating developmental research. The fact that ERP components are direct indicators of the underlying brain processes implies not only that no task assignments are necessary, but also that brain processes evoked by certain stimuli may be detectable before there is a behavioral correspondence observable. Although behavioral methods used in infant research, such as the headturn paradigm and the preferential looking paradigm, require a less complicated set-up and can be performed in a more natural setting, these methods are more prone to external interferences. With respect to imaging techniques, there are some limitations in the work with infants and young children (but see Hebden, 2003; Meek, 2002 on optical imaging in infants). In PET, the invasiveness of the application of a radioactive marker bars the use in developmental research. In fMRI, movement restrictions during brain scanning make it rather difficult to work with children. In addition, there is an ongoing discussion regarding whether the BOLD signal in adults is comparable to the one in children and whether the applied adult models are appropriate for infant research (for discussion, see Marcar, Strassle, Loenneker, Schwarz, & Martin, 2004; Rivkin et al., 2004; Schapiro et al., 2004).

The evaluation and interpretation of ERP components in developmental populations call for some additional considerations. While neurophysiological changes take place far into adolescence (e.g., Gield et al., 1999), in infants and children, the permanent changes in synaptic density, myelination,

skull thickness, cortex folding, and fontanel state are particularly profound (e.g., Mrzljak, Uylings, Van Eden, & Judas, 1990; Pujol et al., 2006; Toro & Burnod, 2005; Uylings, 2006). Accordingly, these maturational variations affect the ERP outcome in developmental populations at different age levels. For instance, the reduced synaptic density in infants yields a greater slow wave activity, possibly explaining why infant ERPs do not exhibit as many well-defined peaks as adult ERPs (Nelson & Luciana, 1998). Infant ERPs usually feature larger amplitudes than adult data, possibly attributable to differences in skull thickness. Also, infant ERPs usually show longer latencies than adult ERPs, probably denoting more time needed for a particular process. Both amplitude and latency measures gradually decrease with increasing age (e.g., Jing & Benasich, 2006; Kushnerenko et al., 2002). These maturational changes need to be considered when comparing ERP components across different age groups. First, infants and children should be tested in narrow age ranges to allow for valid statements about specific developmental states. Second, paradigms used in children ERP experiments should additionally be applied in adult studies. In this way, target adult ERP patterns can be achieved that enable developmental comparisons across different age levels.

In summary, the ERP method represents a highly suitable research tool for developmental populations, since it places virtually no demands on children's behavior and delivers online measures of information processing in the brain. Given the described language-related ERP components in adults, these components may serve as templates to describe the neurophysiological mechanisms of the language acquisition process as children develop their perceptive language skills. In this way, ERPs not only provide information regarding whether there are specific ERP indicators of particular language processes in infants and children, but also allow for sketching of the hallmarks of the language acquisition process (for reviews see Friederici, 2005, 2006a; Kuhl, 2004).

Part III

Empirical Investigations

Chapter 6

Research questions

As proposed by the prosodic bootstrapping hypothesis (e.g., Gleitman & Wanner, 1982), the perception of prosodic information in the speech input plays a crucial role in the initial stages of language acquisition. As outlined in 1.1, spoken language contains various acoustic cues – such as pause and durational differences and changes in fundamental frequency – that conjointly signal prosodic boundaries. Given the close match of prosodic and syntactic structure, the speech stream can be segmented into smaller linguistically relevant units on the basis of these prosodic cues. Thus, the detection of prosodic boundaries delivers a first good guess for the language learner as to where syntactic boundaries occur in continuous speech, providing the basis for further lexical and syntactic learning. In this regard, the early perception of large prosodic units seems to be particularly relevant for language learning (2.2). For this reason, further studies are required that investigate the principles underlying infants' early perception of prosodic boundary cues that mark IPs, the largest units in phrasal prosody (1.1.2). In contrast to behavioral studies, the ERP method allows investigating the ongoing stimulus processing at different levels, from perceptual to cognitive stages (4.1). Early components in the ERP are known to reflect lower-level perceptual processing (N1-P2 pattern; Crowley & Colrain, 2004; Näätänen & Picton, 1987), while later components reflect cognitive processes. For the late processing domain, the CPS has been described as an indicator of IP processing (Steinhauer, Alter, & Friederici, 1999). *Study I* examines the neurophysiological basis of IP processing in 5-month-old infants and adults and, furthermore, aims to specify the role of the pause as one of the three acoustic parameters marking prosodic boundaries.

As discussed in 1.2.2, there is a close interaction between prosodic and syntactic information in adult sentence processing, such that phrase-level prosody influences syntactic parsing preferences and initiates the anticipation of syntactic structure. In turn, prosodic structure is in large part determined by syntactic structure, with nearly every prosodic boundary also being a syntactic boundary. Given the interdependence of prosody and syntax in language perception, the neurophysiological correlates of IP processing may change across developmental stages in syntax acquisition. As syntactic rules become particularly relevant between children's second and third year, when they start to combine words to sentences and begin to analyze sentential relations, ERP studies have revealed a developmental shift in syntactic phrase structure processing between 24 and 32 months (Oberecker, Friedrich, & Friederici, 2005; Oberecker & Friederici, 2006). *Study II* investigates the neurophysiological correlates of IP processing in 21-month-old, 36-month-old, and 6-year-old children, thus addressing age levels before and after this developmental shift in syntax acquisition.

Chapter 7

General methods

The realization of the ERP experiments and their analysis all followed, as far as possible, the same standardized procedures. The following chapter gives an overview of the general methods applied in all of the experiments. Details that are specific to a particular age group are denoted in the respective method sections (see 8.2 and 9.2).

7.1 Subjects

7.1.1 Adults

Adult participants were students of the University of Leipzig. All students were native speakers of German and right-handed, as assessed by a German version of the *Edinburgh Handedness Inventory* (Oldfield, 1971). These subjects reported having no known hearing deficits or neurological problems.

7.1.2 Children

5-month-olds were recruited from the Infant Database of the Max Planck Institute for Human Cognitive and Brain Sciences in Leipzig and the Database of the German Language Development Study in Berlin. 21-month-olds, 3-year-olds, and 6-year-olds were all participants of the German Language Development Study in Berlin. According to parental information, all children were born at full-term after a normal course of pregnancy and normal birth. Furthermore, children did not have any known hearing deficits or neurological problems. All participants came from monolingual German families. Prior to their participation, parental informed consent was obtained for all children.

The *German Language Development Study (GLaD Study)* is a longitudinal research project (age 0-6 years), funded by the German Research Foundation and the Max Planck Institute for Human Cognitive and Brain Sciences Leipzig. The aim of the project is to investigate the neurophysiological mechanisms of normal and impaired language processing across different age levels. In addition, the project targets the identification of electrophysiological precursors in preverbal infants' language processing for their risk to experience later language problems. Accordingly, for participation, both infants with and without a family history of Specific Language Impairment and Developmental Dyslexia were recruited. As part of the project, ERP studies and standardized language tests are carried out at several age levels, for monitoring children's developing language perception and production skills. For the current ERP studies of children's prosodic processing during normal language development, children's scores of the most recent language test *SETK-5* (Grimm, 2001) were obtained, performed at the age of 5 years. In the final ERP analyses, only data of those children were included who performed within the normal range ($T > 40$; $PR > 15.87$) in at least four of the five subtests of the *SETK-5*.²³

EEG recordings in infants and children typically contain disproportionate numbers of artifacts in the EEG signal, caused by exaggerated movement, perspiration (skin potentials), crying, or non-compliance. For the final analyses, only data of those children who produced a sufficient number of artifact-free trials were considered. The data of about 30% of all infants and toddlers and 25% of the older children tested was excluded. The final sample of each age group is reported in the respective method section.

7.2 Stimulus material

Subjects were either presented with *Naturally spoken sentences* of two conditions (with and without IPB) or the same sentences, for which, however, the pause at the IPB was deleted. Accordingly, these *Sentences with neutralized pause* consisted of the two conditions: with IPB (pause deleted) and without IPB.

All sentences were produced in a soundproof chamber by a trained female speaker, who was instructed to speak in an infant-directed manner. After recording, sentences were digitized (44.1 kHz/16bit sampling rate, mono) and normalized in amplitude to 70%. By using infant-directed sentences,

²³Based on their performance at the *SETK-5*, approximately 20% of the children were excluded from further analyses.

it was ensured that infants and toddlers were presented with the characteristic language input they are typically exposed to in their natural environment. As outlined in section 2.1, infant-directed speech is characterized by a simplified structure, slow speech rate, and exaggerated use of prosodic features, e.g., greater pitch variability and longer pauses (Fernald et al., 1989). In the current studies, this was important for two reasons: 1) attracting the children's attention to the stimulus material, as it is known infants prefer to listen to infant-directed speech over adult-directed speech (Cooper & Aslin, 1990; Fernald, 1985), and 2) ensuring an effective experimental manipulation by presenting prosodic boundary features in a manner that would be readily perceived by the infants. For comparability across age groups, older children and adults were presented with the same infant-directed sentences.

Note that the construction of the sentence material followed from previous adult studies on the processing of IPBs (see Steinhauer, Alter, & Friederici, 1999). For the infant studies, however, the sentences were shortened, to minimize both the trial time and overall experiment time. For this reason, short sentences were designed without IPB versus sentences with IPB instead of longer sentences containing one IPB versus two IPBs. The contrast between ERP components elicited for the two types of short sentences should in principle reveal, whether infants are able to process IPBs.

7.2.1 Naturally spoken sentences

All Naturally spoken sentences either contained or lacked an IPB, thus differing in their intonational realization. The intonation differences resulted from the underlying syntactic structures that differed dependent on the valence of the second verb. Sentences with IPB contained two IPs divided by an IPB, whereas sentences without IPB only consisted of one IP and, consequently, lacked an IPB (for example sentences see Table 7.1 and Appendix B). Sentences with IPB contained a transitive verb at the end. For the example *Tommi verspricht Papa zu helfen* (Tommi promises to help papa) *zu helfen* (to help) is the transitive verb and it requires to be accompanied by a noun phrase, which in this case is *Papa* (direct object). As a consequence, an IPB occurred at the first verb, marking a first syntactic phrase *Tommi verspricht* (Tommi promises), which was followed by a second phrase *Papa zu helfen* (to help papa). In contrast, sentences without IPB ended with an intransitive verb, e.g., *Tommi verspricht Papa zu schlafen* (Tommi promises papa to sleep) was followed by *zu schlafen* (to sleep). Here, the noun phrase *Papa* is the indirect object of the first verb *verspricht* (promises), and

therefore, sentences of this type did not contain a sentence-internal IPB. The sentences were designed with each sentence pair being identical in wording up to the second verb, which could be either transitive or intransitive. The identical word order in German actually imposes a structural ambiguity on the listener's parsing process since the syntactic role of the noun phrase, i.e., direct object or indirect object, is not resolved until the occurrence of the second verb at the end of the sentence, i.e., the transitive verb or the intransitive verb.²⁴ However, the syntactic structure can be easily determined prior to the appearance of the second verb, since the prosodic information varies significantly between both sentence types from the sentence onset, with intonation and duration parameters signaling the respective syntactic units (see paragraph Acoustic parameters for Naturally spoken sentences, below).

Table 7.1: Stimulus examples for Naturally spoken sentences (with literal translations).

1) Example sentence with IPB (two IPs)
<i>[Tommi verspricht,] IP1 [Papa zu helfen.] IP2</i>
[Tommi promises] IP1 [papa to help.] IP2
2) Example sentence without IPB (one IP)
<i>[Tommi verspricht Papa zu schlafen.] IP1</i>
[Tommi promises papa to sleep.] IP1

All sentences (50 of each type) were designed so that the eight noun phrases (*Oma, Opa, Mama, Papa, Lena, Tina, Tommi, Kevin*) were counterbalanced across their role as subject or object of the sentence. Furthermore, noun phrases were counterbalanced across the five different verbs in the first sentence part. The selection of the verbs at the end of the sentences, either transitive or intransitive, was realized so that verb frequencies were about equivalent between conditions (according to the *WebCELEX* database, Max Planck Institute for Psycholinguistics, 2001).

²⁴This is different for the English version of the example sentences. In English, the word order directly indicates the syntactic role of Papa: *Tommi promises to help papa* versus *Tommi promises papa to sleep*. Thus, the prosodic realization of the English sentences does not play the same disambiguating role as it does in the German sentences.

Table 7.2: Stimulus examples for the long version of Naturally spoken sentences (with literal translations).

1) Example sentence with two IPBs (three IPs)

[Tommi verspricht,] IP1 [Papa zu helfen] IP2 [und ganz lange lieb zu sein.] IP3

[Tommi promises] IP1 [papa to help] IP2 [and to be a good boy for a while.] IP3

2) Example sentence with one IPB (two IPs)

[Tommi verspricht Papa zu schlafen] IP1 [und ganz lange lieb zu sein.] IP2

[Tommi promises papa to sleep] IP1 [and to be a good boy for a while.] IP2

Long version of Naturally spoken sentences For the experiments with 21-month-olds and 3-year-olds, the infant-directed sentences were originally designed similarly as the sentences of the adult studies to enable a direct developmental comparison (see Pannekamp, 2005; Pannekamp et al., 2005). As exemplified in Table 7.2, this stimulus material comprised sentences with two IPBs and sentences with one IPB, resulting in sentences of up to 4.5 s duration. However, since children's attention decreased towards the end of the sentences and to ensure a high signal-to-noise ratio (i.e., more individual averages to reach the inclusion criterion), shorter EEG segments were chosen for data analysis. Thus, ERP averages covered only the first critical part of the sentences resulting in a contrast between sentence parts containing an IPB, e.g., *Tommi verspricht, Papa zu helfen* (Tommi promises to help papa) and sentence parts without an IPB, e.g., *Tommi verspricht Papa zu schlafen* (Tommi promises papa to sleep). In other words, for these children, the same comparison across conditions was performed as in the experiments with short Naturally spoken sentences used for all other age groups (see above). In this way, comparisons across infant and children studies were possible.²⁵ To describe the according conditions, the same terms are used as for the short sentence version, i.e., *Sentences with IPB* (originally two IPBs) and *Sentences without IPB* (originally one IPB).

For details on the construction of the long version of Naturally spoken sentences and their acoustic analyses, the reader is referred to Pannekamp (2005) and Pannekamp et al. (2005).

²⁵While comparisons across age groups were only drawn visually and not statistically, the critical comparison regarding the emergence of the CPS between 21 months and 3 years concerned studies using identical stimulus material.

Acoustic parameters for Naturally spoken sentences

For the Naturally spoken short sentences, acoustic analyses (Adobe Audition 1.0; Praat 4.4.18) revealed clear differences between sentences with IPB and sentences without IPB regarding their durational and tonal characteristics.

For the analysis, both sentence types were divided into three sections of interest by markers that were manually set in each audio file: 1) sentence part 1 *Tommi verspricht* (Tommi promises), 2) pause (following the first verb), and 3) sentence part 2 *Papa zu schlafen/helfen* (papa to sleep/to help papa). As can be seen from Figure 7.1, sentence part 1 is significantly longer for sentences with IPB than for sentences without IPB [independent t-test; $t(98)=-10.78$, $p \leq .01$].

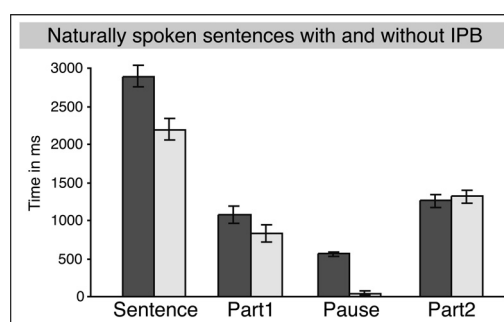


Figure 7.1: Naturally spoken sentences: Duration parameters of sentences, sentence parts 1 & 2, and pauses for sentences with IPB (dark grey) and sentences without IPB (light grey); error bars indicate SD.

This difference is mainly accounted for by the significantly longer syllable at the end of the first part in sentences with IPB [$t(98)=-22.99$, $p \leq .01$]. In contrast to sentences without IPB, sentences with IPB included a rise in pitch at the end of the first sentence part [$t(98)=-36.22$, $p \leq .01$; see Figure 7.2 for the F0 contour from two example sentences]. Furthermore, the pause following the first sentence part is significantly longer [$t(98)=-106.38$, $p \leq .01$] for sentences with IPB (560 ms, SD=26 ms) than for sentences without IPB (45 ms, SD=22 ms). As a result, the overall sentence length differs significantly between conditions [$t(98)=-24.71$, $p \leq .01$]. Sentences with IPB averaged 2890 ms (SD=136 ms) and sentences without IPB averaged 2200 ms (SD=145 ms).

In summary, the acoustic analyses confirmed that sentences with IPB contained an IPB at the end of the first sentence part, while the sentences without IPB did not. The IPB was acoustically realized by an increase in pitch level, a lengthening of the last syllable, and a protracted pause following a phrase-final increase in pitch.

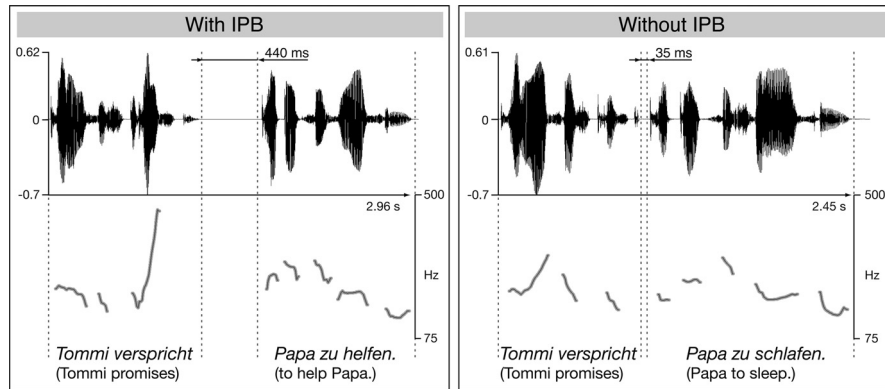


Figure 7.2: Naturally spoken sentences: Waveform (normalized values) and pitch track (F0 contour in Hz) for examples of sentences with IPB (left panel) and sentences without IPB (right panel).

7.2.2 Sentences with neutralized pause

Sentences of the type *with neutralized pause* were created from the Naturally spoken sentences by neutralizing differences in pause length between conditions. This was done by removing the pause following the boundary tone in the sentence condition containing the IPB (see Figure 7.3), hereafter called Sentences with neutralized pause (with IPB). Again, the sentence material comprised 50 sentences without IPB and 50 sentences with IPB (pause deleted).

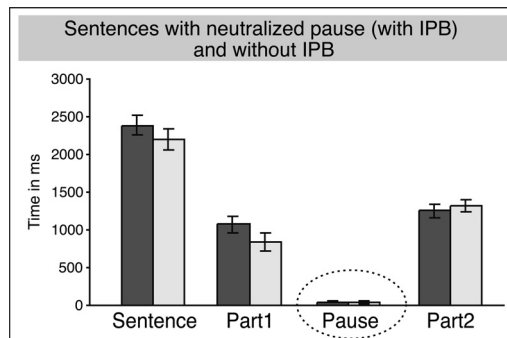


Figure 7.3: Sentences with neutralized pause: Duration parameters of sentences, sentence parts 1 & 2, and pauses for sentences with IPB (dark grey) and sentences without IPB (light grey); error bars indicate SD. Except for pause length, all other duration parameters were the same as in Naturally spoken sentences.

Acoustic parameters for Sentences with neutralized pause

For creation of the Sentences with neutralized pause (with IPB), about 500 ms of silence were deleted at the boundary in the Naturally sentences with IPB, preserving voice offset and onset for the adjacent

words, thus ensuring the naturalness of the new material by retaining the brief pause that typically occurs between words in sentences. The remaining pauses did not significantly differ from the pauses at the same sentence position in sentences without IPB [$t(98)=-1.03$, $p=.31$]. Apart from shortening the pauses in the Sentences with neutralized pause (with IPB), all other acoustic features remained the same for both sentence types (see Figure 7.4). As a result of pause deletion, the sentences with IPB were shorter than the original Naturally spoken sentences with IPB, but there was still a significant difference in total duration between the IPB and without IPB conditions [$t(98)=-6.65$, $p\leq.01$]. The mean length for Sentences with neutralized pause (with IPB) was 2380 ms (SD= 132 ms), while for Sentences without IPB it was 2200 ms (SD=145 ms).

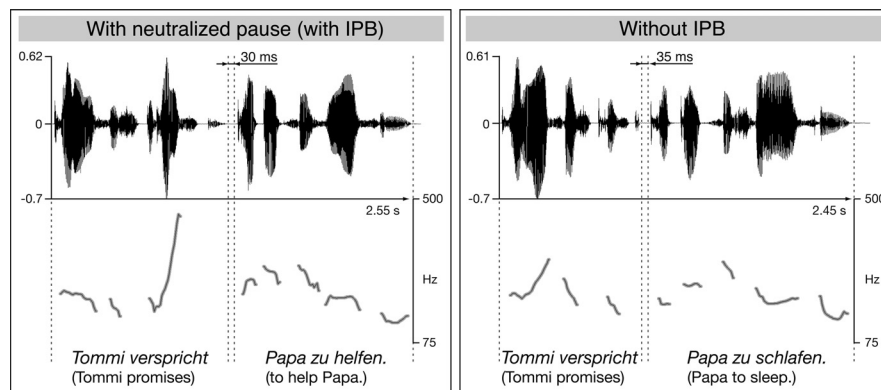


Figure 7.4: Sentences with neutralized pause: Waveform (normalized values) and pitch track (F0 contour in Hz) for examples of Sentences with IPB (left panel) and Sentences without IPB (right panel).

7.3 Experimental procedure

During the experimental procedure, children sat in an arm chair, on their parent's lap or in a car seat in an electrically shielded and sound-attenuated testing booth. The sentence material was delivered via loudspeaker, controlled by *ERTS* software (BeriSoft Cooperation). While the children were listening to the sentences, a visual distraction (silent child video or puppet) was presented on demand to keep them entertained. Adults passively listened to the sentences, while keeping their eyes fixated on the screen.²⁶ They were asked to refrain from blinking during sentence presentation.

²⁶In contrast to other adult ERP studies on IPB processing (Pannekamp et al., 2005; Steinhauer, Alter, & Friederici, 1999), adults received no task, thus keeping the experimental conditions the same as in the infant and children ERP studies.

Fifty sentences for each condition, with IPB and without IPB, were presented in a pseudo-random order in blocks of 25 trials. Subjects received one of eight lists, in which the order of presentation of the sentences was randomized. Essentially, a sentence (2-3 s) was presented, followed by an inter-stimulus interval of 1.5 s. In total, the presentation of the short Naturally spoken sentences lasted about 8 min, while the presentation of the Sentences with neutralized pause lasted about 7 min due to the pause neutralization. Experiments with Naturally spoken sentences of the longer version resulted in longer trial time and longer overall experiment time. These sentences comprised 3-4.5 s, followed by an inter-stimulus interval of 1.5 s. Due to additionally inserted probes (for a probe recognition task in the adult study; see Pannekamp et al., 2005), the experiment lasted about 16 min.

7.4 EEG recordings

The EEG was continuously recorded from 23 Ag/AgCl ring electrodes attached to an elastic cap (for children, *Easy Cap GmbH*, Germany; for adults, *Electro Cap International, Inc.*). The electrodes were positioned across the scalp according to the 10-10 system (Chatrian, Lettich, & Nelson, 1988): F7, F3, FZ, F4, F8, FC3, FC4, T7, C3, CZ, C4, T8, CP5, CP6, P7, P3, PZ, P4, P8, O1, O2, M1, and M2. Additionally, an electrooculogram (EOG) was recorded from two electrodes placed at the outer canthi of both eyes (horizontal EOG) and from single electrodes on the infra- and supraorbital ridges of the right eye (vertical EOG). The recordings were referenced to CZ, while an additional electrode served as common ground (placed at FP1 for children and on the sternum for adults). For children, electrode impedances were in most cases kept below 10 k Ω (at least below 20 k Ω); for adults in all cases below 5 k Ω . The EEG signal was amplified with a gain of 20, using a PORT-32/MREFA (*Twente Medical Systems*), with an input impedance of 1012 Ω . The EEG data were digitized online at a rate of 250 Hz (AD converter with 22 bit, digital filter from DC to 125 Hz) and stored on a hard drive for further analyses.

7.5 Data processing and analysis

Offline, the EEG data were processed using the *EEP 3.3* software package (Max Planck Institute for Human Cognitive and Brain Sciences, Germany). At first, the EEG data were algebraically re-referenced to the average of both mastoids (M1, M2). To remove very slow drifts and muscle artifacts

from the EEG, a digital band-pass filter ranging from 0.2 Hz to 20 Hz (-3dB cutoff frequencies of 0.25 Hz and 19.91 Hz) was applied. For analyses targeting IP processing across the whole sentence, time segments of 3500 ms (in older children and adults 2500 ms), relative to sentence onset, were extracted from the continuous EEG signal and adjusted to a pre-stimulus baseline of 200 ms. For analyses targeting the processing of particular sentence parts, shorter EEG epochs were extracted (see according result sections).

In infants, EEG responses exceeding a SD of 70 μ V in a sliding window of 500 ms were considered invalid and were excluded. Additionally, manual screening of all trials ensured the exclusion of artifacts not detected by the automatic rejection criterion (e.g., slow drifts). In older children and adults, EEG epochs were individually checked for blinks and eye movements and corrected by a computer algorithm (implemented in EEP 3.3, Max Planck Institute for Human Cognitive and Brain Sciences, Germany). All other artifacts were detected manually. The remaining trials were separately averaged for sentences with and without IPB for each subject.

Statistical analyses were performed separately for mean amplitudes on midline and lateral electrode sites. For midline sites (FZ, CZ, PZ), a two-way analysis of variance (ANOVA) was computed with the factors Condition (with IPB, without IPB) and Region (anterior, central, posterior). For lateral sites, six regions of interest (ROIs) were created by combining hemisphere (left, right) and region (anterior, central, posterior) information. Each of the six ROIs covered three electrode sites: left anterior (F7, F3, FC3), right anterior (F8, F4, FC4), left central (T7, C3, CP5), right central (T8, C4, CP6), left posterior (P7, P3, O1), and right posterior (P8, P4, O2). Subsequently, a three-way ANOVA was computed with the factors, Condition (with IPB, without IPB), Region (anterior, central, posterior), and Hemisphere (left, right). Significant interactions involving the factor Condition were further analyzed using one-way ANOVAs for regions, hemisphere, and sites/ROIs respectively. All ANOVAs were calculated for the mean amplitude in defined time windows (TWs) or mean peak amplitude measures (see respective result sections); the Greenhouse-Geisser correction (Greenhouse & Geisser, 1959) was applied when there was more than one degree of freedom (df) in the numerator to account for potential violations of sphericity.

Chapter 8

Study I – Pauses and intonational phrasing: ERP studies in 5-month-old German infants and adults

8.1 Introduction

In accordance with the prosodic bootstrapping hypothesis (e.g., Gleitman & Wanner, 1982), behavioral developmental research has provided ample evidence of infants' early sensitivity to prosodic information in the speech input. Numerous studies have focused on determining the developmental stages during which infants encode the acoustic cues naturally provided by their native language and utilize them for speech segmentation.

Acoustic analyses of continuous speech show that syntactic boundaries often coincide with prosodic boundaries, with preboundary lengthening, pitch change, and pausing conjointly signaling the edges of syntactic units (e.g., Beckman & Edwards, 1990; Cooper & Paccia-Cooper, 1980; Ladd, 1988; Pierrehumbert, 1980; Scott, 1982; Wightman et al., 1992). Since nearly every prosodic boundary is also a syntactic boundary, the processing of prosodic boundary cues during the language acquisition process can deliver a first indicator for where syntactic boundaries occur in the speech stream, thus promoting, for example, the detection of syntactic phrases and clauses.

Behavioral evidence of infants' perception of prosodic boundary information at the sentence level can be roughly grouped into two lines of research. First, studies using the pause insertion technique have demonstrated that infants prefer sequences containing pauses at clause/phrase boundary positions, over those passages with pauses inserted at various non-boundary positions (Hirsh-Pasek et al., 1987; Jusczyk, Hohne, & Mandel, 1995; Jusczyk et al., 1992). Second, studies have described

infants' preference for familiar sequences presented in larger test passages when these sequences occurred as syntactic units (within prosodic boundaries) as opposed to when they occurred in syntactic non-units (across prosodic boundaries) (Nazzi, Kemler Nelson, et al., 2000; Seidl, 2007; Soderstrom, Nelson, & Jusczyk, 2005; Soderstrom et al., 2003). From the latter studies, the authors concluded that infants not only perceive prosodic cues, but actually utilize them for the detection of linguistic units in continuous speech. For both lines of research, the data suggest that infants perceive larger linguistic units, like clauses, earlier in continuous speech than smaller units, such as syntactic phrases. For example, 6-month-old English-learning infants detect clauses in continuous speech, but not yet reliably syntactic phrases (Nazzi, Kemler Nelson, et al., 2000; Seidl, 2007; Soderstrom, Nelson, & Jusczyk, 2005; Soderstrom et al., 2003), while 9-month-olds show this ability at both clause and phrase level (Soderstrom et al., 2003). The recognition of larger linguistic units can in turn support lexical segmentation. Gout and colleagues demonstrated that word detection in 10-month-olds was facilitated when words occurred at phrase boundary positions (Gout, Christophe, & Morgan, 2004; see also Seidl & Johnson, 2007). Thus, from a developmental perspective, the initial analysis and segmentation of larger linguistically relevant units seems to be particularly important during language acquisition and likely facilitates bootstrapping into smaller syntactic and lexical units in the speech signal later in the development of infants.

Given the potential significance of prosodic processing abilities for later stages of lexical-semantic and syntactic acquisition, it seems essential to investigate the principles underlying the infants' early perception of prosodic cues that signal prosodic units. In this context, the processing of IPs is particularly relevant, as they are the largest units of phrasal prosody and are marked by more pronounced boundary features than smaller prosodic units (Cooper & Paccia-Cooper, 1980). Although a number of behavioral studies have contributed to the description of the developmental course of infants' sensitivity to IPs (e.g., Seidl, 2007), the underlying neurophysiological basis remains widely unknown. However, the neurophysiology can be explored using the ERP method that provides an online measure of the ongoing stimulus processing at different levels, from perceptual to cognitive processing (see, e.g., Friederici & Thierry, 2008). Early components in the ERP, occurring between 100-200 ms, are known to reflect sensory-perceptual levels of processing, whereas later ERP components reflect cognitive processes. In the late processing domain, the CPS has been found, i.e., a positive shift in the

ERP that occurs in correspondence to IPBs in adults (e.g., Pannekamp et al., 2005; Steinhauer, Alter, & Friederici, 1999). ERP measures allow for the identification of the processing levels involved, in principle, and additionally, may do so specifically for the processing of IPBs in infants.

In addition to investigating the neurophysiological correlates of infants' prosodic processing, it is of special interest to target German-learning infants' processing abilities, since most of the behavioral studies on phrase and clause segmentation have been carried out in English (see studies above). However, English and German intonation systems differ with respect to the particular acoustic realization of IPs. In English, IPs are predominantly marked by their functional pitch contour, while in German, length and loudness seem to be equally important (Delattre, 1966; Markus, 2006).

It is still under discussion which acoustic cues are required to trigger the perception of prosodic boundaries in a given language at different developmental stages. Behavioral studies in English suggest that adults rely more heavily on both pitch changes and preboundary lengthening than on pausing (Aasland & Baum, 2003; Scott, 1982; Streeter, 1978; Wightman et al., 1992). For infants learning English, Seidl (2007) found that pitch plays an important role in phrase boundary perception. However, pitch alone was not sufficient for triggering phrase boundary perception; it had to co-occur with either preboundary lengthening or with pausing. Similarly, Gerken, Jusczyk, and Mandel (1994) found that English-learning infants required a combination of both pitch change and preboundary lengthening to identify phrase boundaries. Thus, there is some evidence, at least for English stimulus material that infants and adults weight specific boundary cues differently in the perception of phrasal units. In adults, only the manipulation of boundary length affected speech segmentation, whereas in infants either boundary lengthening or pausing had to co-occur with particular variations in pitch patterns.

Given the behavioral evidence showing English-learning infants' sensitivity to prosodic phrasing, *Study I* of the current thesis has three aims. First, infant ERP experiments will test the ability of 5-month-old German-learning infants to process IPs. Using ERPs, it is possible to determine whether 1) infant responses to IPBs are primarily attributable to lower-level processing of acoustic stimulus features reflected in obligatory components,²⁷ such as the N1-P2 complex in adults (Crowley & Colrain, 2004; Näätänen & Picton, 1987), or 2) whether they indicate higher-level cognitive processing reflected in the CPS (Steinhauer, Alter, & Friederici, 1999). Here, no hemispheric lateralization of the

²⁷These ERP components are called *obligatory* components, since they are invariably elicited when input reaches the sensory systems. Accordingly, these components are modulated by the physical properties of the eliciting stimuli.

ERP effects is expected, given that subjects are presented with natural sentence material, containing both segmental and suprasegmental information (see 3.1). Second, the role of the pause as one of the three acoustic cues signaling prosodic boundaries will be specified. In this context, the particular international characteristics of German may yield cross-linguistic differences in the weighting of particular boundary cues, such that German-learning infants rely more heavily on the boundary pause than their English peers. Third, the comparison of infant and adult ERP data collected in response to identical stimulus material will provide insight into developmental changes in IP processing. Specifically, the nature of the underlying processes will be considered and potential developmental differences in the weighting of specific boundary cues will be investigated. Here, the results of studies using English stimulus material lead to the assumption of developmental differences but the nature of these differences needs to be examined for German. The according hypotheses are given in Table 8.1.

Table 8.1: Hypotheses of Study I on IP processing in 5-month-old German infants and adults

1) IP processing in infants

Infants process IPs – reflected in the occurrence of 1a) an adult-like CPS (i.e., higher-level, cognitive processing) in addition to obligatory components or 1b) obligatory ERP components (i.e., lower-level, acoustic processing).

2) Role of the pause as acoustic boundary cue in infants' IP processing

Infants show different ERP responses to IPBs in the presence and absence of the boundary pause, thus the pause is a necessary acoustic cue in IPB processing (i.e., cross-linguistic differences).

3) IP processing in infants and adults: Developmental comparison regarding the nature of IP processing & the role of the boundary pause

Infants and adults show different ERP responses to IPBs with and without the boundary pause (i.e., developmental differences in IP processing).

8.2 Methods

8.2.1 Subjects

Adults The experiment with Naturally spoken sentences involved 27 adults (14 female, mean age 24.4 years, range 18-30 years); while the experiment with Sentences with neutralized pause included 28 adults (13 female, mean age 24.5 years, range 19-29 years).

5-month-olds For the experiment with Naturally spoken sentences, the final subject sample consisted of 34 infants (19 female; mean age 22.1 weeks, range 21-23 weeks); for the experiment with Sentences with neutralized pause, the final sample also comprised 34 infants (17 female; mean age 22.2 weeks, range 21-23 weeks), who had not taken part in the first experiment.

8.2.2 Stimuli

Adults and 5-month-olds were presented with the short version of Naturally spoken sentences (see 7.2.1); additional groups of adults and infants were presented with the Sentences with neutralized pause (see 7.2.2).

8.2.3 Data analysis

Adults In adults, at least 37 artifact-free trials (approx. 75%) were required per condition for an individual average to enter the final sample. In the experiment Naturally spoken sentences, the resulting mean number of averaged trials across subjects was 46 (SD=3) for sentences with IPB and 45 (SD=4) for sentences without IPB; in the experiment Sentences with neutralized pause, 44 (SD=4) for sentences with IPB and 43 (SD=5) for sentences without IPB. In both experiments, trial numbers did not significantly differ between conditions.

5-month-olds In infants, at least 12 artifact-free trials (approx. 25%) were required per condition for an individual average to enter the final sample. The resulting mean number of averaged trials across subjects was 23 (SD=9) in the experiment with Naturally spoken sentences and 25 (SD=9) in the experiment with Sentences with neutralized pause; these numbers did not differ between conditions.

8.3 Results

For the initial statistical analysis of the ERP data, ANOVAs were performed with the factors Condition, Region, and Hemisphere across TWs of 500 ms, relative to sentence onset. Only significant amplitude differences involving the factor Condition are reported here. For adults, ERP responses covering 2.5 s post-sentence onset were analyzed, while in infants longer segments of 3.5 s were chosen, thus accounting for slower information processing in infants.²⁸

8.3.1 Naturally spoken sentences

Adults Figure 8.1 displays the ERP responses to sentences with IPB and sentences without IPB relative to sentence onset. The ERP response to sentences with IPB, but not to sentences without IPB, revealed a positive shift starting at around 1000 ms after sentence onset that lasted for about 1000 ms. This effect was validated by the results of ANOVAs performed across TWs of 500 ms starting at sentence onset. As the results in Table 8.2 demonstrate, main effects of Condition were observed for the TWs 1000-1500 ms and 1500-2000 ms.²⁹ Although for both TWs, the interaction effects between the factors Condition x Region suggested topographical differences, the condition effect was broadly distributed over the scalp. Subsequent one-way ANOVAs calculated for each region and electrode site revealed main effects of Condition for anterior, central, and posterior regions. Additional effects involving Condition were observed before and after the time interval of 1000-2000 ms; however, subsequent one-way ANOVAs for regions and hemispheres did not deliver any condition differences. In summary, the statistical analyses revealed processing differences between sentences with IPB and sentences without IPB that were apparent in a positive shift in the ERP in response to sentences containing IPBs.

²⁸Slower information processing in children as compared to adults has been previously reported in studies on the acquisition of semantics and syntax (e.g., Friedrich & Friederici, 2004; Oberecker, Friedrich, & Friederici, 2005).

²⁹The condition effect in the later TW is certainly amplified by the contrarily proceeding ERP to sentences without IPB. For this TW, the ERP to this generally shorter sentence type most likely merges into a pronounced positivity (starting with a negative deflection) in response to the sentence end prosody.

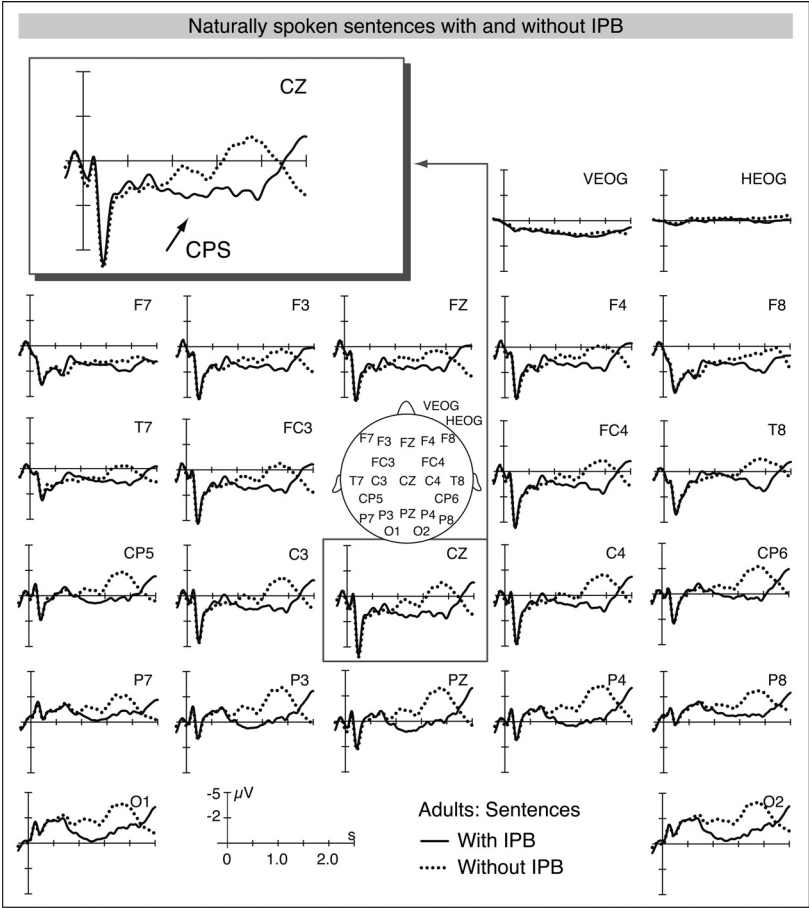


Figure 8.1: ADULTS Naturally spoken sentences: Grand average ERPs for sentences with IPB (solid line) and without IPB (dotted line). ERPs to sentences with IPB display a positive shift, starting at about 1000 ms relative to sentence onset.

Table 8.2: ADULTS Naturally spoken sentences: Significant effects of ANOVAs for the 0-2500 ms latency range relative to sentence onset (Cond = Condition; Reg = Region; Hem = Hemisphere; Ant = anterior; Cen = central; Post = posterior).

TW (ms)	Lateral ROIs			Midline sites		
	<i>Effect</i>	<i>df</i>	<i>F</i>	<i>Effect</i>	<i>df</i>	<i>F</i>
500-1000	Cond x Reg	2,52	6.28*			
1000-1500	Cond	1,26	14.9**	Cond	1,26	15.49**
	Cond x Reg	2,52	8.65**	Cond x Reg	2,52	3.95*
	Ant	1,26	4.54*	FZ	1,26	6.16*
	Cen	1,26	8.8**	CZ	1,26	12.23**
	Post	1,26	26.43**	PZ	1,26	17.1**
1500-2000	Cond	1,26	39.26**	Cond	1,26	25.24**
	Cond x Reg	2,52	6.15*	Cond x Reg	2,52	10.77**
	Ant	1,26	15.19**	FZ	1,26	10.25**
	Cen	1,26	53.66**	CZ	1,26	27.56**
	Post	1,26	46.67**	PZ	1,26	30.8**
2000-2500	Cond x Hem	1,26	10.99**			

* $p \leq .05$; ** $p \leq .01$

5-month-olds In infants, the ERP response to sentences with IPB, but not for sentences without IPB, showed a clear positive shift starting at around 2000 ms after sentence onset and that lasted for about 1000 ms (Figure 8.2). Accordingly, ANOVAs revealed a main effect of Condition for the TW 2000-2500 ms at midline electrodes [$F(1,33)=14.63$, $p \leq .01$] and lateral ROIs [$F(1,33)=11.05$, $p \leq .01$]. In addition, an interaction between the factors Condition x Region was observed at lateral sites [$F(2,66)=9.2$, $p \leq .01$]. The main effect Condition continued for the subsequent TW 2500-3000 ms at both midline [$F(1,33)=10.79$, $p \leq .01$] and lateral sites [$F(1,33)=8.77$, $p \leq .01$]. For the same TW, an interaction of Condition x Region was again found at lateral ROI positions [$F(2,66)=5.09$, $p \leq .05$]. When testing the interaction in both TWs, one-way ANOVAs computed for each region revealed main effects of Condition at anterior [TW 2000-2500 ms: $F(1,33)=13.82$, $p \leq .01$; TW 2500-3000 ms: $F(1,33)=10.94$, $p \leq .01$] and central regions [TW 2000-2500 ms: $F(1,33)=14.67$, $p \leq .01$; TW 2500-3000 ms: $F(1,33)=11.37$, $p \leq .01$]. Thus, the statistical analyses revealed the occurrence of a positive shift in the sentences with IPB, predominantly at anterior and central sites, while none was observed in the sentences without IPB.

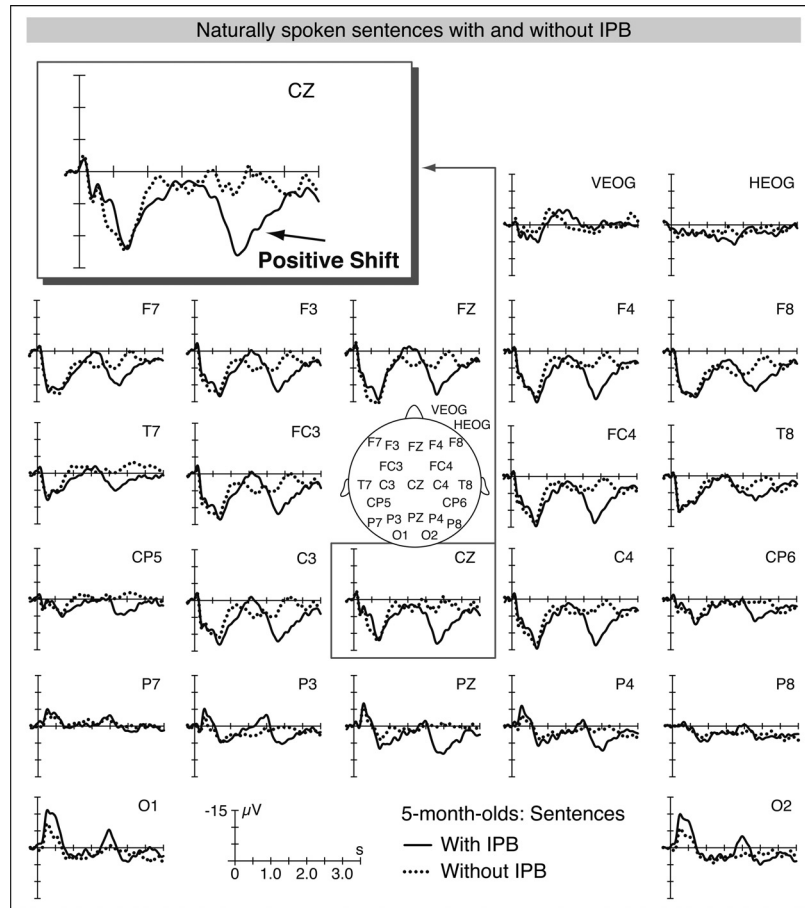


Figure 8.2: 5-MONTH-OLDS Naturally spoken sentences: Grand average ERPs for sentences with IPB (solid line) and without IPB (dotted line). ERPs to sentences with IPB display a positive shift, starting at about 2000 ms relative to sentence onset.

8.3.2 Sentences with neutralized pause

Adults The ERP responses to Sentences with neutralized pause (with IPB) and sentences without IPB are provided in Figure 8.3. Similar to the ERP pattern displayed in Figure 8.1, Sentences with neutralized pause (with IPB) evoked a positive shift, whereas no such shift was observed for the sentences without IPB. Again, ANOVAs delivered effects involving the factor Condition for the TWs 1000-1500 ms and 1500-2000 ms at lateral ROIs and midline sites (Table 8.3). Thus, statistical

analyses revealed processing differences between both sentence types, indicated by a positive shift in the sentences with IPB, even in the absence of the pause boundary.

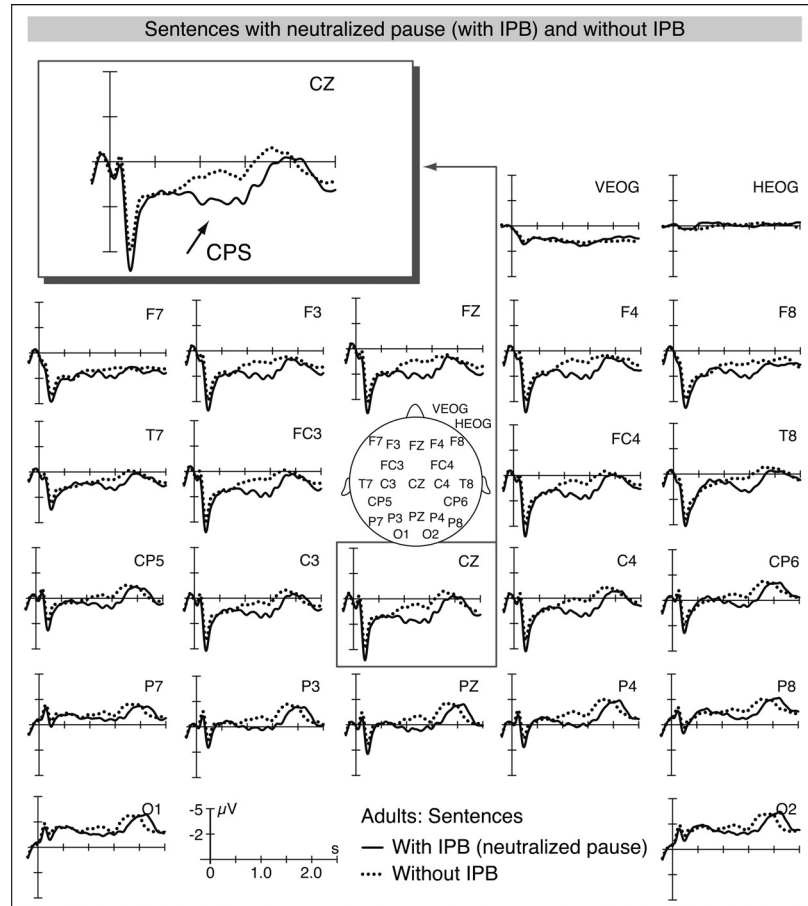


Figure 8.3: ADULTS Sentences with neutralized pause: Grand average ERPs for sentences with IPB (solid line) and without IPB (dotted line). ERPs to sentences with IPB display a positive shift, starting at about 1000 ms relative to sentence onset.

Table 8.3: ADULTS Sentences with neutralized pause: Significant effects of ANOVAs for the 0-2500 ms latency range relative to sentence onset (Cond = Condition; Reg = Region; Ant = anterior; Cen = central; Post = posterior).

TW (ms)	Lateral ROIs			Midline sites		
	<i>Effect</i>	<i>df</i>	<i>F</i>	<i>Effect</i>	<i>df</i>	<i>F</i>
1000-1500	Cond	1,27	10.59**	Cond	1,27	14.91**
	Cond x Reg	2,54	7.47**	Cond x Reg	2,54	5.44*
	Ant	1,27	16.69**	FZ	1,27	21.0**
	Cen	1,27	9.58**	CZ	1,27	16.67**
				PZ	1,27	5.54*
1500-2000	Cond	1,27	11.84**	Cond	1,27	8.01**
2000-2500	Cond x Reg	2,54	14.31**	Cond x Reg	2,54	14.16**
	Post	1,27	8.76**	PZ	1,27	6.29*

* $p \leq .05$; ** $p \leq .01$

5-month-olds For infants, the ERP responses to Sentences with neutralized pause (with IPB) and sentences without IPB are displayed in Figure 8.4. In contrast to the ERP pattern observed to Naturally spoken sentences with IPB (Figure 8.2), there is no positive shift in the Sentences with neutralized pause (with IPB) within the reported time range. Accordingly, the ANOVAs did not deliver any significant condition differences in the seven TWs previously analyzed. However, the ERP waveforms indicated condition differences, starting later and being of a shorter duration than the effects observed in the experiment with Naturally spoken sentences. As the waveforms suggest, the ANOVA revealed a main effect of Condition at lateral sites in the newly defined TW 2200-2700 ms [$F(1,33)=10.49$, $p \leq .01$].

The condition difference can be accounted for by either of two explanations. This difference may reflect a true condition effect, which was characterized by a longer latency and shorter duration in comparison to that of the experiment with Naturally spoken sentences. Alternatively, this effect may have resulted from the different sentence lengths; Sentences with neutralized pause (with IPB) were about 200 ms longer than sentences without IPB. Thus, condition differences might stem from the respective termination of stimulus processing in each sentence condition that accordingly stops earlier in the Sentences with neutralized pause (with IPB) than in the sentences without IPB. To determine which of these hypotheses better explains this phenomenon, the duration differences between the two

sentence types were minimized by shifting the ERP analysis window to the onset of the second sentence part (i.e., pause offset). If the condition difference remains, then there must be a true condition effect, and if not, the sentence duration must be the critical feature. Since the ANOVA performed for three TWs across 500 ms revealed no condition effect, it was concluded that the condition difference observed in this experiment is primarily attributable to the different sentence lengths and does not derive from the presence of the IPB in the Sentences with neutralized pause.

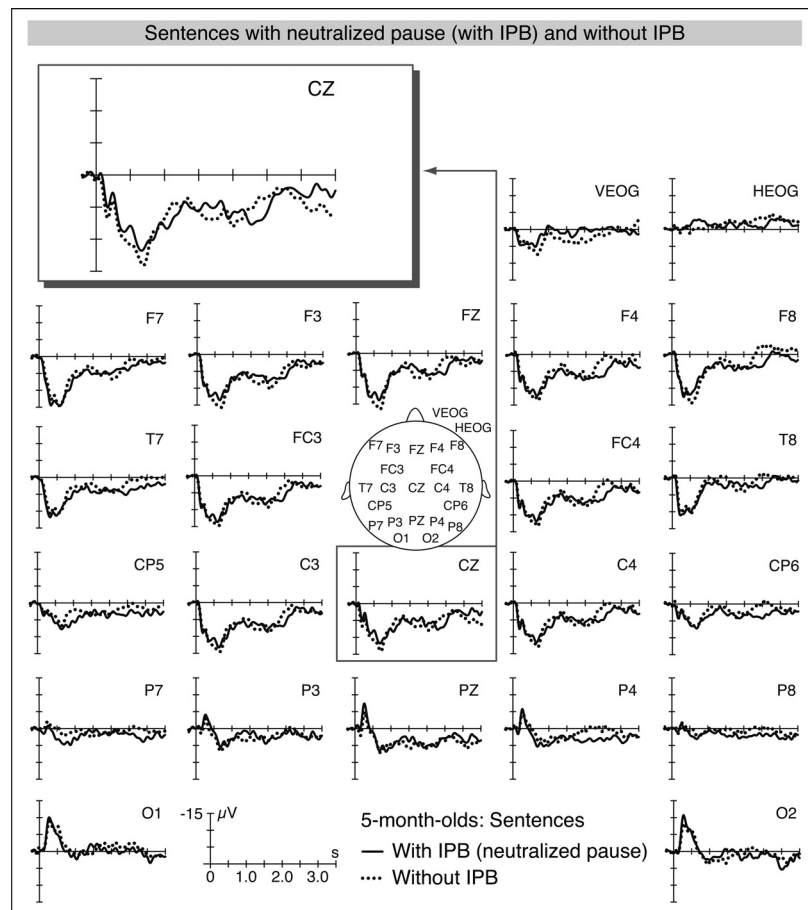


Figure 8.4: 5-MONTH-OLDS Sentences with neutralized pause: Grand average ERPs for sentences with IPB (solid line) and without IPB (dotted line). ERPs to sentences with IPB do not display a positive shift.

8.3.3 Positive shift in the infant ERP: CPS or obligatory onset response

Given the resemblance of the positive shift observed in the Naturally spoken sentences with IPB and the pronounced obligatory positive wave at their corresponding sentence onsets (especially at anterior and central sites), the positive deflection following the IPB was further investigated. Each sentence onset or phrase onset following a pause evokes an obligatory response that signals speech input after a period of silence. In infants, this obligatory response is reflected in positive waves at frontal and central electrode sites (P150 and P350; see Kushnerenko et al., 2002). It follows that the positive deflection following the IPB may either reflect 1) a true phrasing effect comparable to the CPS observed in adults, 2) an obligatory response to the onset of the second part of the sentence, or 3) a combination of both these effects (see also Steinhauer, 2003; for a methodological distinction between the CPS and the adult obligatory component P2). To further examine the positive shift observed in sentences with IPB, the ERPs evoked by the sentence onset and the onset of the second noun phrase (henceforth called NP2 onset) were directly compared by looking for response disparities between sentence part 1 *Tommi verspricht* (Tommi promises) and sentence part 2 *Papa zu helfen* (to help papa). If, in addition to the obligatory onset response, the observed positive deflection also includes a CPS, this should be apparent in at least one of the following ways: 1) a difference in amplitude (a larger amplitude would be expected for NP2 than for sentence onsets due to additive effects), 2) a difference in scalp distribution (produced by amplitude differences at posterior sites for the CPS), or 3) a difference in the appearance of the wave forms (e.g., overlap at posterior sites for the CPS). For this analysis, EEG epochs of 1500 ms were averaged relative to their corresponding onsets and adjusted to a pre-stimulus baseline of 50 ms.³⁰ ANOVAs were performed across three TWs of 500 ms with the factors Onset Type, Region, and Hemisphere for lateral ROIs, and Onset Type and Region for midline sites.

As can be seen from Figure 8.5 (left panel), ERP responses to both onset types were almost identical, displaying the obligatory infant ERP components: P150, N250, and P350 (see Kushnerenko et al., 2002). However, at lateral fronto-central sites, these obligatory components were less pronounced for NP2 than for sentence onset. Accordingly, for the TW 0-500 ms, ANOVAs revealed an interaction of

³⁰This relatively short pre-stimulus baseline was chosen since this was about the minimal pause length (for both sentences with and without pause at the IPB) preceding the NP2 onset. Thus, only for this short time period were there no condition differences between the pre-stimulus intervals of the two onset types.

Onset Type \times Region [$F(2,66)=7.19$, $p \leq .01$] at lateral sites, while there was no effect involving Onset Type in the later TWs 500-1000 ms and 1000-1500 ms. Follow-up one-way ANOVAs yielded main effects of Onset Type for anterior [$F(2,66)=7.08$, $p \leq .05$] and central regions [$F(2,66)=4.75$, $p \leq .05$]. These amplitude differences are most likely attributable to differences in stimulus intensity and pause length, as has been shown for the modulation of obligatory components in older children and adults (see Coch, Skendzel, & Neville, 2005; Crowley & Colrain, 2004). Thus, longer pauses (1500 ms preceding sentence onset vs. 560 ms preceding NP2 onsets) and higher intensity (58 dB for sentence onsets vs. 51 dB for NP2 onsets) result in larger ERP amplitudes. A more fine-grained analysis of the Onset Type effect across TWs of 100 ms revealed that the effect spans the time period of 100-400 ms relative to sentence/NP2 onset (Table 10.1, Appendix A).

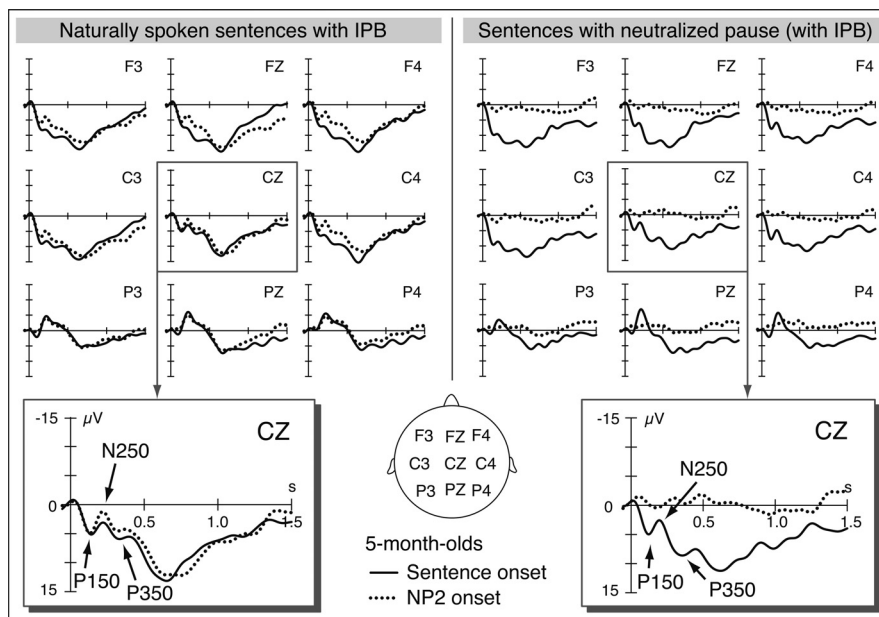


Figure 8.5: 5-MONTH-OLDS Sentences with IPB: Grand average ERPs to Naturally spoken sentences (left panel) and Sentences with neutralized pause (right panel) relative to sentence onset (solid line) and NP2 onset (dotted line). For Naturally spoken sentences, ERPs show obligatory components (P150, N250, P350) to both onset types; for Sentences with neutralized pause, only to the sentence onset.

In contrast to the Naturally spoken sentences with IPB, the Sentences with neutralized pause with IPB were found to evoke obligatory ERP responses to sentence onsets but not to NP2 onsets (Figure 8.5, right panel). This was reflected in a zero-level ERP for NP2 onset processing, while the ERP

responses relative to sentence onset showed a similar pattern as in the experiment with Naturally spoken sentences. Accordingly, for all three TWs, ANOVAs revealed main effects of Onset Type at midline sites [TW 0-500 ms: $F(1,33)=16.12$, $p \leq .01$; TW 500-1000 ms: $F(1,33)=21.92$, $p \leq .01$; TW 1000-1500 ms: $F(1,33)=6.0$, $p \leq .05$] and lateral ROIs [TW 0-500 ms: $F(1,33)=36.07$, $p \leq .01$; TW 500-1000 ms: $F(1,33)=17.17$, $p \leq .01$; TW 1000-1500 ms: $F(1,33)=7.22$, $p \leq .05$]. Additional interaction effects involving Onset Type (Table 10.2, Appendix A) mainly demonstrate Onset Type differences at anterior and central sites.

For the Naturally spoken sentences with IPB, the direct comparison of sentence onset and NP2 onset suggests that the observed positive shift can be accounted for by an obligatory response to the NP2 onset, since none of the expected differences in favor of a CPS were observed. Amplitudes were more pronounced for sentence onset than for NP2 onset, excluding the possibility of additive effects. Furthermore, no amplitude differences occurred at posterior sites where the occurrence of a CPS in response to the IPB, but not obligatory components, would have been expected. However, these results do not yet rule out the possibility of a CPS preceding the obligatory onset response. Therefore, Sentences with neutralized pause (with IPB) were contrasted with sentences without IPB relative to NP2 onsets by covering preceding and subsequent TWs. As can be seen for C3, there is no positive shift starting prior to the IPB (left panel of Figure 8.6 for Naturally spoken sentences; right panel of Figure 8.6 for Sentences with neutralized pause). In summary, the positive shift observed in the Naturally spoken sentences with IPB is accounted for by the obligatory ERP response to the NP2 onset following the IPB. Importantly, this obligatory response in infants disappears when no boundary pause is present.

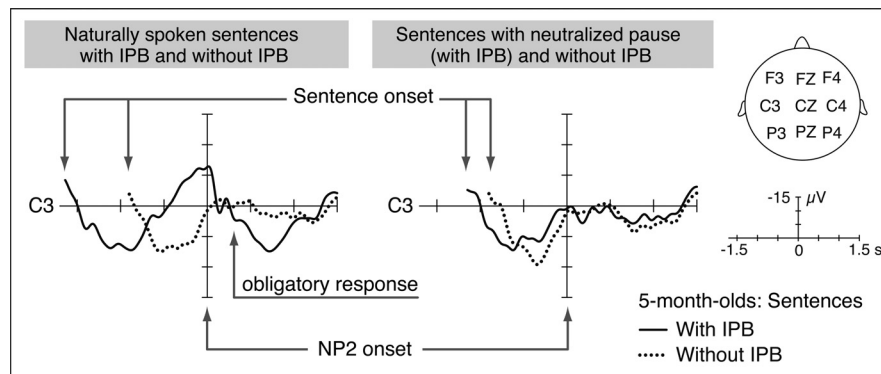


Figure 8.6: 5-MONTH-OLDS Grand average ERPs (displayed at C3) to Naturally spoken sentences (left panel) and Sentences with neutralized pause (right panel). Sentences with IPB (solid line) and sentences without IPB (dotted line) are displayed relative to NP2 onsets; sentence onsets are indicated. In sentences with IPB, no positive shift (CPS) is directly preceding the IPB.

8.3.4 The role of the pause in obligatory onset responses: Infant and adult ERPs

The analyses of infant ERPs to sentences with IPB revealed an obligatory response to NP2 onsets. However, this ERP component only occurred for Naturally spoken sentences with pauses at IPBs, but not for Sentences with neutralized pause without pauses at IPBs. In other words, infants seem to process sentence interruptions caused by pauses, but only when the prosodic break is signaled by a pause. Importantly, the detection of this type of speech interruption reflects low-level acoustic processing, rather than perception of combined prosodic boundary cues to IPs at a cognitive level, the latter being indicated by a CPS.

From the described results in 5-month-olds, one can derive two possible explanations. Either the obligatory response is triggered 1) by the actual pause (and accordingly, does not occur when the pause is absent), or 2) by a break signaled by the combined information of several boundary features. When the pause is absent, however, the remaining boundary cues are not sufficient to signal a speech interruption. These assumptions were tested across age groups to tease apart general versus infant-specific processing mechanisms. In adults, both sentence and NP2 onsets of Naturally spoken sentences with IPB evoked typical obligatory adult ERP responses, the N1-P2 complex, although they were less pronounced for NP2 onsets (Figure 8.7, left panel). Interestingly, a similar ERP pattern occurred for sentence onsets and NP2 onsets of Sentences with neutralized pause (with IPB) (Figure 8.7,

right panel). Thus, in contrast to the infant data, the NP2 onsets evoked obligatory ERP components in adults even in the absence of pause at the IPB.

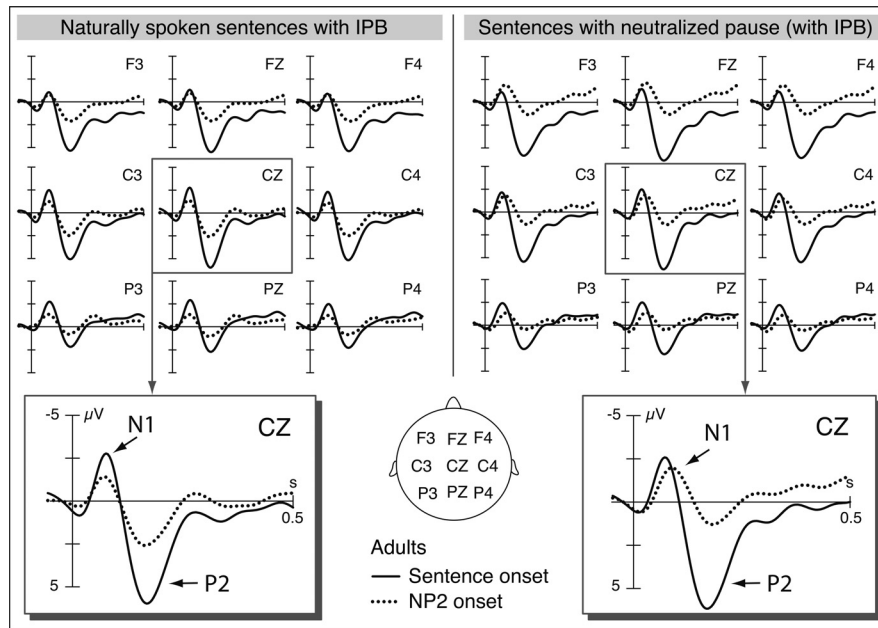


Figure 8.7: ADULTS Sentences with IPB: Grand average ERPs to Naturally spoken sentences (left panel) and Sentences with neutralized pause (right panel) relative to sentence onset (solid line) and NP2 onset (dotted line). ERPs show obligatory responses (N1-P2 complex) to both onset types for Naturally spoken sentences and Sentences with neutralized pause.

To quantify amplitude and latency differences of the N1 and P2 components of both onset types across sentences with IPB from both experiments, peak maxima and minima and their respective latencies were extracted in the following TWs: 50-100 ms for the N1, and 120-220 ms for the P200. Amplitude and latency values are given in Table 10.3 (Appendix A) for Naturally spoken sentences with IPB and in Table 10.4 (Appendix A) for Sentences with neutralized pause (with IPB).

As the amplitude measures in Tables 10.3 & 10.4 (Appendix A) indicate, N1 and P2 were generally more pronounced for sentence onsets than for NP2 onsets. These amplitude differences correspond to the effects observed in infants, although with an even broader appearance in adults, and are due to variations in stimulus intensity and pause length (see Coch, Skendzel, & Neville, 2005; Crowley & Colrain, 2004).

Accordingly, ANOVAs performed for both experiments revealed main effects and interaction effects involving Onset Type (Tables 8.4 and 8.5). For Naturally spoken sentences with IPB, latency measures provided shorter N1 and P2 latencies for NP2 than for sentence onset responses, while for Sentences with neutralized pause (with IPB) the reverse pattern applied. As noted, NP2 onsets evoked obligatory components following the IPB in both Naturally spoken sentences (Figure 8.7, left panel) and in Sentences with neutralized pause (Figure 8.7, right panel). This was statistically confirmed by multiple one-sample t-tests against the test value 0, which revealed significant deviations for all amplitude measures at midline and lateral sites (Tables 10.3 & 10.4, column 5, Appendix A).

Table 8.4: ADULTS Naturally spoken sentences with IPB: Significant effects of ANOVAs for N1 and P2 peak amplitudes and latencies (Amp = amplitude; Lat = latency; Onset = Onset Type; Reg = Region; Ant = anterior; Cen = central; Post = posterior).

TW (ms)	Lateral ROIs			Midline sites		
	<i>Effect</i>	<i>df</i>	<i>F</i>	<i>Effect</i>	<i>df</i>	<i>F</i>
<i>N1-Amp</i>	Onset	1,26	7.57*	Onset	1,26	7.68**
	Onset x Reg	2,52	14.56**	Onset x Reg	2,52	9.31**
	Cen	1,26	5.2*	CZ	1,26	7.37*
	Post	1,26	28.17**	PZ	1,26	18.21**
<i>N1-Lat</i>	Onset	1,26	5.03*			
<i>P2-Amp</i>	Onset	1,26	64.59**	Onset	1,26	60.33**
	Onset x Reg	2,52	35.55**	Onset x Reg	2,52	12.91**
	Ant	1,26	133.11**	FZ	1,26	106.23**
	Cen	1,26	58.16**	CZ	1,26	56.48**
	Post	1,26	4.86*	PZ	1,26	13.07**
<i>P2-Lat</i>	Onset x Reg	2,52	4.44*			
	Post	1,26	6.52*			

* $p \leq .05$; ** $p \leq .01$

Table 8.5: ADULTS Sentences with neutralized pause (with IPB): Significant effects of ANOVAs for N1 and P2 peak amplitudes and latencies (Amp = amplitude; Lat = latency; Onset = Onset Type; Reg = Region; Ant = anterior; Cen = central; Post = posterior).

TW (ms)	Lateral ROIs			Midline sites		
	<i>Effect</i>	<i>df</i>	<i>F</i>	<i>Effect</i>	<i>df</i>	<i>F</i>
<i>N1-Amp</i>	Onset x Reg	2,54	26.77**	Onset x Reg	2,54	22.85**
	Post	1,27	13.37**	PZ	1,27	8.78**
<i>N1-Lat</i>	Onset	1,27	9.17*	Onset	1,27	7.26*
<i>P2-Amp</i>	Onset	1,27	63.64**	Onset	1,27	62.33**
	Onset x Reg	2,54	74.13**	Onset x Reg	2,54	31.02**
	Ant	1,27	130.06**	FZ	1,27	103.66**
	Cen	1,27	71.93**	CZ	1,27	57.72**
	Post	1,27	6.62*	PZ	1,27	20.98**
<i>P2-Lat</i>	Onset x Reg	2,52	6.52**	Onset x Reg	2,54	3.31*
	Ant	1,27	5.11*			

* $p \leq .05$; ** $p \leq .01$

Figure 8.8 (left panel) convincingly illustrates the similarity of the NP2 onset responses to the Naturally spoken sentences with IPB and the Sentences with neutralized pause (with IPB) for adult listeners. In contrast, the infant ERP data demonstrate the described discrepancy between ERP responses to NP2 onsets in the presence and the absence of the boundary pause (Figure 8.8, right panel). For statistical comparisons of the adult NP2 onset responses across experiments, ANOVAs were performed with the additional between-subject factor Experiment for N1 and P2 amplitude and latency measures at lateral and midline sites. ANOVAs revealed Experiment x Region interaction effects for N1 amplitudes at lateral [$F(2,106)=6.45$, $p \leq .01$] and midline sites [$F(2,106)=7.79$, $p \leq .01$]. Subsequent independent two-sample t-tests showed that these differences were restricted to anterior lateral ROIs [$t(53)=2.42$, $p \leq .05$] and FZ [$t(53)=2.39$, $p \leq .05$]. The similarity of the NP2 onset responses across experiments was further supported by ANOVAs calculated for N1-P2 peak-to-peak measures. Here, no peak-to-peak latency differences were obtained across experiments. Peak-to-peak amplitude differences were reflected in an Experiment x Region interaction at midline electrodes [$F(2,106)=4.17$, $p \leq .05$], for which however, subsequent independent two-sample t-tests delivered no significant effects at single electrode sites.

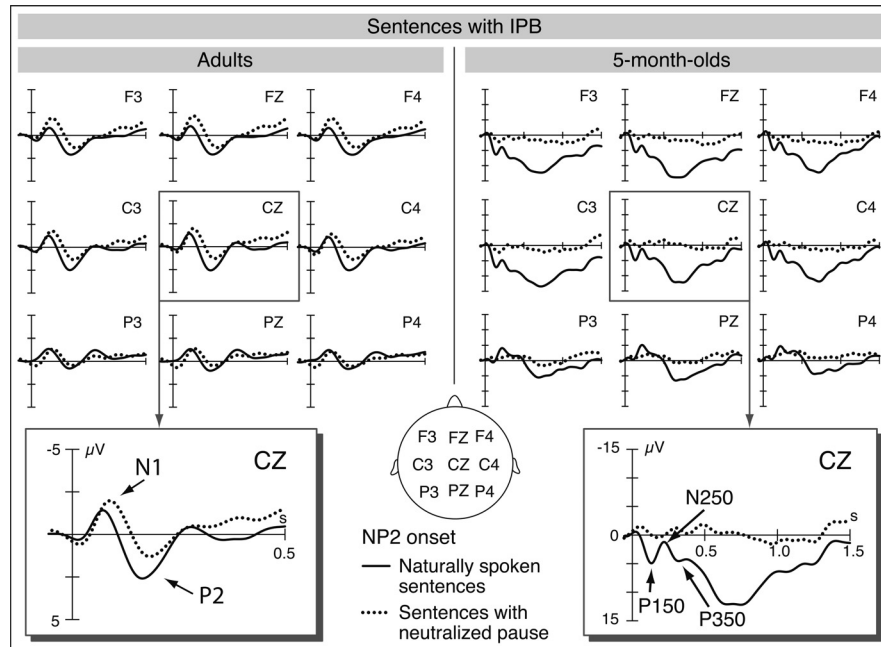


Figure 8.8: NP2 onset: Grand average ERPs of adults (left panel) and 5-month-olds (right panel) to NP2 onsets of Naturally spoken sentences (solid line) and Sentences with neutralized pause (dotted line). In adults, ERPs display obligatory components to both sentence types. In infants, ERPs show obligatory components only to Naturally spoken sentences.

In summary, from the study of adult ERP responses using the same sentence material as for infants, one can conclude that adults' perception of speech interruptions are not solely based on pausing but are the result of a combination of prosodic boundary features. Thus, even when the pause at the IPB is deleted, adults still show obligatory onset responses, with preboundary lengthening and pitch change being sufficient cues for signaling prosodic breaks.

8.4 Discussion and interim conclusions

Study I investigated the neurophysiology underlying how 5-month-old German-learning infants process prosodic boundaries by measuring the associated ERPs. In addition, developmental differences between infants and adults were examined by presenting both cohorts with sentences that were either naturally spoken or had no pause cue at the IPB, thus specifying the role of the pause as prosodic boundary cue.

For adults, a CPS and obligatory N1-P2 responses were observed to both Naturally spoken sentences with IPB and Sentences with neutralized pause (with IPB). Naturally spoken sentences with IPB contained all of the available prosodic boundary information, i.e., pitch change, preboundary lengthening and pausing, while Sentences with neutralized pause (with IPB) retained the effects caused by pitch change and preboundary lengthening. Thus, IPBs evoked boundary perception (and the lower-level detection of an acoustic interruption) even when the pause at the IPB was deleted. In other words, preboundary lengthening and pitch change are sufficient to signal prosodic breaks, independent of the presence of a boundary pause.³¹ These results are in agreement with previously reported CPS in IP processing in adults (Steinhauer, Alter, & Friederici, 1999; Steinhauer, 2003).

In infants, the ERP patterns to the Naturally spoken sentences with IPB also exhibited a positive shift in response to IPBs. This positive shift, however, did not reflect an adult-like CPS but instead was an infant obligatory ERP response to the onset of speech after the IPB. It was surmised that infants detect speech interruptions by low-level acoustic processes, rather than by higher-order perception of combined prosodic boundary cues to IPs. In contrast to the Naturally spoken sentences, the Sentences with neutralized pause (with IPB) did not elicit a positive shift in the ERP. Thus, the obligatory response to IPBs disappeared when no boundary pause was present, indicating that infants process sentence interruptions caused by acoustic cues only when the prosodic break is signaled by a pause.

There are two possible explanations for these observations in young infants. First, German-learning 5-month-olds do not yet process IPBs. Instead, infants' detection of speech interruptions is driven by the pause and, consequently, does not occur when the pause is absent. Alternatively, German-learning infants at this age may identify prosodic breaks composed of combined boundary

³¹The fact that in adults pauses are not necessary for IPB perception in the presence of other boundary cues does not exclude that pausing becomes relevant in the absence of other cues (see *cue trading*; Beach, 1991)

cues, but only if speech interruptions are signaled by a pause. In contrast to adults, these processes happen at a lower-level perceptual stage and, therefore, do not elicit a CPS. Independent of which explanation is correct, the results offer two conclusions. First, infants' processing of breaks in the speech signal happens at a lower-order perceptual level, and second, the pause is a particularly salient cue in the processing of those breaks by German infants.

Regarding the first interpretation, the current results are in disagreement with behavioral data that have previously described how English-learning infants process prosodic boundary information. These studies have revealed that at the age of 6 months, infants are able to perceive syntactic clauses in continuous speech and at 9 months, even syntactic phrases (Nazzi, Kemler Nelson, et al., 2000; Seidl, 2007; Soderstrom, Nelson, & Jusczyk, 2005; Soderstrom et al., 2003). These conclusions were drawn based on infants' preference of familiar sequences when such sequences were presented in larger test passages as well-formed, syntactic units (within prosodic boundaries), as opposed to when they occurred as ill-formed, syntactic non-units (across prosodic boundaries). Assuming our ERP study and the named behavioral studies tested similar prosodic processing abilities, cross-linguistic differences seem to be a critical factor, since German 5-month-olds, in contrast to English 6-month-olds, seem unable to process prosodic boundaries at clause level. The interpretation of cross-linguistic differences can be approached by the evaluation of differences in the German and the English intonation systems (see Gibbon, 1998). The functional demands on prosody are likely to be lower in German than in English, since German has a larger number of inflections and a relatively flexible word order. Word order serves as a focalization device, as it is applied in topicalizations and used to denote new information. Furthermore, German employs a large number of discourse particles that most likely serve functions represented by intonation patterns in other languages (see Schubiger, 1980). Consequently, relative to English, German features a lower number of intonation patterns and a reduced range of pitch variation, most likely resulting in less variation across boundary tones (Gibbon, 1998; Markus, 2006). Indeed, in a cross-linguistic analysis of prosodic cues in infant-directed speech, Fernald et al. (1989) found that American English parents used the most exaggerated speech (intonational modifications), as compared with, for example, German, French and Italian speaking parents. Thus, it might be the case that German and English infants differ in their ability to process prosodic breaks based on the respective strength of IP marking in their native language.

The second interpretation of the current ERP data is that German-learning infants process prosodic breaks, via lower-level perceptual processes, but only when the speech interruption is signaled by a pause. Further studies comparing pause perception at prosodic boundary positions and non-boundary positions will be required to determine the particular role of pausing in infants' IPB processing. However, the current results already point to the generally important role of pausing in the detection of speech interruptions. A study by Seidl (2007) revealed that English-learning infants were able to perceive IPs when presented with sentences lacking pauses as boundary information. The fact that the absence of the pause cue seems to matter to German-learning but not to English-learning infants again points to cross-linguistic differences, particularly in the weighting of acoustic cues.³² As mentioned above, the flexible German word order takes over functions, which are accomplished by particular pitch patterns in other languages. Thus, it seems plausible that pausing in German plays a role as an additional syntactic structuring device (see also Butcher, 1981). Furthermore, less intonation patterns and less pitch variations are likely to yield less modulated boundary tones, which without being marked by pauses, may not be sufficient for triggering boundary detection. This explanation finds support through a recent behavioral study investigating clause segmentation abilities in Dutch 6-month-olds (Johnson & Seidl, 2008). This study paralleled the study in 6-month-old English-learning infants (Seidl, 2007) and revealed that Dutch 6-month-olds, like the English infants, readily perceived clausal units but were more reliant on the boundary pause than their English peers. Given that Dutch, comparable to German, features a narrower pitch range than English (Willems, 1982), this result adds further evidence to the explanation of cross-linguistic differences. In this context, another recent study by the same research group provided new input for the discussion of developmental differences, concerning the ability of English-learning 4-month-olds to segment clauses (Seidl & Cristia, 2008). Interestingly, in contrast to the 6-month-olds, infants at 4 months required the presence of each of the three acoustic boundary cues for clause segmentation, i.e., also the presence of the pause. These results imply a developmental shift between 4 and 6 months in English-learning infants' clause segmentation, such that the younger infants require all available information to be present for boundary detection, while for the older infants the weighting of particular cues changes as a function of native-

³²The possibility that German-learning infants would be able to perform phrase segmentation at the behavioral level seems unlikely given that they did not show an obligatory ERP effect to the IPB at the neurophysiological level. During the developmental course, neurophysiological evidence typically precedes behavioral performance and not vice versa.

language experience (e.g., with pitch being the most important cue for English-learning infants). It follows that the current ERP results of German-learning infants, targeting the age between 4 and 6 months, can be interpreted in terms of both cross-linguistic and developmental differences for two reasons. First, German infants may be generally more reliant on the pause as boundary cue, given the intonational characteristics of the language input to which they are exposed. Second, the developmental stage of the tested German infants may fall within the developmental phase described for the English-learning 4-month-olds.

The comparison of the infant and the adult ERP data suggests two types of developmental differences: first, differences in the underlying neurophysiological processes and second, differences in the role of the pause as an acoustic boundary cue. Concerning the latter, the differential weighting of acoustic cues might change as language acquisition progresses (see discussion above). At later developmental stages, children have successfully identified basic syntactic structure and are less dependent on prosodic markers, so pausing may no longer be as important for them. However, reliance on pause as a boundary cue can still be observed in adults when the language input is not well phrased and is prosodically ambiguous (see Dankovicova, Pigott, Wells, and Peppe, 2004).

Regarding developmental differences in the underlying neurophysiological processes, the current ERP data suggest that German infants primarily incorporate prosodic boundary information by using low-level sensory processing. In accordance with prosodic bootstrapping, infants initially detect salient acoustic cues in the speech input, such as silences or large pitch changes. These cues signal the location of constituents and eventually enable infants to bootstrap into other cues associated with the edges of these constituents. Thus, as language acquisition progresses, children learn that certain acoustic cues correlate and conjointly mark structural units. It is hypothesized that these processes are characterized by different underlying neurophysiological mechanisms. More specifically, attention to salient acoustic cues is characterized by sensory processing mechanisms (obligatory ERP responses), while perception of a boundary as a correlation of several cues (i.e., one integrated percept) is characterized by cognitive processing mechanisms (CPS response). Thus, acquiring the concept of a prosodic boundary is a gradual process that develops out of the early response to acoustically salient cues, such as pauses. The comparison of the current infant data with the results by Pannekamp, Weber, and Friederici (2006), who described a CPS-like positive shift in response to IPBs in 8-month-olds

suggests a developmental shift in IP processing between the age of 5 and 8 months. However, given the particular analysis of the data in 8-month-olds, similar low-level perceptual mechanisms (i.e., obligatory onset responses) are assumed to be active at 8 months. Final conclusions may not be drawn until the data for 8-month-olds are replicated and subjected to the same analyses as applied here. Taken together, further developmental studies need to determine when the processes indicated by the CPS emerge and under which circumstances they are likely to be elicited, e.g., boundary strength and presence of certain boundary cues.

In summary, the existing data suggest that during early development, German-learning infants are able to detect particularly salient acoustic cues in the speech input, which are likely contributors to the recognition of prosodic boundaries. Later, these early processing tendencies develop so that children are eventually able to recognize prosodic boundaries on the basis of combined acoustic information and ultimately use this knowledge to extract structural units from continuous speech.

Interim conclusions

In conclusion, *Study I* provides neurophysiological evidence showing the ability of 5-month-old German-learning infants to process sentence internal pauses, as revealed by obligatory ERP responses following the IPBs. The fact that prosodic breaks elicit obligatory ERP components in infants, but not an adult-like CPS, suggests these processes still reflect low-level sensory processing (Hypothesis 1b). In addition, this study points to cross-linguistic and developmental differences in the weighting of particular boundary cues. The absence of obligatory ERP components for sentences lacking pauses at boundary locations, as compared to sentences with boundary pause (Hypothesis 2), indicates that infants are more reliant than adults on pausing as boundary information, suggesting a developmental shift in the weighting of boundary cues (Hypothesis 3).

Chapter 9

Study II – The emergence of the CPS during childhood: ERP studies on intonational phrase processing in 2-, 3-, and 6-year-old children

9.1 Introduction

Numerous studies on adult sentence processing have revealed a close interaction of prosodic and syntactic information. Prosodic boundary cues signal syntactic constituents and the intonation contour of a sentence can influence syntactic parsing preferences and initiate the anticipation of syntactic structure (e.g., Grosjean, 1983; Marslen-Wilson et al., 1992; Schafer et al., 2000; Warren, Grabe, & Nolan, 1995). In a recent study, for example, Millotte et al. (2008) have demonstrated that prosodic boundary cues constrain syntactic analysis, with the more pronounced prosodic cues being even more successful than less pronounced ones in triggering local syntactic ambiguity resolution. Importantly, the prosody-syntax interface does not work unidirectionally but prosodic structure is in language production to a large extent determined by syntactic structure (e.g., Ferreira, 1988; Gee & Grosjean, 1983; Selkirk, 2000; Truckenbrodt, 1999). Specifically, syntactic structure is highly predictive of prosodic phrasing with nearly every prosodic boundary also being a syntactic boundary. Thus, in both language perception and production, prosody and syntax are strongly tied together.

Studies within the prosodic bootstrapping account (e.g., Gleitman & Wanner, 1982) have shown infants' early ability to process prosodic information (for an overview, see Jusczyk, 1997). Importantly, infants do not only generally prefer pronounced prosodic patterns, as in infant-directed speech

(Cooper & Aslin, 1990; Fisher & Tokura, 1996b), but they actually use this kind of information to identify linguistically relevant units in the speech stream (Nazzi, Kemler Nelson, et al., 2000; Seidl, 2007; Soderstrom, Nelson, & Jusczyk, 2005; Soderstrom et al., 2003). More specifically, since almost every prosodic boundary is also a syntactic boundary, children can, based on prosodic boundary information, segment the incoming speech stream into smaller linguistically relevant units. Speech segmentation is fundamental to any further language learning, since linguistic units first have to be extracted before lexical-semantic information and syntactic functions associated with these units can be acquired. It has been suggested that the early ability to process prosodic information provides an entry into the discovery of syntactic structure at later developmental stages (e.g., Gleitman & Wanner, 1982).

The results of *Study I* have delivered electrophysiological evidence that infants at the age of 5 months are able to detect particularly salient acoustic cues in the speech input, which are likely contributors to the recognition of prosodic boundaries. For infants, the fact that prosodic breaks evoke obligatory ERP components, but not an adult-like CPS, suggests these processes still reflect low-level sensory processing. In contrast, adult data revealed a CPS in addition to obligatory components, indicating that adults perceive prosodic phrase structure at higher processing levels. Given the close interplay between prosodic and syntactic information, it is conceivable that the developmental differences in the nature of phrase-level prosodic processing are influenced by the degree of existing syntactic structure knowledge. During language acquisition, two processes are likely to be active: 1) the processing of prosodic phrase information enables a sequential build-up of syntactic structure knowledge and 2) the nature of prosodic phrase processing is in turn influenced by the increasing syntactic structure knowledge. Accordingly, the electrophysiological processes underlying the processing of prosodic phrasing may change as a function of syntax acquisition. In other words, the CPS as an indicator of prosodic boundary perception, which has not been observed during infancy, might appear at later developmental stages when some syntactic structure knowledge has been acquired. It thus seems essential to study IPB processing at different stages of structure knowledge during childhood.

When aiming to study the interaction of syntactic knowledge and the processing of prosodic phrasing across developmental stages, the question arises when syntax comes into play. In the ac-

quisition of syntax, the language learner has to detect relevant units (see *prosodic bootstrapping*), categorize them and eventually combine them. By means of syntactic rules, a limited number of linguistic units can be produced and comprehended in an unlimited number of combinations. For syntax acquisition in German, five stages have been suggested (Szagun, 2006; Wode, 1993): 1) *first words, one-word sentences* between 10–18 months, 2) *two-word sentences* between 18–24 months, 3) *three-/more-word sentences with simple syntax* (e.g., correct word order, first inflections) between 24–30 months, 4) *three-/more-word sentences with more complex syntax* (e.g., relative clauses, more sophisticated inflections) between 2.5–4 years, and 5) *longer sentences with complex syntax* between 4–12 years (e.g., passive constructions). Given the core steps of language production, it is apparent that syntactic rules become especially relevant when children start to combine single words into simple and more complex sentences between their second and third year (Clark, 2003; Szagun, 2006, Wode, 1993).

In accordance with the fast growing language production abilities of children around the age of 2-3 years, the majority of studies on syntax acquisition have focused on production. These studies revealed that between two and three years of age, children acquire a great deal of syntactic and morphosyntactic knowledge,³³ such as word order and first inflections (for an overview of case studies, see Guasti, 2002; Hirsh-Pasek & Golinkoff, 1996; Szagun, 2006). More specifically, children of this age learn to produce sentences that follow the particular word order rules of their target language, e.g., *subject-verb-object* in English and *verb second position* (in main clauses) in German. They furthermore start to express grammatical relations by the use of inflections, such as the inflectional marker *-s* for number in nouns (*cat* versus *cats*) or the tense marker *-ed* in verbs (*paint* versus *painted*).

With respect to syntax perception, several studies have provided evidence of children's early sensitivity to morpho-/syntactic information. One-year-old infants are perceptually sensitive to function words, as they detect replacements of function words by nonce words (e.g., Shi, Werker, & Cutler, 2006). In artificial grammar studies, infants of a similar age have been shown to discover abstract patterns and generalize them to different sets of stimuli (e.g., Gomez & Gerken, 1999). At about 1.5 years, language-specific syntax seems to become increasingly evident, as toddlers are sensitive to violations of grammatical relations in their target language (e.g., *is* and *-ing* in English), which has been

³³Morphosyntax refers to grammatical relations within a sentence that are realized in bound morphemes, e.g. inflections like case and number in nouns/adjectives or inflections like tense, mood, person and number in verbs.

reported for English-learning children (Santelmann & Jusczyk, 1998) and German-learning children (Höhle, Schmitz, Santelmann, & Weissenborn, 2006). English-learning toddlers of a comparable age were shown to perceive word order in reversible active sentences (Hirsh-Pasek & Golinkoff, 1996) and by the end of their second year to use word order information for the interpretation of sentences containing novel verbs (Gertner, Fisher, & Eisengart, 2006). Soderstrom (2003) investigated toddlers' knowledge of inflections and found that by 19 months children are sensitive to the presence of the inflectional marker *-s*. However, neither 19-month-olds nor 23-month-olds had full comprehension of the appropriate grammatical use of the inflectional marker. During their third year, children's increasing knowledge of complex syntax becomes more and more evident. For example, 3-year-old children use syntactic information to assign word meaning, e.g., distinguishing between *red* as noun (*Mr. Red*) and as adjective (*a red one*) (Hall, Geoffrey, Waxmann, Bredart, & Nicolay, 2003). Furthermore, 3-year-olds were shown to comprehend complex sentence structures, as they distinguish sentences with embedded clauses of different structure (Cohen Sherman & Lust, 1993).

Taken together, behavioral studies of both syntax perception and production suggest a pivotal increase in knowledge between the age of two and three years. To examine whether this kind of knowledge has an impact on the emergence of the CPS, the aim of the current study is to test children's IPB processing before and after this developmental stage, namely at 21 months and 36 months. The decision to test these age groups was further based on ERP studies investigating children's perception of phrase structure violations, such as **The dog in the barks* as opposed to correct sentences like *The dog barks* (Oberecker & Friederici, 2006; Oberecker, Friedrich, & Friederici, 2005). These studies revealed developmental processing differences such that the two syntax-related ERP components, as reported in adult ERP studies in response to phrase structure violations (Hahne & Friederici, 1999), were not yet both present at the age of two years. In children at 32 months, however, an adult-like ELAN and P600 were observed, further suggesting a developmental shift between children's second and third year.

In summary, *Study II* of the current thesis aims to test whether the processing of prosodic phrase structure is influenced by syntactic structure knowledge, as reflected in the underlying electrophysiological processes. More specifically, ERPs will reveal whether the CPS is observed in response to IP processing in 36-month-olds who have already acquired some syntactic phrase structure knowledge,

while the CPS is not expected to occur in 21-month-olds who have not yet reached this developmental stage. In addition, 6-year-old pre-schoolers who are even more advanced in their syntactic comprehension and production skills (e.g., passive constructions; Savage, Lieven, Theakston, & Tomasello, 2003), served as control group. Again, no hemispheric lateralization of the ERP effects is expected, given that subjects are presented with natural sentence material (see 3.1). The according hypotheses are listed in Table 9.1.

Table 9.1: Hypotheses of Study II on IP processing in 21-month-old, 3-year-old and 6-year-old children

1) IP processing in 21-month-old children
21-month-olds do not show a CPS in response to IPBs.
2) IP processing in 3-year-old children
3-year-olds show a CPS in response to IPBs.
3) IP processing in 6-year-old children
6-year-olds show a CPS in response to IPBs.

9.2 Methods

9.2.1 Subjects

For the 21 month age group, the final subject sample consisted of 40 toddlers (22 female; mean age 91.9 weeks, range 90-95 weeks). In the 3 year age group, the data of 44 children (15 female, mean age 156.7 weeks, range 154-160 weeks) entered the final analyses. For the 6 year age group, the data of 48 pre-school children (22 female; mean age 314.2 weeks, range 310-318 weeks) were included in the final analyses.

9.2.2 Stimuli

21-month-olds and 3-year-olds were presented with the long version of Naturally spoken sentences, while 6-year-olds were given the short version of Naturally spoken sentences (see 7.2.1).³⁴ Since for

³⁴The rationale of this approach is that 21-month-olds and 3-year-olds were tested before the short version of Naturally spoken sentences was created, which was designed later for the infant study. When the short sentence version existed, 6-year-olds were also tested with these sentences for efficiency reasons.

the long version of Naturally spoken sentences only the first sentence part was analyzed, covering the first IPB (in the sentence condition with IPBs), the analyses of both short and long versions targeted the same sentence sections and were thus comparable. For this reason, both long and short sentence versions are henceforth referred to as Naturally spoken sentences with and without IPB, or in short form, sentences with IPB and sentences without IPB.

9.2.3 Data analysis

For all children, at least 12 artifact-free trials (approx. 25%) were required per condition for an individual average to enter the final sample. In the 21-month-olds, the resulting mean number of averaged trials across subjects was 24 (SD=6) for Naturally spoken sentences with IPB and also 24 (SD=6) for sentences without IPB. For the 3-year-old children, the mean number of averaged trials was 26 (SD=7) for sentences with IPB and also 26 (SD=8) for sentences without IPB. In the 6-year-old children, an average trial number of 35 (SD=6) was obtained for sentences with IPB and 36 (SD=7) for sentences without IPB. For all age groups, trial numbers did not significantly differ between conditions.

9.3 Results

For the initial statistical analysis of the ERP data across all age groups, ANOVAs were performed with the factors Condition, Region, and Hemisphere across TWs of 500 ms, for segments of 2.5 s relative to sentence onset. Only significant amplitude differences involving the factor Condition are reported here.

9.3.1 ERP data of 21-month-olds

Figure 9.1 displays the average ERP responses to Naturally spoken sentences with and without IPB for 21-month-old children. An initial view of the results demonstrates that there is virtually no difference between the ERP responses to both sentence types. Accordingly, ANOVAs revealed only for the TW 2000-2500 ms an interaction of Condition x Region at lateral ROIs [$F(2,78)=5.96, p \leq .01$]. Since subsequent one-way ANOVAs for single regions did not deliver any condition differences, this effect was disregarded. It follows that for 21-month-old children, statistical analyses revealed no processing differences between sentences with IPB and sentences without IPB.

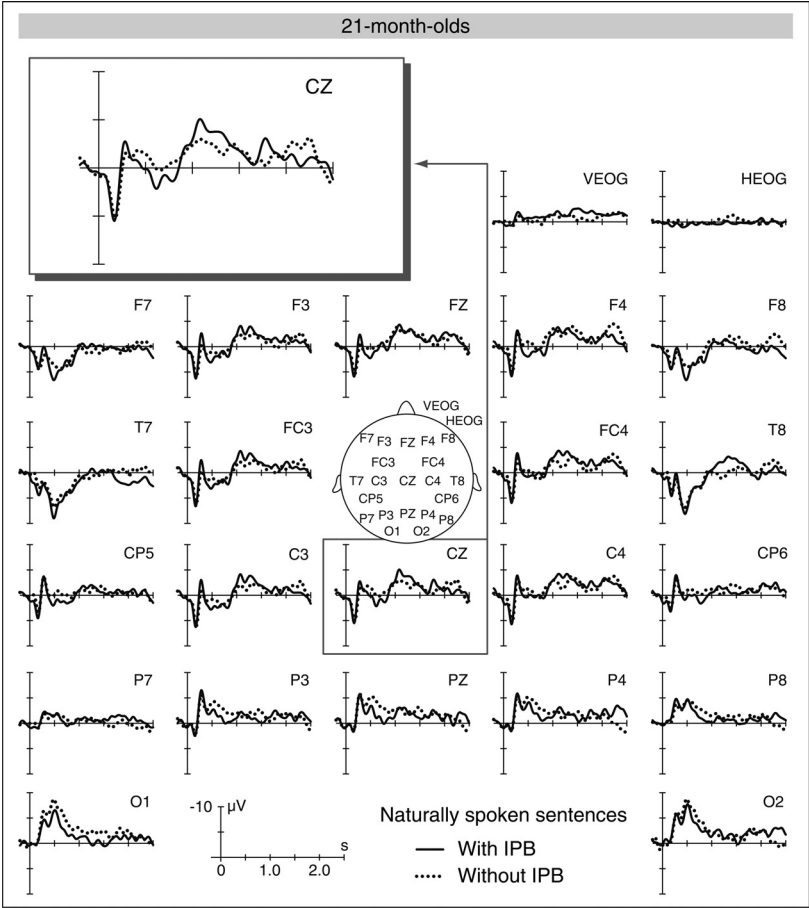


Figure 9.1: 21-MONTH-OLDS Grand average ERPs for Naturally spoken sentences with IPB (solid line) and without IPB (dotted line). ERP responses display no significant differences between sentence types.

9.3.2 ERP data of 3-year-olds

In contrast to the ERP data in 21-month-olds, the data of 3-year-olds showed a positive shift in response to sentences with IPB as compared to sentences without IPB (Figure 9.2). This positive shift occurred predominantly at anterior and central sites and displayed its peak between 1500-2000 ms.

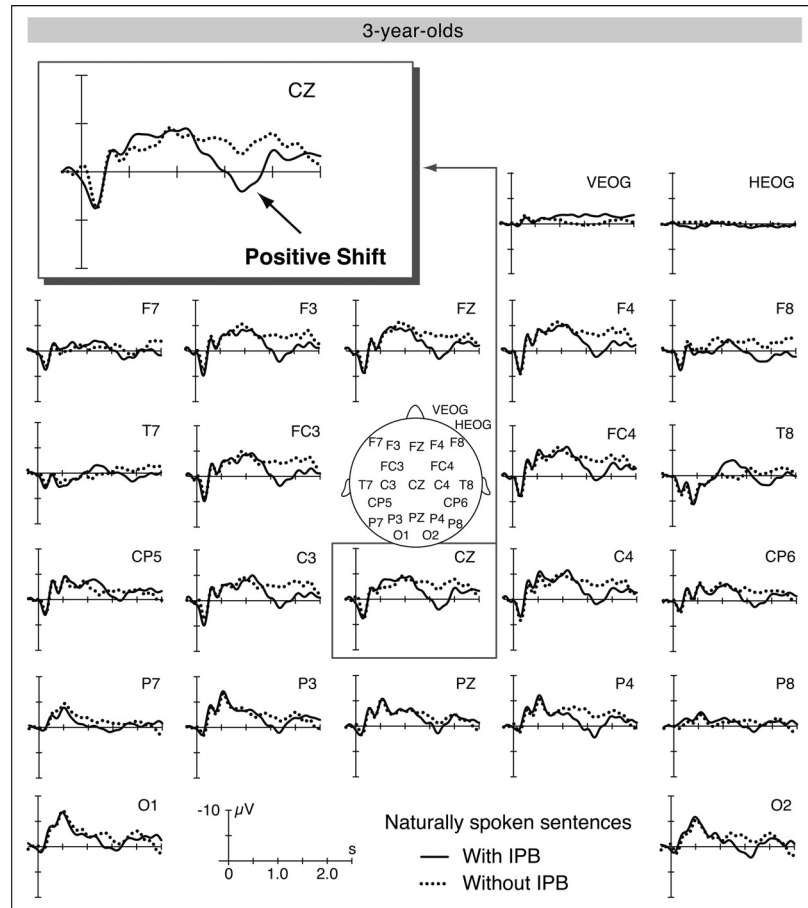


Figure 9.2: 3-YEAR-OLDS Grand average ERPs for Naturally spoken sentences with IPB (solid line) and without IPB (dotted line). ERPs to sentences with IPB display a positive shift, starting at about 1500 ms relative to sentence onset.

This observation was proven by ANOVAs that revealed for TWs between 1500-2500 ms post-sentence onset effects involving the factor Condition.³⁵ More specifically, in the TW 1500-2000 ms, a main effect Condition was observed at lateral ROIs [$F(1,33)=11.05$, $p \leq .01$] and an interaction of Condition x Region at midline electrodes [$F(2,68)=8.75$, $p \leq .01$]. When testing this interaction, one-way ANOVAs revealed main effects of Condition at FZ [$F(1,43)=8.75$, $p \leq .01$] and CZ [$F(1,43)=9.84$,

³⁵ Additionally, in the TW 500-1000 ms, an interaction of Condition x Region x Hemisphere was observed at lateral ROIs [$F(2,86)=3.44$, $p \leq .05$]. However, since subsequent one-way ANOVAs at single electrode sites did not reveal any condition differences, this effect was disregarded.

$p \leq .01$]. For the subsequent TW 2000-2500 ms, the condition difference continued for lateral anterior sites, as an interaction of Condition x Region [$F(2,86)=6.39$, $p \leq .01$] and respective one-way ANOVAs revealed a main effect of Condition for the anterior region [$F(1,43)=5.7$, $p \leq .05$]. In summary, for 3-year-old children, statistical analyses evidenced processing differences between sentences with IPB and sentences without IPB. This difference was apparent in a positive shift in the ERP, with a fronto-central distribution, in response to sentences containing IPBs.

9.3.3 ERP data of 3-year-olds and 21-month-olds: A developmental comparison

ERP analyses across age groups revealed age-related differences such that for 3-year-olds, but not for 21-month-olds, a positive shift occurred for Naturally spoken sentences with IPB, while there was none for sentences without IPB. The exact nature of this positive shift, however, requires to be determined. As outlined in the ERP analyses for 5-month-olds in *Study I*, the observed effect may either reflect 1) a true phrasing effect in response to IPB perception (as indicated by a CPS in adults), 2) an obligatory onset response to the restart of speech after the pause (as indicated by obligatory components, e.g., the adult N1-P2 complex), or 3) a combination of both these effects (see Steinhauer, 2003; for a methodological distinction between the CPS and the P2 in adult ERP data). To test for the different explanations accounting for the positive shift in sentences with IPB, the actual timing of the effect was examined by aligning the analysis window to the onset of NP2 *Papa zu helfen* (to help papa), which coincides with the pause offset. This procedure allows for differentiation of ERP responses that 1) start prior to the NP2 onset, at a time when boundary information has already been presented and 2) follow the NP2 onset, covering (at least partially) obligatory onset responses that are automatically evoked by the auditory input after the pause. Importantly, if the positive shift occurs or starts prior to the NP2 onset, it cannot merely be ascribed to onset responses but should also be attributed to IPB processing.

For the suggested analyses, ERP responses to both sentences with IPB and sentences without IPB were analyzed relative to NP2 onset, covering preceding and subsequent TWs. For monitoring processes following the end of the first sentence part (i.e., the IPB in the sentence condition with IPBs), ERPs were adjusted to a baseline of 100 ms relative to the offset of the first sentence part.³⁶

³⁶This baseline correction was applied to ERPs of both sentences with and without IPB. Given the different pause lengths in the sentence conditions, this adjustment resulted in different baseline intervals across sentence types, thus barring direct

For 3-year-olds (Figure 9.3, right panel), the ERPs to sentences with IPB displayed the expected obligatory response to the NP2 onset after the pause, most apparent in a positivity peaking between 100-200 ms post-onset. Notably, however, the positive shift as a whole started prior to the NP2 onset, most likely merging into and thus contributing to the amplitude of the obligatory component.

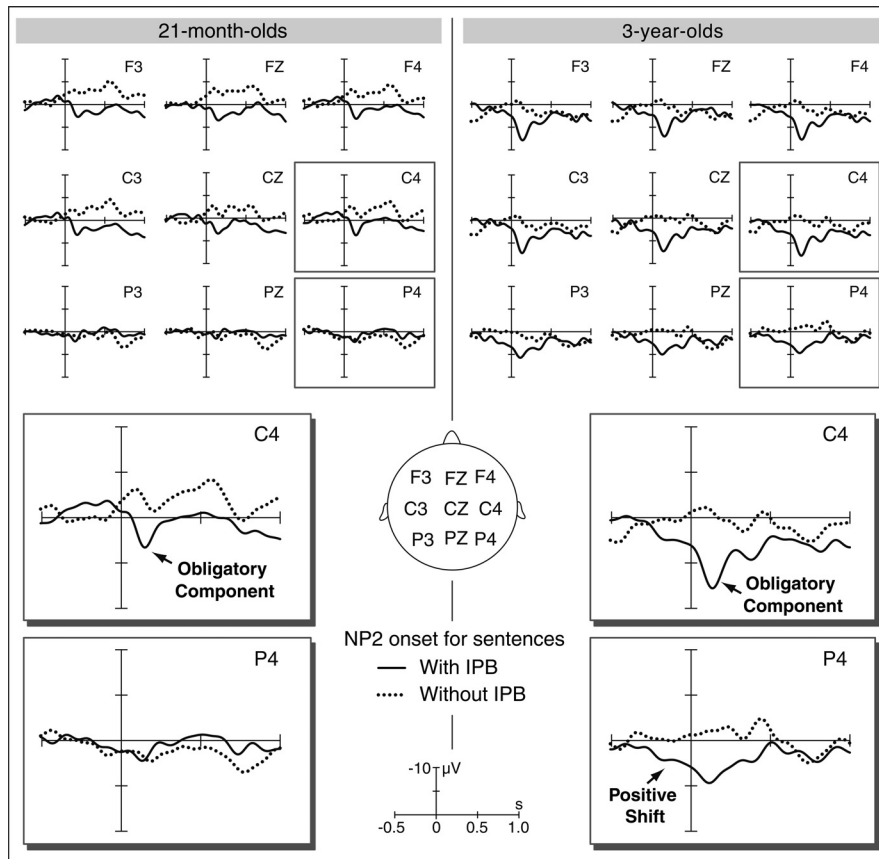


Figure 9.3: 21-MONTH-OLDS & 3-YEAR-OLDS Grand average ERPs for Naturally spoken sentences with IPB (solid line) and without IPB (dotted line) relative to NP2 onset. In 21-month-olds (left panel), ERPs show an obligatory component following the NP2 onset. In 3-year-olds (right panel), ERPs additionally reveal a positive shift starting prior to the NP2 onset, likely contributing to the amplitude of the subsequent obligatory component.

comparisons between sentences with and without IPB in the same TWs. For this reason, comparison between the ERPs of both sentence types were only drawn visually, while statistical analyses in the critical TWs in sentences with IPB were performed in multiple one-sample t-tests against a test value of 0.

The described ERP effects were quantified by computing mean amplitude measures for the sentences with IPB for the following TWs: TW -500-0 ms for the positive shift starting prior to the NP2 onset and TW 0-300 ms for the obligatory response following the NP2 onset.³⁷ These amplitude measures were subjected to multiple one-sample t-tests against the test value 0 at lateral ROIs and midline sites. For the observed positive shift prior to the NP2 onset, significant deviations were revealed for posterior lateral ROIs and midline sites: Right posterior [$t(43)=2.59$, $p \leq .01$], Left posterior [$t(43)=3.22$, $p \leq .01$], CZ [$t(43)=2.03$, $p \leq .05$], and PZ [$t(43)=2.06$, $p \leq .05$].³⁸ The mean amplitude in the TW of the obligatory response was shown to be significantly different from zero at all lateral ROIs and midline sites (Table 9.2). As the mean amplitude measures in Table 9.2 indicate, the ERP response following the NP2 onset was most pronounced at anterior sites and decreased towards posterior sites.

Table 9.2: 3-YEAR-OLDS Sentences with IPB: Mean amplitudes (SD indicated) in the TW following the NP2 onset (0-300 ms) (Ant = anterior; Cen = central; Post = posterior).

ROIs/ sites	TW 0-300 ms	
	<i>Amp</i> (μV)	<i>t</i> (43)
Right ant	4.11 (6.59)	4.14**
Left ant	4.16 (6.51)	4.24**
Right cen	3.10 (6.10)	3.37**
Left cen	2.88 (5.71)	3.35**
Right post	2.63 (4.46)	3.91**
Left post	2.71 (4.41)	4.07**
FZ	4.61 (7.69)	3.98**
CZ	5.17 (7.50)	4.57**
PZ	3.84(6.33)	4.02**

** $p \leq .01$; one sample t-test against the test value 0

Taken together, for 3-year-old children, analyses relative to NP2 onset, covering preceding and subsequent TWs, revealed both a positive shift in the ERP starting prior to the NP2 onset and obligatory responses following the NP2, apparent in a positivity peaking between 100-200 ms post-onset. Given the broad distribution of the obligatory onset response (which is usually predominantly observed at fronto-central sites, e.g., Ceponiene, Lepisto, Alku, Aro, & Näätänen, 2003; Wunderlich, Cone-Wesson, & Shepherd, 2006) and its enhanced amplitude, it can be assumed that the preceding

³⁷These TWs were chosen upon visual inspection.

³⁸These results did not change when choosing a shorter TW of -300-0 ms relative to NP2 onset.

positive shift contributes to the appearance of the obligatory component. From these results, it follows that the positive shift, which was observed in the analyses across the whole sentence length (9.3.2), is not only attributable to obligatory onset responses to sentence continuation after the pause, but is additionally composed of a positive-going ERP component with a posterior distribution that reflects IPB processing similar to the CPS in adults (Steinhauer, Alter & Friederici, 1999).

In contrast, for 21-month-olds, who did not show a positive shift for sentences with IPB for the analyses across the whole sentence, Figure 9.3 (left panel) demonstrates that the NP2 onset was followed by an obligatory onset response, which was not, however, preceded by a positive shift. Accordingly, multiple one-sample t-tests against the test value 0 did not deliver any significant deviations for the TW -500-0 ms preceding the NP2 onset. For the subsequent TW of 0-300 ms, t-tests proved the occurrence of the obligatory response at anterior ROIs and midline sites: Right anterior [$t(39)=2.40$, $p \leq .05$], Left anterior [$t(39)=1.91$, $p \leq .10$],³⁹ FZ [$t(39)=3.22$, $p \leq .01$], and CZ [$t(39)=2.74$, $p \leq .01$]. Additional analyses performed for single lateral electrode sites (motivated by visual inspection) revealed that the effect extended towards the central sites C3 [$t(39)=2.36$, $p \leq .05$] and C4 [$t(39)=2.07$, $p \leq .05$]. Thus, in 21-month-old children, analyses relative to NP2 onset revealed an obligatory onset response at fronto-central sites but no positive shift preceding the NP2 onset, as a potential indicator of IPB processing.⁴⁰

In summary, for both 21-month-olds and 3-year-olds, the analysis of ERPs to sentences with IPB relative to the NP2 onset provided important specifications of the initial results from the analysis across the whole sentence length. For 21-month-olds, the NP2 onset analysis revealed an obligatory onset response to the sentence restart after the pause that was previously masked in the analysis across the whole sentence.⁴¹ Furthermore, as indicated by the absence of a positive shift in the whole-sentence analysis, no positive-going ERP effect was found to precede the NP2 onset. The fact that 21-month-old toddlers, similar to the 5-month-old infants in *Study I*, show an obligatory onset response, but no adult-like CPS, suggests that they respond to prosodic phrasing at a perceptual

³⁹Given the hypothesis, the significance level can be set to $p \leq .10$.

⁴⁰Given the considerably younger age of the 21-month-olds as compared to the 3-year-olds, a potential phrasing effect in the ERP might have featured a longer latency and thus not preceded the NP2 onset but coincided with the onset ERP response. However, the shape and amplitude of the obligatory response as well as the component's fronto-central distribution exclude this possibility.

⁴¹This does not conflict with the results in 5-month-olds (*Study I*) – where the obligatory component was clearly apparent in the sentence analysis – given that the amplitude and latency of obligatory components decrease with increasing age (e.g., Jing & Benasich, 2006; Kushnerenko et al., 2002).

level, triggered by the interruption of sentences by prosodic breaks. For 3-year-olds, it was confirmed that the positive shift observed in the whole-sentence analysis does not only reflect obligatory onset responses at lower-level processing stages but can be (additionally) attributed to IPB processing as indicated by the CPS. This conclusion is based on 1) the occurrence of the positivity preceding the NP2 onset and 2) the differences in distribution of the ERP effects in the NP2 onset TW across age groups. In 21-month-olds, the occurrence of this ERP effect was restricted to fronto-central regions, as has been typically described for obligatory components in children and adults (e.g., Ceponiene, Lepisto, Alku, Aro, & Näätänen, 2003; Wunderlich, Cone-Wesson, & Shepherd, 2006). In contrast, in 3-year-olds, the ERP effect in the same TW was broadly distributed over the scalp, suggesting an overlap of the phrasing effect (CPS) and the obligatory onset effect at posterior sites.

9.3.4 ERP data of 6-year-olds

To validate the findings in 3-year-olds, the ERP data collected from 6-year-olds were subjected to the same analyses as the previous ERP data. First, analyses across the whole sentence length were performed for Naturally spoken sentences with and without IPB. As can be seen from Figure 9.4, sentences with IPB, but not sentences without IPB, evoked a pronounced positive shift that occurred with a broad distribution across the scalp. Accordingly, ANOVAs performed across TWs of 500 ms relative to sentence onset revealed effects involving Condition for the time interval 1500-2500 ms (Table 9.3). Thus, statistical analyses confirmed the occurrence of a sustained and broadly distributed positive shift for sentences with IPB as compared to sentences without IPB.

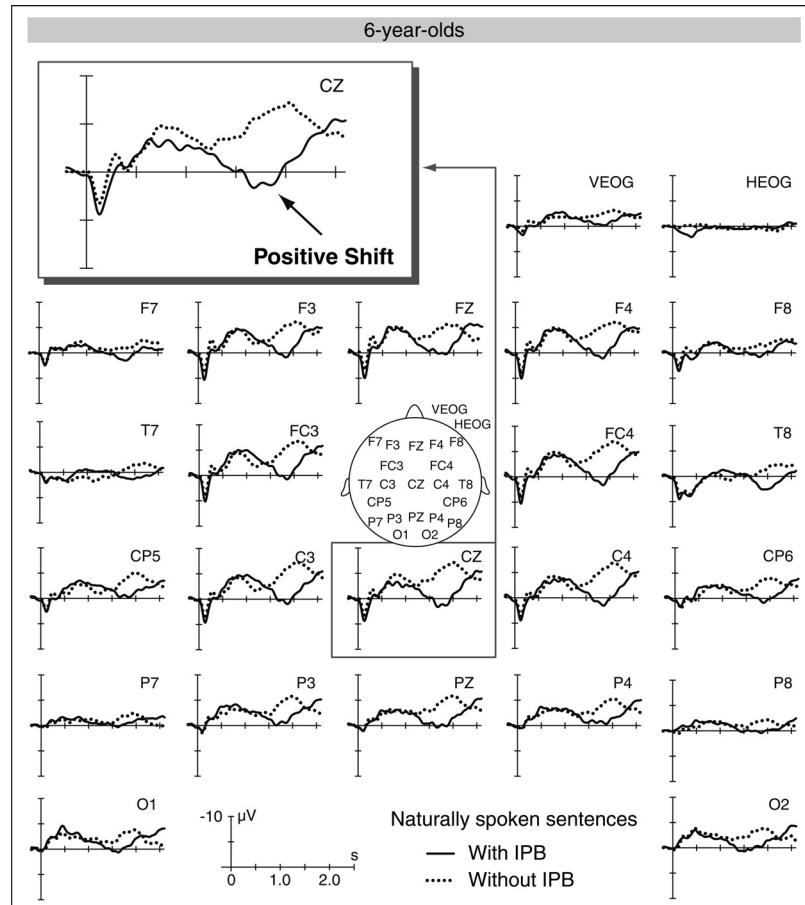


Figure 9.4: 6-YEAR-OLDS Grand average ERPs for Naturally spoken sentences with IPB (solid line) and without IPB (dotted line). ERPs to sentences with IPB display a positive shift, starting at about 1500 ms relative to sentence onset.

Table 9.3: 6-YEAR-OLDS Naturally spoken sentences: Significant effects of ANOVAs for the 0-2500 ms latency range relative to sentence onset (Cond = Condition; Reg = Region; Ant = anterior; Cen = central; Post = posterior).

TW (ms)	Lateral ROIs			Midline sites		
	<i>Effect</i>	<i>df</i>	<i>F</i>	<i>Effect</i>	<i>df</i>	<i>F</i>
0-500	Cond x Reg	2,94	3.51*			
1000-1500				Cond	1,47	4.89*
1500-2000	Cond	1,47	44.34**	Cond	1,47	47.54**
				Cond x Reg	2,94	5.11*
				FZ	1,47	27.41**
				CZ	1,47	48.25**
				PZ	1,47	36.06**
2000-2500	Cond	1,47	12.87**	Cond x Reg	2,54	5.97**
	Cond x Reg	2,94	11.11**	CZ	1,47	6.09*
	Ant	1,47	6.92*			
	Cen	1,47	36.92**			

* $p \leq .05$; ** $p \leq .01$

As is apparent from Figure 9.5 (left panel), the analysis relative to NP2 onset delivered a similar ERP pattern in 6-year-olds as in 3-year-olds (Figure 9.5, right panel). ERPs of both age groups displayed a positive shift starting prior to the NP2 onset and merging into the obligatory response following the NP2 onset. For 6-year-olds, multiple one-sample t-tests confirmed the occurrence of both ERP effects (Table 9.4), with significant deviations from zero for both TW -500-0 ms and TW 0-300 ms at all lateral ROIs and midline sites. Thus, in the older children, the obligatory component appeared with a broad distribution across the scalp, as in the 3-year-olds. In addition, the positive shift prior to NP2 was also broadly distributed.

Up to this point, for both 3- and 6-year-olds, the conclusion of overlapping ERP components around the onset of NP2 has been based on 1) the fact that a positive shift preceded the NP2 onset and 2) the rather untypical broad distribution of the obligatory onset responses when they were preceded by a positive shift (as in 3- and 6-year-olds) as opposed to the typical fronto-central distribution when they were not preceded by a positive shift (as in 21-month-olds). In addition, in 6-year-olds, a closer inspection of the ERPs relative to the NP2 onset (Figure 9.5, left panel) reveals that the positive shift starting prior to the NP2 onset has a different shape (evolving slower and less steep)

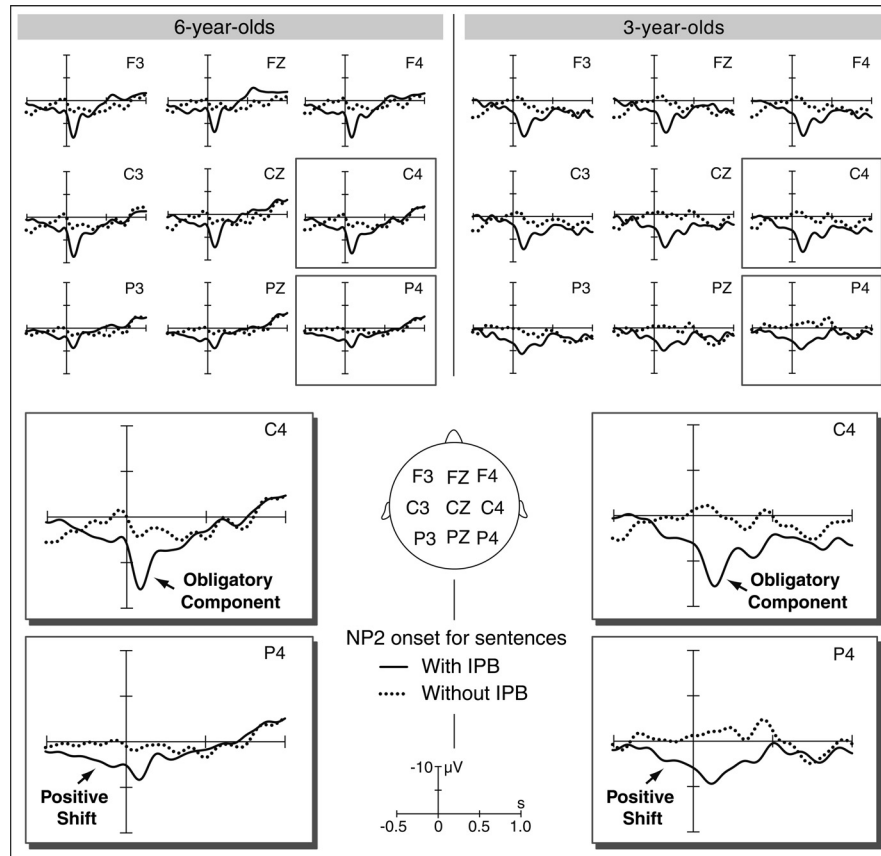


Figure 9.5: 6-YEAR-OLDS & 3-YEAR-OLDS Grand average ERPs for Naturally spoken sentences with IPB (solid line) and without IPB (dotted line) relative to NP2 onset. For both age groups, ERPs display a positive shift starting prior to the NP2 onset, which likely contributes to the amplitude of the subsequent obligatory component in response to the NP2 onset.

than the onset response in the TW following the NP2 onset (showing a short pronounced peak at around 100 ms post-onset). This difference appeared to be more evident in 6-year-olds than in 3-year-olds, suggesting more defined components or less temporal overlap in the older children.⁴² To gain a more advanced statistical separation of the two temporally overlapping ERP components, the data of 6-year-old children were additionally subjected to Principal Component Analysis (PCA).

⁴²Due to the different stimulus material used for both age groups, no conclusion can be drawn whether the different appearance of the ERP effects across age groups – possibly reflecting less temporal overlap in the older children – resulted from processing differences because of age or the acoustic realization of the sentences.

Table 9.4: 6-YEAR-OLDS Sentences with IPB: Mean amplitudes (SD indicated) in TWs preceding (-500-0 ms) and following NP2 onset (0-300 ms) (Ant = anterior; Cen = central; Post = posterior).

ROIs/ sites	TW -500-0 ms		TW 0-300 ms	
	<i>Amp</i> (μV)	<i>t</i> (47)	<i>Amp</i> (μV)	<i>t</i> (47)
Right ant	1.83 (3.24)	3.85**	4.18 (3.89)	7.43**
Left ant	1.59 (3.02)	3.66**	4.06 (2.96)	9.50**
Right cen	1.26 (3.10)	2.82**	3.88 (3.16)	8.52**
Left cen	0.94 (2.57)	2.54*	3.24 (2.87)	7.82**
Right post	1.78 (2.80)	4.41**	1.88 (3.36)	3.87**
Left post	0.94 (2.64)	2.45*	1.04 (3.04)	2.37*
FZ	1.95 (3.91)	3.46**	3.53 (4.63)	5.28**
CZ	1.54 (4.06)	2.63*	3.83 (4.51)	5.89**
PZ	1.85(3.17)	4.05**	2.46 (3.99)	4.26**

* $p \leq .05$; ** $p \leq .01$; one sample t-test against the test value 0

9.3.5 PCA on the ERP data of 6-year-olds

Principal Component Analysis (PCA) PCA is a multivariate method that seeks to uncover latent variables in a numerical dataset by extracting linear combinations of a number of factors that account for patterns of covariance in the given data (Gorsuch, 1983; Harman, 1976). In ERP research, PCA has been applied as a statistical method to decompose the ERP signal for the purposes of data reduction, exploration, and description (for more detail, see Dien & Frishkoff, 2004; Donchin & Heffley, 1979; Möcks & Verleger, 1991). More specifically, in the event-related recording of EEG signal at consecutive time points and across a number of electrodes, the main source of covariance is assumed to be ERP components, i.e., typical waveforms that spread across multiple time points and electrode sites. After decomposition and factor rotation, each factor (ideally) corresponds to a separate ERP component, thus greatly facilitating ERP data analysis and interpretation.

Mathematically, the starting point of a PCA is a relationship matrix, typically a *covariance matrix* or *correlation matrix*, which expresses the relationship between all variables (e.g., time points) and observations (e.g., EEG measures for different subjects, electrodes and experimental conditions). More specifically, the data matrix may be organized in rows listing the variables and columns containing the respective observations. The covariance matrix of the variables is the squared data matrix,

while the entry of each cell depicts the relationship (covariance or correlation) between the respective variables. In a first step, the *factor extraction*, the PCA algorithm computes an eigenvalue decomposition, which consists of a set of eigenvalues and corresponding eigenvectors (for more detail, see, e.g., Fischer, 2000). The eigenvalues are sorted according to their magnitude, which refers to the explained data variance. This process re-expresses the data as a set of linear combinations (factors) arranged in order of decreasing size.⁴³ From the obtained factors, only those factors with the largest eigenvalues are retained⁴⁴ (see *scree test* by Cattell, 1966 and the eigenvalue criterion by Kaiser, 1960, for decisions on factor retention). In a second step, the *factor rotation*, the interpretability of the retained factors is increased by maximizing the variance of squared factor loadings, so that variables load high on some factors and low on others. Generally, factors can be described and interpreted in terms of their loadings and scores. *Factor loadings* refer to the correlation between factors and variables. *Factor scores* express the magnitude of a factor for each observation.

Dependent on the question of interest, a PCA can be performed for the temporal or the spatial domain. Here, a general rule is that if temporal changes are the object of investigation, a spatial PCA should be computed, and vice versa (Dien, 1998). The rationale of this approach is that if, for example, spatial information (electrode positions) is specified in the variables, it is reflected in the factor loadings, which are the same for all observations (i.e., the same electrode positions across all subjects, time points, and experimental conditions). Temporal information, on the other hand, is expressed in factor scores, which are free to vary between subjects and conditions, thus allowing for the examination of temporal changes.

Spatial PCA on the ERP data of 6-year-olds For further analysis of the ERP data in 6-year-olds relative to NP2 onset, topographical information (amplitude values at electrode sites) was subjected to decomposition, potentially allowing for a temporal dissociation of the suggested ERP components preceding and following the NP2 onset. Thus, a spatial PCA was computed in *Matlab 7.6* (The MathWorks, Inc.) that allowed for the detection of characteristic spatial patterns (factor loadings) along the time domain (factor scores). Accordingly, the data matrix contained electrode sites as variables and experimental condition, subjects, and time points as observations. Specifically, the

⁴³The maximal number of factors equals the number of variables.

⁴⁴Since the eigenvalue refers to the amount of variance explained by one factor (relative to the overall explained variance), it describes the substantive importance of a factor.

covariance among the 21 electrode sites was analyzed across a number of defined time points of the averages for sentences with IPB for each of the 48 subjects. Since the ERP measures of interest concerned TWs preceding and following the NP2 onset of sentences with IPB, a TW of -500 to 500 ms, resulting in 251 time points,⁴⁵ was subjected to PCA. Given the assumption of two different foci of the suggested ERP components – a fronto-central distribution of the obligatory components following the NP2 onset and a posterior distribution of the positivity preceding the NP2 onset – factor extraction was limited to two spatial factors (SFs). For the factor rotation procedure, the varimax rotation (Kaiser, 1958) was applied.

For the two derived SFs, topographic maps with spatial factor loadings are provided in Figure 9.6.⁴⁶ These maps display characteristic spatial patterns of the ERP averages for sentences with IPB in the TW -500-500 ms relative to the NP2 onset across all subjects. Loadings correspond to the correlation between the data recorded at each electrode site and the respective SF. As the maps illustrate, SF1 is heavily weighted at fronto-central electrode sites, while SF2 is mainly weighted at posterior sites.

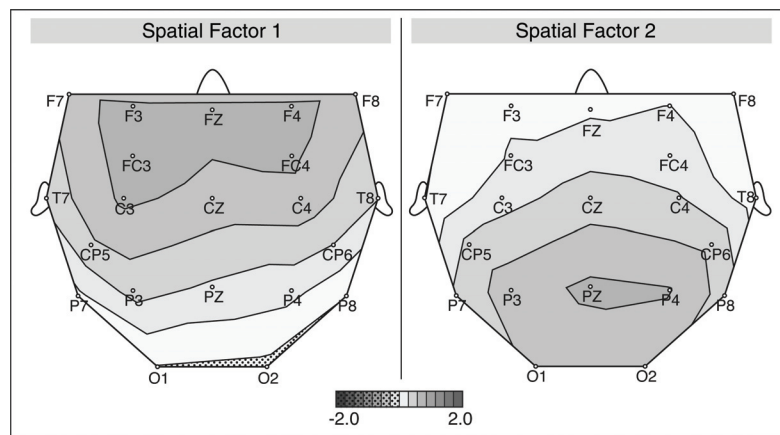


Figure 9.6: 6-YEAR-OLDS Topographic maps of spatial factor (SF) loadings for sentences with IPB relative to NP2 onset. SF1 (left panel) shows a fronto-central distribution, while SF 2 (right panel) is primarily weighted at posterior sites.

⁴⁵This number was derived given the sampling rate of 250 Hz.

⁴⁶SF loadings and scores are centered (i.e., baseline-adjusted to the mean of the full epoch length) and normalized (i.e., their variance equals 1).

Figure 9.7 delivers the according factor scores that express the contribution of each SF at each time point for the ERPs of all subjects. When the weightings are plotted as a function of time, it becomes apparent that SF1 (fronto-central distribution) has its largest amplitude in the TW 0-200 ms following the NP2 onset, while the waveform for SF2 (posterior distribution) shows a deflection in the TW -300-0 ms preceding the NP2 onset that extends into the following TW. The interpretability of both the factor loading maps and the factor scores is limited by the fact that 1) neither loadings nor scores correspond to actual amplitude measures (i.e., μV), and 2) the sign of a given value of factor loadings or factor scores is equivocal.⁴⁷ These limitations were overcome by computing the product of factor loadings and factors scores, thus deriving a Factor-EEG that corresponds to the original data in an unequivocal way.

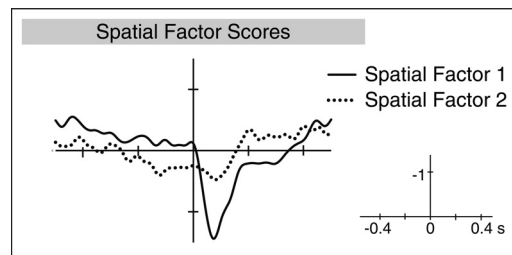


Figure 9.7: 6-YEAR-OLDS Spatial factor (SF) scores for sentences with IPB relative to NP2 onset. SF1 (solid line) features a pronounced amplitude in the TW 0-200 ms following the NP2 onset, while SF2 (dotted line) shows a deflection in the preceding TW -300-0 ms that extends into the following TW.

Figure 9.8 displays the topographic maps of the Factor-EEGs of SF1 and SF2, computed for TWs capturing each factor's highest loadings, i.e., for SF1 the TW 0-200 ms post-NP2 onset and for SF2 the TW -300-0 ms pre-NP2 onset. Similar to the distribution of the respective factor loadings map, the signal of the Factor1-EEG was mainly distributed over fronto-central sites, while the signal of the Factor2-EEG featured its largest amplitudes over posterior electrode sites.

To depict the time course of the Factor-EEGs, electrode positions representative for each distribution were chosen, i.e., FZ as one of the high-loading frontal electrodes for SF1 and PZ with the

⁴⁷Mathematically, signal decomposition divides the original data into parts (i.e., factor loadings and factor scores) that, as a product, have to reconstruct the original data with its original sign (i.e., + or -). However, this can be achieved in different ways (e.g., an original positive value is either achieved by the product of two positive or two negative values), so that the value assignment in the decomposition is finally equivocal.

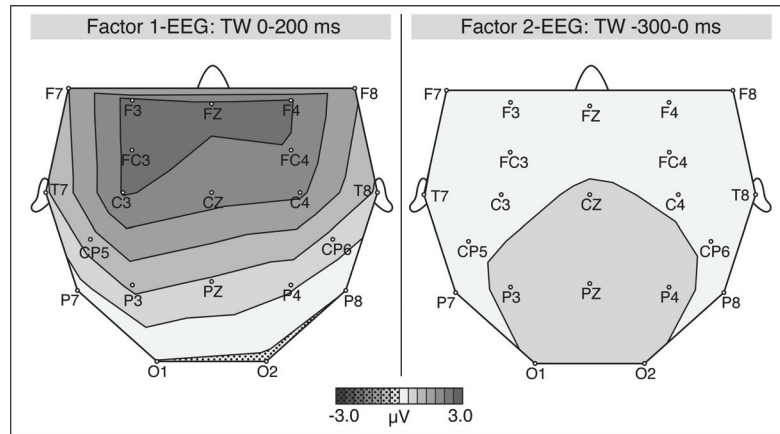


Figure 9.8: 6-YEAR-OLDS Topographic maps of Factor-EEGs for sentences with IPB relative to NP2 onset. Maps are computed for TWs representative for each spatial factor's (SF) loadings. In the according TWs, SF1 (left panel) shows a fronto-central distribution, while SF2 (right panel) is primarily weighted at posterior sites.

largest amplitude measures for SF2. The according Factor-EEGs of both factors are given in Figure 9.9 (left panel) for FZ and Figure 9.9 (right panel) for PZ.

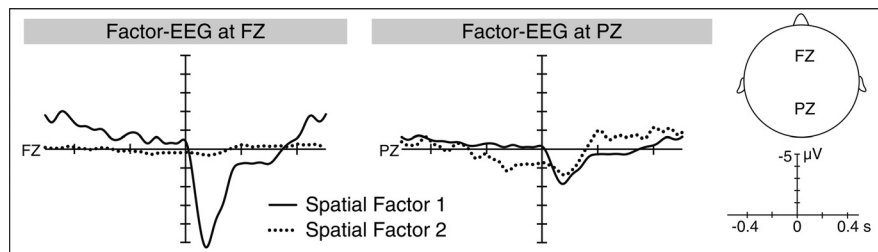


Figure 9.9: 6-YEAR-OLDS Factor-EEGs for sentences with IPB relative to NP2 onset. The time course is plotted at electrode positions representative for each spatial factor's (SF) distribution. SF1 obtained its largest amplitudes at FZ in the TW 0-200 ms (left panel), while SF2 shows pronounced amplitudes at PZ in the TW -300-0 ms (right panel).

As the Factor-EEGs demonstrate, SF1 obtained its largest amplitudes in the TW 0-200 ms post-NP2 onset at FZ, while SF2 featured pronounced amplitudes in the TW -300-0 ms pre-NP2 onset at PZ. These effects were statistically confirmed by one-way ANOVAs with the factor FACTOR (SF1, SF2), which revealed significant effects for the TW 0-200 ms at FZ [$F(1,47)=41.03$, $p \leq .01$] and for the TW -300-0 ms at PZ [$F(1,47)=9.17$, $p \leq .01$]. Thus, the analysis in the time domain demonstrates that the signal of the two extracted SFs – SF1 with a frontocentral distribution and SF2

with a posterior distribution – can, to a large degree, be attributed to different TWs, revealing the required temporal dissociation of the derived spatial patterns. Interestingly, the data also indicate an overlap of the suggested phrasing effect (pre-onset TW) and the obligatory onset effect (post-onset TW), since inspection of the TW 0-200 ms at PZ shows converging effects: 1) SF1 even loads at PZ, although less pronounced than at FZ, suggesting a broadly distributed obligatory onset effect, which decreases in amplitude towards posterior sites, and 2) SF2 loads in the pre-onset TW, but the loading continues for the post-onset TW, suggesting a sustained positive-going phrasing effect that starts prior to the NP2 onset but extends into NP2.

In an additional analysis performed on a subgroup of the 6-year-old children, successful signal decomposition by PCA and factor rotation was even more convincingly demonstrated. Here, the data of 25 children were chosen based upon visual inspection of individual ERP averages with respect to the size of both ERP effects relative to NP2 onset. For this subgroup, topographic maps of the Factor-EEGs (Figure 9.10) and their time course (Figure 9.11) display, even more distinctly, the patterns of the overall group.

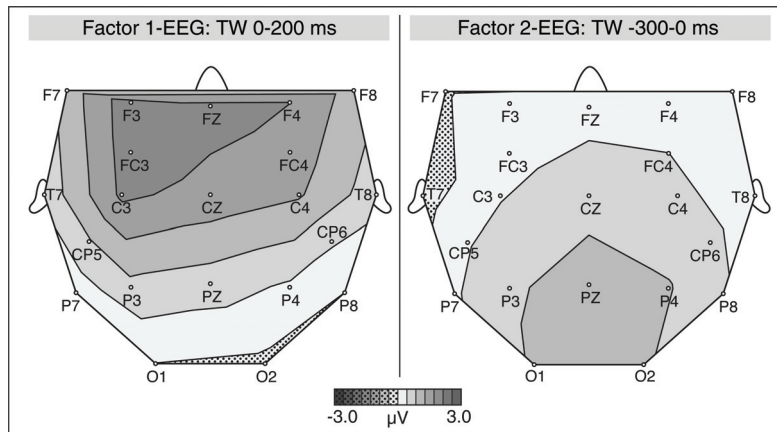


Figure 9.10: SUBGROUP OF 6-YEAR-OLDS Topographic maps of Factor-EEGs for sentences with IPB relative to NP2 onset. Maps are computed for TWs representative for each spatial factor's (SF) loadings. In the according TWs, SF1 (left panel) shows a fronto-central distribution, while SF2 (right panel) is primarily weighted at posterior sites.

In summary, for the ERP data in 6-year-olds, signal decomposition by PCA and factor rotation revealed two spatial patterns that obtained different temporal foci relative to the NP2 onset. Specifically,

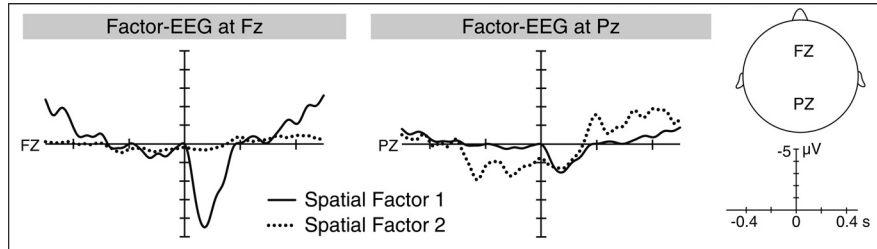


Figure 9.11: SUBGROUP OF 6-YEAR-OLDS Factor-EEGs for sentences with IPB relative to NP2 onset. The time course is plotted at electrode positions representative for each spatial factor's (SF) distribution. SF1 obtained its largest amplitudes at FZ in the TW 0-200 ms (left panel), while SF2 shows pronounced amplitudes at PZ in the TW -300-0 ms (right panel).

SF1 was characterized by a fronto-central distribution and featured most pronounced amplitudes in the TW 0-200 ms after the NP2 onset. Thus, SF1 most likely reflects the obligatory onset response to the sentence continuation after the pause that in the ERP occurs as pronounced positivity, peaking at about 100 ms post-onset. In contrast, SF2 featured a posterior distribution and showed pronounced amplitudes that clearly start prior to the NP2 onset. Thus, SF2 may well be related to a phrasing effect indicating higher-level perception of IPBs that in the ERP appears as a positive component, starting prior to the NP2 onset. In conclusion, the additional analyses proved the occurrence of two overlapping ERP components – reflecting a phrasing effect similar to the adult CPS and an onset effect similar to the adult N1-P2 pattern – that both contribute to the pronounced positivity observed for the sentences with IPB.

9.4 Discussion and interim conclusions

Study II investigated the neurophysiology underlying prosodic boundary processing at different developmental stages in language learning by measuring the associated ERPs. More specifically, it was sought to capture the influence of syntactic phrase structure knowledge on the mechanisms of children's prosodic phrase processing, by testing IPB processing in 21-month-old, 3-year-old and 6-year-old children. The rationale of this approach was that – as children acquire a great deal of morpho-/syntactic knowledge between their second and third year of life – children at the age of 3 years, and especially at 6 years, have already passed this developmental phase, while 21-month-olds have not.

For 21-month-olds, the ERP in response to Naturally spoken sentences with IPB revealed no positive shift, thus indicating no processing differences between sentences with and without IPB. Accordingly, analyses relative to the NP2 onset after the pause uncovered an obligatory onset response but no onset-preceding positivity, with the latter as a potential indicator of IPB perception similar to the adult CPS. It follows that at an age when toddlers have not yet acquired sufficient syntactic phrase structure knowledge, they continue to detect speech boundaries by low-level acoustic processes, rather than by higher-order perception of combined prosodic boundary cues to IPs.

In contrast, for both 3-year-olds and 6-year-olds, a pronounced positive shift was observed to sentences with IPB, suggesting an adult-like CPS. This was confirmed by the analysis relative to the NP2 onset after the pause that delivered a pronounced onset effect, which, however, was preceded and enhanced by a positive shift starting prior to the NP2. Here, the spatial decomposition of the ERP data obtained from 6-year-olds confirmed the occurrence of two temporally overlapping ERP components. Both these effects merged into the observed pronounced positivity in sentences with IPB. Thus, in the older children, IPBs evoked both lower-level detection of an acoustic interruption, reflected in obligatory components, and boundary perception indicated by an adult-like CPS.

Taken together, the results of *Study II* demonstrate developmental differences in IPB processing, which are directly linked to children's progress in language acquisition. Here, the CPS in response to IPBs was observed at an age when children are more linguistically advanced and have gained some syntactic phrase structure knowledge. To fully rate the implications of these results, they need to be viewed with respect to the available evidence of prosodic phrase processing in children and adults.

Regarding the processing of phrasal prosody during language acquisition, behavioral studies have demonstrated infants' early sensitivity to prosodic boundary information (e.g., Christophe, Mehler, & Sebastián-Gallés, 2001) and their evolving ability to utilize prosodic boundary cues for speech segmentation at both clause and phrase level (Nazzi, Kemler Nelson, et al., 2000; Seidl, 2007; Soderstrom, Nelson, & Jusczyk, 2005; Soderstrom et al., 2003). The relevance of prosodic cues in speech segmentation has, for example, been demonstrated in an artificial language study (Thiessen, Hill, & Saffran, 2005), where 7- and 8-month-olds' word segmentation from fluent speech was facilitated, when presented with infant-directed speech (i.e., containing exaggerated prosody), but not when presented with adult-directed speech. This evidence is in line with the prosodic bootstrapping hypothesis

(e.g., Gleitman & Wanner, 1982) that states that infants initially rely on prosodic cues to identify linguistically relevant units in the speech stream and thus eventually arrive at the syntactic structure of their target language at later developmental stages. In this context, the ERP results of *Study I* on IP processing in 5-month-old infants suggest that these early processes reflect lower-level perceptual processing, such as the detection of speech interruptions by salient acoustic cues.

For adults, prosodic information has been shown to play an important role in sentence comprehension, since prosodic boundary cues signal syntactic structure and can thus guide syntactic parsing, which becomes particularly relevant in syntactic ambiguities (e.g., Marslen-Wilson et al., 1992; Nagel et al., 1996; Schafer et al., 2000; Warren, Grabe, & Nolan, 1995). In adult ERP studies, the processing of IPBs has been found to evoke a particular ERP component, the CPS, which was interpreted as an indicator for the perception of closure by prosodic phrase boundaries or, more generally, as being related to the cognitively-driven process of structuring incoming speech and redirecting attention to the subsequent input (Steinhauer, Alter, & Friederici, 1999).

Given that *Study II* has delivered evidence that children at the age of 3 years show a CPS in response to IPBs but children at the age of 21 months do not, the question arises how these facts on prosodic processing – that at first sight seem inconsistent – may be reconciled. Specifically, why does the CPS as an electrophysiological indicator of IPB processing only emerge between a child's second and third year, given that prosodic cues are among the earliest information infants can perceive from spoken language. The discussion of these issues is approached by first looking at the mechanisms of phrase-level prosodic processing in adults, followed by a discussion of these processes in children.

In adult sentence processing, the ERP component CPS has been observed in response to IPBs, which divide the continuous speech stream into prosodic units, such as IPs (e.g., Pannekamp et al., 2005; Steinhauer, Alter, & Friederici, 1999). Accordingly, the CPS has been interpreted as an indicator for the perception of prosodic phrasing, enabling the structuring of incoming speech based on prosodic boundary cues. However, as Steinhauer and colleagues have pointed out, the data as such do not allow for excluding an alternative, although closely related, explanation. Since in natural speech most prosodic boundaries are also syntactic boundaries, both kinds of boundary information are available at most speech breaks and either one can trigger segmentation. It follows that the CPS might be an indicator of prosodic or syntactic structuring abilities. This issue was further addressed by

Pannekamp and colleagues, who studied IPB processing in sentences with differing linguistic content (Pannekamp, 2005; Pannekamp et al., 2005). Most importantly, the authors used *inter alia* hummed speech material, which contained only suprasegmental information, while all segmental information (lexico-semantic and syntactic) was removed. Given that a CPS was even evoked in response to IPBs in hummed sentences (i.e., independently of the presence of segmental information), the authors concluded that the CPS indeed reflects the processing of prosodic phrasing. However, in this study, subjects have not been screened for their listening behavior. Given adults' fully established structural knowledge, prosodic information might automatically trigger attempts to map prosodic onto syntactic information. This could have been captured by asking subjects about their listening behavior, possibly revealing an intentional reasoning about the sentence structure. Thus, the described data still leave open the question of whether the CPS reflects processing of prosodic phrasing *per se* or whether it indicates structure perception based on syntactic knowledge, with prosodic cues – given the highly functional prosody-syntax interface in adult language comprehension – being sufficient to trigger these processes.

Accordingly, in language acquisition, the emergence of the CPS between children's second and third year might indicate the interdependence of prosodic and syntactic knowledge in the evolving ability to perceive structural units at higher-cognitive processing levels. At early stages of language learning, the perception of salient acoustic cues provides an entry into the discovery of speech units. These processes eventually contribute to the comprehension of language as being organized in structural units related by means of syntactic rules. The arising syntactic knowledge in turn reinforces the perceptually-driven analysis of the speech input, so that both processes develop interdependently until some syntactic structure knowledge has been gained. The emergence of the CPS after a developmental period in language acquisition, during which children significantly advance their syntactic skills, might thus indicate that children have gained a *concept* of speech structure based on syntactic knowledge and triggered by the tightly-linked phrase-level prosodic cues in the speech input.

Given the close interaction of prosodic and syntactic cues in the perception of speech boundaries, it seems essential to further disentangle the neurophysiology underlying the processing of both kinds of linguistic information. The first ERP study to address the dissociation of prosodic and syntactic boundary processing was recently introduced by Kerkhofs et al. (2007). The authors investigated

phrase processing in discourse by creating matches and mismatches of syntactic and prosodic boundaries. This was realized by establishing expectations of the occurrence or absence of a syntactic break, which was either met or not met by the occurrence of a prosodic break. The authors found that the CPS at the prosodic break was smaller in amplitude, when it was aligned with a syntactic break than when it was not aligned with a syntactic break. Unfortunately, the authors did not report all results of their crossed design, which also included the establishment of an expected syntactic boundary that was not accompanied by a prosodic break. Although these data make an important contribution to providing evidence of the interaction between prosodic and syntactic boundary cues in discourse comprehension, the interpretation of the reported effects demands some caution, given that crucial comparisons regarding the CPS were made across match and mismatch conditions. Thus, a drawback of the described study is the use of a violation paradigm, which introduces additional processes to the subject of interest, namely boundary processing. As previously discussed, in natural language, prosodic and syntactic boundary information are difficult to disentangle without violating language constraints. One possibility to overcome this problem is the use of artificial language studies, which have been utilized to simulate second language learning in adults and also provide insights in respect of first language acquisition (e.g., Bahlmann, Gunter, & Friederici, 2006; Friederici, Steinhauer, & Pfeifer, 2002; Mueller, Bahlmann, & Friederici, 2008). In such an approach, prosodic and syntactic cues can, in principle, be manipulated independently in signaling the respective boundary without creating violation conditions, since syntactic rules are yet to be acquired.

Interim conclusions

In conclusion, the results of *Study II* deliver neurophysiological evidence illustrating developmental differences in IP processing during language acquisition. The fact that children at the age of 21 months do not yet show a CPS in response to IPBs (Hypothesis 1) but older children aged 3 and 6 years do (Hypotheses 2 & 3), suggests that the syntactic knowledge emerging within this developmental period has an influence on the mechanisms underlying prosodic phrase processing. Here, children might initially detect prosodic breaks via lower-perceptual processing mechanisms until a degree of syntactic structure knowledge is formed through continued language experience that in turn reinforces the ability of children to perceive prosodic phrasing at a cognitive level.

Chapter 10

General discussion and future directions

The present studies investigated the neurophysiology underlying phrase-level prosodic processing during early infancy and preschool age. In addition to examining IP processing across developmental stages, it was sought to 1) specify the role of the pause as prosodic boundary cue and 2) evaluate the interaction between prosodic processing abilities and the progression of syntax acquisition at different age levels. ERP recordings were the method of choice, as they provide an online measure of information processing in the brain and have been successfully proven a suitable research tool to study the brain mechanisms of early language acquisition. In contrast to behavioral studies, the ERP method allows for investigating ongoing stimulus processing at different levels, from perceptual to cognitive stages. Using ERPs, it is possible to determine whether infants' and children's responses to intonational phrasing are primarily attributable to lower-level processing of acoustic stimulus features reflected in obligatory components (such as the adult N1-P2 complex; Crowley & Colrain, 2004; Näätänen & Picton, 1987) or whether they indicate higher-level cognitive processing reflected in the CPS (Steinhauer, Alter, & Friederici, 1999).

10.1 Summary of Study I

In language acquisition, infants are faced with the challenge to segment the continuous speech stream into relevant linguistic units, before further learning can take place. As proposed by the prosodic bootstrapping hypothesis, infants approach this segmentation problem by relying on prosodic information in the speech input (e.g., Gleitman & Wanner, 1982). Spoken language contains various acoustic cues – such as pause and durational differences and changes in fundamental frequency – that conjointly

signal prosodic boundaries. Given the close match of prosodic and syntactic structure, it follows that for infants, the detection of these prosodic boundaries delivers a first good guess as to where syntactic boundaries occur in continuous speech, providing the basis for further lexical and syntactic learning. While behavioral studies have revealed evidence of English-learning infants' early sensitivity to prosodic phrasing, the underlying neurophysiological basis remains widely unknown. In this context, it is still under discussion which acoustic cues are required to trigger the perception of prosodic boundaries in a given language at different developmental stages. So far, research has been mainly carried out for English stimulus material (e.g., Seidl, 2007). However, the weighting of particular cues might differ cross-linguistically, since for example English and German intonation systems differ with respect to the particular acoustic realization of IPs (Delattre, 1966; see also Markus, 2006). Given these considerations, *Study I* sought to determine the neurophysiological basis of IP processing in 5-month-old German infants and adults and, furthermore, specify the role of the pause as one of the three acoustic parameters signaling prosodic boundaries.

This was realized in two experiments where infants and adults were presented 1) with Naturally spoken sentences with and without IPB and 2) with the same sentences, where the boundary pause had been deleted in the sentences with IPB. For adults, ERP analyses revealed a CPS and obligatory N1-P2 responses to both Naturally spoken sentences with IPB and Sentences with neutralized pause (with IPB). Given that IPBs evoked boundary perception (and the lower-level detection of an acoustic interruption) even when the pause at the IPB was deleted, it follows that in adults, preboundary lengthening and pitch change are sufficient to signal prosodic breaks, independent of the presence of a boundary pause (see also Steinhauer, Alter, & Friederici, 1999). In infants, IPBs elicited infant obligatory components, but not an adult-like CPS, indicating that infants detect speech interruptions by low-level acoustic processes, rather than by higher-order perception of combined prosodic boundary cues to IPs. For Sentences with neutralized pause (with IPB), the obligatory response to IPBs disappeared, suggesting that infants process sentence interruptions caused by acoustic cues only when the prosodic break is signaled by a pause. Taken together, the results revealed developmental differences regarding both the underlying nature of IP processing and the role of the pause in IP processing. Furthermore, the comparison with behavioral studies in English-learning infants' IP processing suggests cross-linguistic differences.

10.2 Pauses and intonational phrasing: When infants learn German

In the previous discussion of the results, two interpretations regarding the ability of 5-month-olds to process IPs have been offered. First, given that German infants at 5 months show obligatory components, but no CPS, in response to IPBs, they may not yet be able to process IPBs. Instead, infants process mere speech interruptions that are marked by a pause and, consequently, infants show no detection of an acoustic break in the absence of the pause (as in the Sentences with neutralized pause at the IPB). Second, German-learning infants at this age may be able to process IPBs, but only if the prosodic boundary, although composed of several acoustic cues, is indicated by a boundary pause. These processes happen at a lower-perceptual stage and are not yet indicated by a CPS, as is the case for adults.

As the current ERP study in German infants is the first to investigate the neurophysiological correlates of IP processing at this young age, there is no further evidence to decide, which of the alternatives is correct. Here, the results of an ongoing ERP study (being carried by the author) will contribute towards an increased understanding of this issue by comparing German-learning 5-month-olds' processing of pauses at prosodic boundary positions with pauses at non-boundary positions. In this new study, the original stimulus material has been altered, resulting in the following two sentence types: Sentences with IPB and Sentences without IPB, for which, however, artificial pauses were inserted at one of four possible sentence positions. Importantly, pauses in the first sentence type coincide with other phrase boundary cues, i.e., preboundary lengthening and pitch change, while pauses in the second sentence type do not. The results of this study will reveal whether infants process pauses in sentences differently when they are related to other boundary cues than when they are not. In this context, the occurrence of processing differences would implicitly point to infants' ability to process IPBs. Independent of which of the above interpretations will be favored by these new findings, the current data allow for two conclusions: First, infants' processing of breaks in the speech signal happens at a lower-order perceptual level, and second, the pause is a particularly salient cue in the processing of those breaks by German infants.

Regarding the first conclusion, the current ERP results in infants and adults imply that the neurophysiological mechanisms underlying IP processing change across development stages (for adult

data, see also Pannekamp et al., 2005; Steinhauer, Alter, & Friederici, 1999). It has been surmised that during early stages of language acquisition, infants initially start speech segmentation by detecting salient acoustic cues in the speech input, such as silences or large pitch changes. These cues signal the location of constituents and enable infants to bootstrap into other cues associated with the edges of these constituents (i.e., prosodic bootstrapping hypothesis). With respect to artificial grammar studies, Mehler, Endress, Gervain, and Nespor (2008) offer a similar discussion of perceptual mechanisms in language learning. The authors illustrate how the findings of most studies on artificial grammar learning can be explained by *perceptual primitives*, such that language learners direct their attention to repetitions and acoustically marked edges of speech units in the language input. As language acquisition progresses, children learn that certain acoustic cues correlate and conjointly mark structural units. These processes are believed to be represented by different underlying neurophysiological mechanisms: 1) the attention to salient acoustic cues represented by sensory processing mechanisms (obligatory ERP responses); and 2) the perception of a boundary as a correlation of several cues, i.e., one integrated percept, represented by cognitive processing mechanisms (CPS response). Thus, the acquisition of the concept of a prosodic boundary is viewed as a gradual process that develops out of the early response to acoustically salient cues, such as pauses.

Further developmental research is required to pinpoint the actual time course of the proposed progression in phrase-level prosodic processing. Here, the ERP study by Pannekamp, Weber, and Friederici (2006) has made an important contribution to the subject. This study was the first to address IP processing during children's first year. The authors recorded ERPs in 8-month-olds and reported a CPS-like positive shift in response to IPBs, thus suggesting a developmental shift in IP processing between the age of 5 and 8 months. However, given the particular analysis of the ERP data in 8-month-olds (i.e., without directly relating sentence and NP2 onset to specify the nature of the observed positive shift), similar low-level perceptual mechanisms are assumed to be active at this age, as for 5-month-olds. The supposition that the reported positive shift in 8-month-olds does not yet represent an adult-like CPS finds indirect support by the results of Study II that indicate that the CPS only emerges between children's second and third year (see 10.3). Final conclusions may not be drawn until the data in 8-month-olds are replicated and subjected to the same analyses as applied for the younger infants. Taken together, further developmental studies need to determine when the

processes indicated by the CPS emerge and specify under which circumstances they are likely to be elicited. Regarding the first point, it is recommended that studies define particular qualifications on the listener's side, e.g., children's developmental stage (see Study II). With respect to the second point, further studies are required to describe characteristics of the language input that influence boundary detection at different developmental stages, such as boundary strength (e.g., larger prosodic units are marked more pronouncedly than smaller units; Cooper & Paccia-Cooper, 1980) and the presence of particular boundary cues (see developmental and cross-linguistic differences in the weighting of prosodic boundary cues, below).

Since the comparison of infant and adult ERP data revealed developmental differences in the role of the pause as a boundary cue (see also Steinhauer, Alter, & Friederici, 1999), it was concluded that pausing is a particularly relevant cue in German-learning infants' processing of speech breaks. The differential weighting of acoustic cues might change, as language acquisition progresses. Once children have successfully gained some knowledge of the structure of their native language and are thus not entirely dependent on prosodic markers, pausing may no longer be of the same importance. Interestingly, in a behavioral study with adults, Beach (1991) observed that in syntactic ambiguity resolution, duration and fundamental frequency stand in a *cue trading* relation. It follows that prosodic boundary perception can be viewed as an interactive process, where in the absence of one boundary cue, the other cues become more relevant. Thus, once children have acquired the concept of a boundary as a correlation of several cues, less prosodic information might be sufficient to trigger boundary perception, with the remaining cues standing in, for example, for the absent pause. However, reliance on the pause as boundary cue is still observed in adults when the language input is not well phrased and is prosodically ambiguous. Dankovicová, Pigott, Wells, and Peppé (2004) recorded speech from English-speaking 8-year-old children, who used both pausing and preboundary lengthening to mark prosodic boundaries, but did not do so reliably. When adults were asked to rate the certainty of the presence of prosodic boundaries, they used both types of prosodic cues as predictors but were more reliant on pausing. Thus, the uncertainty in adults' phrase processing caused by the prosodically unreliable structure might be to some degree comparable with the situation infants have to face in language learning, where knowledge of relevant structural units still needs to be acquired. In both

learning situations, listeners utilize all of the available prosodic information to segment the language input, with pauses being particularly important.

Additional evidence for the significant role of pauses in language learning comes from studies on the acquisition of artificial grammar, for instance in German-speaking adults (Mueller, Bahlmann, & Friederici, 2008). In this study, syntax acquisition was modeled using rule-based versus random strings of pseudowords to demonstrate how rule acquisition is bolstered by the presence of pauses placed between the units of individual sequences. Although rule-learning was also observed without pauses, it was more effective when pauses were present (see Pena, Bonatti, Nespor, & Mehler, 2002).

Developmental differences in the weighting of acoustic cues in boundary perception have also been revealed in studies using English stimulus material. Behavioral studies in adult listeners suggest that they rely more heavily on both pitch changes and preboundary lengthening than on pausing (Aasland & Baum, 2003; Scott, 1982; Streeter, 1978; Wightman et al., 1992). For English-learning infants, Seidl (2007) found that pitch plays an important role in phrase boundary perception. Although pitch alone was not sufficient to trigger phrase boundary perception, it was a necessary cue, converging with either preboundary lengthening or with pausing (Seidl, 2007). Similarly, Gerken, Jusczyk, and Mandel (1994) observed that infants are sensitive to the combination of preboundary lengthening and pitch change as boundary information, but not to one of these cues alone. Thus, there is some corroborating evidence for the English language, that infants and adults weight specific boundary cues differently in the perception of phrasal units. In adults, only the manipulation of boundary length, but not of pausing, affected speech segmentation, whereas in infants, one of these cues needed to be combined with particular pitch characteristics. Importantly, the results of these studies do not only support the notion of developmental differences but also point to cross-linguistic differences in the weighting of prosodic boundary cues. Specifically, the study by Seidl (2007) included an experiment where 6-month-olds were presented with sentences lacking pauses as boundary information. This experiment revealed that infants were able to segment clauses from text passages even without pauses at boundary locations. Assuming that the infant ERP study and the named behavioral study examine similar prosodic processing abilities, cross-linguistic differences seem to be a critical factor, since the absence of the pause cue matters to German-learning 5-month-olds but not to English-learning 6-month-olds.

The interpretation of cross-linguistic differences can be approached by evaluating intonational characteristics of the infants' respective language input. In this context, a related study revealed that German-learning and French-learning infants as young as 4 months are already tuned to language-specific prosodic patterns, as they showed a native language-specific preference for how stress was applied to bisyllabic words (Friederici, Friedrich, & Christophe, 2007). With respect to intonation differences, English and German feature a differential acoustic marking of IPs, with English applying pitch as a predominant marker, while in German length and loudness are equally important (Delattre, 1966; Markus, 2006). The prominence of pitch variations in English has been validated in a cross-linguistic analysis of infant-directed speech. While in all of the studied languages, parents used more pronounced prosodic cues when speaking to infants, American English parents used the most exaggerated speech regarding intonational modifications (Fernald et al., 1989). In contrast to English, German features a larger number of inflections and discourse particles and a relatively flexible word order that most likely serve functions represented by intonation patterns in other languages (see, e.g., Schubiger, 1980). Consequently, German obtains a lower number of intonation patterns and a reduced range of pitch variation (see Gibbon, 1998; Markus, 2006). In this context, it seems plausible that in German, pausing plays a role as an additional structuring device (see Butcher, 1981). Interestingly, Schmitz (2008) found that German-learning 6-month-olds are sensitive to variations in pause length. In these behavioral studies, infants were only able to differentiate between sentences with pauses either inserted at syntactic boundaries or non-boundaries when the respective pause lengths reflected the structure of natural speech. Thus, even young infants seem to possess some knowledge of natural pause hierarchies. Here, comparative studies are required that target English-learning infants' sensitivity to pause length. These studies may deliver further evidence of early language-specific tuning, since English-learning infants, who seem to be particularly reliant on pitch in boundary perception, but not on pausing, may not possess pause-specific knowledge comparable to their German peers.

The explanation of an early influence of native-language experience on the weighting of prosodic boundary cues finds support through a recent behavioral study of Dutch-learning 6-month-olds' ability to segment clauses from fluent speech (Johnson & Seidl, 2008). This study paralleled the experiments in English-learning 6-month-olds in measuring infants' ability to discriminate between well-formed and ill-formed clausal units embedded in larger sequences when prosodic boundaries

were signaled by different boundary cues (Seidl, 2007). Results revealed that Dutch 6-month-olds, like the English infants, readily perceived clausal units, but Dutch infants were more reliant on the boundary pause than English infants. Given that Dutch, comparable to German, features a narrower pitch range than English (Willems, 1982), this result adds further evidence to the explanation of cross-linguistic differences. In future studies, it will be necessary to investigate language-specific weighting of prosodic boundary cues across a larger number of languages, for example French, where preboundary lengthening may play a particularly important role, since French applies word-final stress, mostly marked by duration (e.g., Di Cristo, 1998).

Regarding the developmental course of prosodic boundary processing, another recent study by Seidl and Cristia (2008) provides new input for the discussion of developmental differences in cue weighting. The authors studied even younger English-learning infants' ability to segment clauses and found that 4-month-olds, in contrast to the 6-month-olds, required the presence of each of the three acoustic boundary cues for clause segmentation. These results imply a developmental shift between 4 and 6 months in the ability of English-learning infants to segment clauses, such that the younger infants rely on all of the available acoustic boundary information, while for the older infants the weighting of particular cues changes as a function of native-language experience (e.g., with pitch being the most important cue for English-learning infants).

Based on these behavioral studies on infants' ability to segment clauses, the ERP data of German-learning 5-month-olds can be interpreted by means of both cross-linguistic and developmental differences. First, German infants may be generally more reliant on the pause, given the intonational characteristics of their native language. Second, the developmental stage of the tested German infants may fall within the developmental phase described for the English-learning 4-month-olds. Infants at this age are not yet acquainted with the language-specific weighting of prosodic boundary cues and therefore, infants require all cues to be present for boundary detection. A related explanation is that the *concept* of a prosodic boundary has not yet been acquired, so that only the combination of all available cues provide sufficient acoustic information to trigger boundary detection. Taken together, the reported behavioral studies indicate that the age of 4 to 6 months is a highly sensitive developmental phase regarding phrase-level prosodic processing. In future studies, combined neurophysiological

and behavioral measures across both languages may allow for further specification of the exact time course of and the respective conditions for IP processing.

10.3 Summary of Study II

Numerous studies on adult language processing and production have shown a close interaction of prosodic and syntactic information. More specifically, phrase-level prosody can influence syntactic parsing preferences and thus aid syntactic ambiguity resolution (e.g., Kjelgaard & Speer, 1999; Marslen-Wilson et al., 1992; Schafer et al., 2000; Warren, Grabe, & Nolan, 1995). In turn, prosodic phrasing is highly determined by syntactic structure, with nearly every prosodic boundary also being a syntactic boundary (e.g., Ferreira, 1988; Gee & Grosjean, 1983; Selkirk, 2000; Truckenbrodt, 1999). As prosodic information is known to play a key role in the initial stages of language learning (e.g., Gleitman & Wanner, 1982) and given the close interaction of prosodic and syntactic information, further studies of phrase-level prosodic processing at different stages of syntax acquisition are required. In this context, it has been hypothesized that the neurophysiological correlates of IP processing change as a function of syntactic structure knowledge acquired at different age levels. As syntactic rules become particularly relevant between children's second and third year, when they start to speak in sentences, studies on syntax perception and production have shown that during this period children acquire a great deal of (morpho)-syntactic knowledge (see Guasti, 2002; Hirsh-Pasek & Golinkoff, 1996). Similarly, ERP studies have revealed a developmental shift in syntactic phrase structure processing between the age of two and three years (Oberecker, Friedrich, & Friederici, 2005; Oberecker & Friederici, 2006). To investigate whether syntactic phrase structure knowledge has an impact on the emergence of the CPS, *Study II* examined the neurophysiological correlates of IP processing in children before and after this developmental phase in syntax acquisition, by testing children at 21 months, 3 years and 6 years. Children at the age of 3 years, and especially at 6 years, have already passed the supposed developmental phase, while 21-month-olds have not.

In three experiments, children at the age of 21 months, 3 years and 6 years were presented with Naturally spoken sentences with and without IPB. For 21-month-olds, ERP analyses revealed an obligatory component in response to IPBs, suggesting that when toddlers have not yet acquired sufficient syntactic phrase structure knowledge, they still detect speech boundaries by low-level acoustic

processes, rather than by higher-order perception of combined prosodic boundary cues to IPs. In contrast, for 3-year-olds and 6-year-olds, both obligatory components and an adult-like CPS were observed in response to IPBs, suggesting that in these older children, IPBs triggered both lower-level detection of an acoustic interruption and higher-level perception of combined boundary cues. In summary, these results highlight developmental differences in IP processing dependent on children's progress in language acquisition.

10.4 Prosody and syntax in language acquisition: An interactive relationship

In the discussion of the results so far, it has been surmised that while children do not yet show a CPS in response to IPBs at 21 months, but instead at 3 years, these results do not necessarily contradict 1) findings on the early ability of infants to process prosodic information nor 2) evidence from ERP studies that describe the CPS as an electrophysiological indicator of IP processing in adults.

More specifically, with respect to the first point, it was outlined how in the initial stages of language learning, infants rely on prosodic cues to identify linguistically relevant units in the speech stream. The prosodic bootstrapping hypothesis postulates that this reliance enables children to eventually arrive at the syntactic structure of their target language at later developmental stages (e.g., Gleitman & Wanner, 1982). In support of this idea, behavioral studies have provided ample evidence of infants' early sensitivity to prosodic boundary information (e.g., Christophe, Mehler, & Sebastián-Gallés, 2001) and their evolving ability to utilize prosodic boundary cues for speech segmentation at both clause and phrase level (Nazzi, Kemler Nelson, et al., 2000; Seidl, 2007; Soderstrom, Nelson, & Jusczyk, 2005; Soderstrom et al., 2003).

Regarding the second point, adult ERP studies on IP processing have revealed a particular ERP component in response to IPBs, the CPS, which is interpreted as an indicator for the perception of closure by prosodic phrase boundaries or, more generally, as being related to the cognitively-driven process of structuring incoming speech (Steinhauer, Alter, & Friederici, 1999). It was reasoned that the CPS might indicate either prosodic or syntactic structuring abilities, since in natural speech, most prosodic boundaries are also syntactic boundaries. However, the fact that the CPS was also observed in hummed sentences (containing only prosodic information), led to the conclusion that the CPS in fact reflects the processing of prosodic phrasing (Pannekamp, 2005; Pannekamp et al., 2005).

This seeming contradiction between the children ERP data, collected in this thesis, and the evidence cited above may be reconciled through the consideration of interactive processes between prosodic and syntactic information. For phrase-level prosodic processing in adults, it has been highlighted that the CPS is evoked, even when only prosodic information is available to signal boundaries, as in hummed sentences (Pannekamp, 2005; Pannekamp et al., 2005). However, given the highly functional prosody-syntax interface in adult language production and processing, one type of information might automatically trigger the other. First, when adults are presented with segmental information only (lexico-semantic and syntactic), such as in written language, they typically experience an *inner voice* (Chafe, 1988). Since written words activate their phonological representations, i.e., phonological recoding (e.g., Share, 1999), intonational patterns are also perceived during reading, where the subvocal activation of prosodic phrasing facilitates the structuring and segmentation of the visual speech input. Steinhauer and Friederici (2001) examined the role of implicit prosody during reading, with commas as triggers of prosodic phrasing (see also Steinhauer, 2003). In one experiment, the authors observed a CPS to the comma-induced boundaries, which was similar to the CPS in the auditory domain, although smaller and of shorter duration (see Steinhauer, Alter, & Friederici, 1999). In a subsequent experiment, the authors found the same comma-induced CPS when subjects replicated sentence melodies (of previously heard low-pass filtered sentences) during silent reading. These results provide evidence of prosodic processes (*inner voice*) during reading, since commas automatically initiated subvocal prosodic phrasing, reflected in a CPS. On the other hand, when adults are presented with suprasegmental information only, as in hummed sentences, prosodic information might automatically initiate access to syntactic structure. In other words, while listening to hummed sentences, the perceived prosodic information might automatically trigger attempts to map prosodic onto syntactic information. From these considerations, it follows that the adult data available so far cannot sufficiently clarify whether the CPS reflects processing of prosodic phrasing per se or whether it indicates structure perception based on syntactic knowledge triggered by prosodic cues.

Similarly, phrase-level prosodic processing during infancy and childhood can be viewed by taking into account the interdependence of prosodic and syntactic information. While in adult processing, structural knowledge is fully established, the language learner has to first reach a stage, at which syntactic representations are formed, such as syntactic categories and syntactic phrase structure rules.

In this context, the emergence of the CPS between children's second and third year may indicate the interdependence of prosodic and syntactic knowledge in the evolving ability to perceive structural units at higher-cognitive processing levels. More specifically, at early stages of language learning, the perception of salient acoustic cues provides an entry into the discovery of speech units. Here, the results of Study I indicate that these processes happen at a lower-perceptual processing level. Continued speech segmentation ultimately results in the perception of speech breaks as a correlation of several acoustic cues (i.e., one integrated percept), so that less acoustic information may be sufficient to trigger boundary perception. These prosodically-driven processes eventually contribute to the comprehension of language as being organized in structural units related by means of syntactic rules. The resulting syntactic knowledge may in turn reinforce the perceptually-driven analysis of the speech input, so that both processes develop interdependently until some syntactic structure knowledge has been gained. The emergence of the CPS after a developmental period in language acquisition, during which children significantly advance their syntactic abilities, may indicate that children have gained a *concept* of speech structure based on syntactic knowledge and triggered by the tightly-linked phrase-level prosodic cues in the speech input.

In this context, further ERP studies are required to specify boundary perception in preschool children by targeting their reliance on the pause as boundary cue. Although ERP data for both 3- and 6-year-old children revealed a CPS in response to IPBs, both age groups may rely differently on pausing in boundary perception. Here, 6-year-olds are expected to be similarly flexible as adults in boundary processing, reflected in a CPS even in the absence of the boundary pause (see current results of the study with Sentences with neutralized pause, and Steinhauer, Alter, & Friederici, 1999). For 3-year-olds, the results of these studies will reveal whether or not these children are still reliant on the pause in boundary perception, given that at this age, the newly established structure representations may not yet be as stable and therefore support from all available cues is needed.

Hirsh-Pasek and Golinkoff (1996) propose a *Coalition model of language comprehension*, in which they deal with the relevance of different kinds of linguistic information at various stages of language acquisition. In their three-phase model of the development of language comprehension, the authors suggest the following stages: 1) *Phase I* at about 0-9 months – with the acquisition processes of extracting and acoustic packaging, 2) *Phase II* at about 9-24 months – with segmentation

and linguistic mapping, and 3) *Phase III* at about 24-36 months – with complex syntactic analysis. As is evident, each phase is signified by a different predominant acquisition process. Within this developmental framework, linguistic information in the language input is viewed as a coalition of cues (e.g., prosodic, lexical, semantic, and syntactic) that is, theoretically, constantly available to the child. However, these cues are not equally accessible to children at all points in their development and are relevant at different phases. At first, infants are drawn to the acoustic features of the input and use the perceived acoustic markers as a guide to segment and unitize linguistically relevant units. In the second step, infants begin to perform analyses within the segmented units and map words and phrases onto the corresponding objects and events. Furthermore, children show evidence of sentence comprehension, but only when supported by the redundant correlation of several linguistic cues. In the last phase, children's reliance on correlated cues decreases with the arising ability to perform syntactic analyses. At this stage, they can also compute inter-clausal relations to further derive meaning (i.e., in the absence of described events). When relating the age of the tested children in the current ERP studies to the model, the infant studies target Phase I, while the children studies span across Phases II and III, thus including a developmental shift. As suggested in the Coalition model of language comprehension, the results of Study I revealed that infants are sensitive to salient acoustic cues in the speech signal, especially pauses, with the ERP effects indicating lower-level processing. With respect to Study II, 21-month-olds fall within Phase II, where children are primarily reliant on semantic cues and only possess an unstable knowledge of syntax that requires reinforcement by other cues, for example, the corroboration of word order by semantics (e.g., *The cat chased the mouse* versus *The mouse chased the cat*). The ERPs of these children did not show a CPS in response to IPBs, leading to the conclusion that children at this age continue to detect speech boundaries by lower-level acoustic processes, rather than through higher-order perception of correlated prosodic boundary cues. In contrast, the tested 3-year-olds rank toward the end of Phase III, where children start to analyze grammatical relations within sentences and thus can comprehend more complex utterances. ERPs of the 3-year-old children revealed a CPS in response to IPBs, suggesting that once children have acquired sufficiently robust syntactic knowledge, they process speech structure marked by prosodic cues at higher-level cognitive stages. Taken together, the current ERP results, tracing the emergence

of the CPS between the age of 21 months and 36 months, add support to the notion of a developmental transition at around 24 months, as proposed by the Coalition model (Hirsh-Pasek & Golinkoff, 1996).

As further evidenced in studies of syntax acquisition (e.g., Gertner, Fisher, & Eisengart, 2006; Soderstrom, 2003), starting at the end of children's second year, a developmental shift occurs, during which syntax becomes increasingly relevant. In this context, further studies are required to narrow down the time frame of and specify the conditions for the emergence of the CPS. This points to a drawback of the ERP studies of this thesis, where the developmental stage of the children was defined by their age (although the age groups were selected using evidence of syntax acquisition). Assuming children have mastered certain steps in syntax acquisition before they show a CPS in response to IPBs, this progress should be evident in children's syntax comprehension. In future studies, the degree of children's syntactic knowledge should be validated by an external test criterion, rather than using age per se. First, this approach would allow for specifying the type of syntactic knowledge that has an impact on the emergence of the CPS. Second, this method would account for inter-individual differences in syntax acquisition, since ERP responses to prosodic phrasing can be correlated with individual test scores. As outlined, between their second and third year, children show an increasing ability to compute sentential relations, e.g., word order and inflections. Accordingly, children can be tested on their knowledge of word order rules, i.e., *verb second position* (in main clauses) in German. The acquisition of the *verb second* rule is essential to further syntactic analyses and is typically accomplished by the age of 2.5 years (Penner & Köllicker Funk, 1998). Knowledge of *verb second position* can be examined by testing the comprehension of wh-questions, e.g., *Was trinkt Anna?* (see Kauschke & Siegmüller, 2002; Subtest 17: *Verständnis von W-Fragen*). Once children have learned that the verb inherits the second position in the sentence, they can adequately answer wh-questions, since these questions target the first position, prior to the verb (e.g., *Anna trinkt Saft.*). Further external criteria of children's syntactic knowledge may be gained from a test of sentence comprehension in children at 2-8 years (Siegmüller, Kauschke, Bartke, & Bittner, in prep).

Given the interaction of prosodic and syntactic cues in signaling speech breaks, it seems essential to further disentangle the neurophysiology underlying the processing of both kinds of linguistic information. However, by virtue of the close match of prosodic and syntactic structure, the dissociation of prosodic and syntactic boundary processing is difficult to realize without creating violation conditions

that initiate collateral processing mechanisms, in addition to structure perception (see e.g., Steinhauer, Alter, & Friederici, 1999; for a prosody-induced gardenpath effect). In a recent study, Kerkhofs et al. (2007) investigated boundary processing in discourse and systematically varied the presence of prosodic and syntactic boundaries. This was realized by an experimental design with matches and mismatches of syntactic and prosodic boundaries. Here, an expectations of the occurrence or absence of a syntactic break was established, which was either met or not met by the occurrence of a prosodic break. Although these data make an important contribution to providing evidence of the interaction between prosodic and syntactic boundary cues in discourse comprehension, a drawback of this study is the use of a violation paradigm. For this reason, the interpretation of the results demands some caution, given that crucial comparisons regarding the CPS were made across match and mismatch conditions. Since in natural language, prosodic and syntactic boundary information are difficult to disentangle without violating language constraints, one possibility to overcome this problem is the use of artificial language studies. Artificial languages have been utilized to simulate second language learning in adults and also provide insights in respect of first language acquisition (e.g., Bahlmann, Gunter, & Friederici, 2006; Friederici, Steinhauer, & Pfeifer, 2002; Mueller, Bahlmann, & Friederici, 2008). In such an approach, prosodic and syntactic cues can, in principle, be manipulated independently in their function to signal the respective boundary without creating violation conditions, since syntactic rules defining the position of phrase and clause boundaries are yet to be established.

10.5 Conclusion

In conclusion, within the field of developmental cognitive neuroscience, the current thesis aims to contribute toward a better understanding of prosodic aspects in language acquisition. By means of ERPs, the present studies examined the neurophysiology underlying IP processing during early infancy and preschool childhood. The results provide evidence that early in their development, infants detect particularly salient acoustic cues in the speech input, which are likely contributors to the recognition of prosodic boundaries. During this period, children initially detect prosodic breaks via lower-perceptual processing mechanisms until such time as a degree of syntactic structure knowledge has been formed through continued language experience, which in turn reinforces their ability to per-

ceive prosodic phrasing at a cognitive level. It follows that during language acquisition, prosodic and syntactic information stand in a highly interactive relationship in the processing of speech structure.

References

- Aasland, W. A., & Baum, S. R. (2003). Temporal parameters as cues to phrasal boundaries: A comparison of processing by left- and right-hemisphere brain-damaged individuals. *Brain and Language*, 87(3), 385–399.
- Abercrombie, D. (1967). *Elements of general phonetics*. Edinburgh: University Press.
- Anderson, A. W., Marois, R., Colson, E. R., Peterson, B. S., Duncan, C. C., Ehrenkranz, R. A., et al. (2001). Neonatal auditory activation detected by functional magnetic resonance imaging. *Magnetic Resonance Imaging*, 19(1), 1–5.
- Armitage, S. E., Baldwin, B. A., & Vince, M. A. (1980). The fetal sound environment of sheep. *Science*, 208, 1173–1174.
- Astesano, C., Besson, M., & Alter, K. (2004). Brain potentials during semantic and prosodic processing in French. *Cognitive Brain Research*, 18, 172–184.
- 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(11), 1829–1842.
- Baum, S. R., & Dwivedi, V. D. (2003). Sensitivity to prosodic structure in left- and right-hemisphere-damaged individuals. *Brain and Language*, 87(2), 278–289.
- Baum, S. R., & Pell, M. D. (1999). The neural bases of prosody: Insights from lesion studies and neuroimaging. *Aphasiology*, 13(8), 581–608.
- Beach, C. M. (1991). The interpretation of prosodic patterns at points of syntactic structure ambiguity: Evidence for cue trading relations. *Journal of Memory and Language*, 30, 644–663.
- Beckman, M., & Edwards, J. (1990). Lengthening and shortening and the nature of prosodic constituency. In J. Kingston & M. Beckman (Eds.), *Papers in laboratory phonology I: Between the grammar and the physics of speech* (p. 152–178). Cambridge, UK: Cambridge University Press.
- Beckman, M., & Pierrehumbert, J. (1986). Intonational structure in Japanese and English. *Phonology Yearbook*, 3, 255–309.

- Bentin, S., Mouchetant-Rostaing, Y., Giard, M. H., Echallier, J. F., & Pernier, J. (1999). ERP manifestations of processing printed words at different psycholinguistic levels: Time course and scalp distribution. *Journal of Cognitive Neuroscience*, 11(3), 235–260.
- Blasko, D. G., & Hall, M. D. (1998). Influence of prosodic boundaries on comprehension of spoken English sentences. *Perceptual and Motor Skills*, 87, 3-18.
- Bosch, L., & Sebastián-Gallés, N. (1997). Native-language recognition abilities in four-month-old infants from monolingual and bilingual environments. *Cognition*, 65, 33-69.
- Bradley, D., Sanches-Casas, R., & Garcia-Albea, J. (1993). The status of the syllable in the perception of Spanish and English. *Language and Cognitive Processes*, 8, 197-233.
- Bradvik, B., Dravins, C., Holtas, S., Rosen, I., Ryding, E., & Ingvar, D. H. (1991). Disturbances of speech prosody following right hemisphere infarcts. *Acta Neurologica Scandinavica*, 84(2), 114–126.
- Brunia, C., Möcks, J., Berg-Lenssen, M. van den, Coelho, M., Coles, M., Elbert, T., et al. (1989). Correcting ocular artifacts in the EEG: A comparison of several methods. *Journal of Psychophysiology*, 3, 1-50.
- Bryan, K. (1989). Language prosody and the right hemisphere. *Aphasiology*, 3, 285-299.
- Butcher, A. (1981). Aspects of the speech pause: Phonetic correlates and communicative functions. In J. Barry & K. J. Kohler (Eds.), *Arbeitsberichte Nr. 15*. Universität Kiel, Institut für Phonetik und digitale Sprachverarbeitung.
- Cattell, R. B. (1966). The scree test for the numbers of factors. *Multivariate Behavioral Research*, 1, 629-637.
- Ceponiene, R., Lepisto, T., Alku, P., Aro, H., & Näätänen, R. (2003). Event-related potential indices of auditory vowel processing in 3-year-old children. *Clinical Neurophysiology*, 114(4), 652–661.
- Chafe, W. (1988). Punctuation and the prosody of written language. *Written Communication*, 5, 396-426.
- Chatrian, G. E., Lettich, E., & Nelson, P. L. (1988). Modified nomenclature for the "10%" electrode system. *Journal of Clinical Neurophysiology*, 5(2), 183–186.

- Christophe, A., Dupoux, E., Bertoncini, J., & Mehler, J. (1994). Do infants perceive word boundaries? An empirical study of the bootstrapping of lexical acquisition. *Journal of the Acoustical Society of America*, 95, 1570-1580.
- Christophe, A., Mehler, J., & Sebastián-Gallés, N. (2001). Perception of prosodic boundary correlates by newborn infants. *Infancy*, 2(3), 385-394.
- Christophe, A., & Morton, J. (1998). Is Dutch native English? Linguistic analysis by 2-month-olds. *Developmental Science*, 1, 215-219.
- Clark, E. V. (2003). *First language acquisition*. Cambridge, MA: Cambridge University Press.
- Clark, J., & Yallop, C. (1995). *An introduction to phonetics and phonology* (2nd ed.). Oxford: Blackwell.
- Clifton, C., Carlson, K., & Frazier, L. (2002). Informative prosodic boundaries. *Language and Speech*, 45, 87-114.
- Coch, D., Skendzel, W., & Neville, H. J. (2005). Auditory and visual refractory period effects in children and adults: An ERP study. *Clinical Neurophysiology*, 116(9), 2184-2203.
- Cohen, M. J., Branch, W. B., & Hynd, G. W. (1994). Receptive prosody in children with left or right hemisphere dysfunction. *Brain and Language*, 47(2), 171-81.
- Cohen Sherman, J., & Lust, B. (1993). Children are in control. *Cognition*, 46, 1-51.
- Cooper, N., Cutler, A., & Wales, R. (2002). Constraints of lexical stress on lexical access in English: Evidence from native and non-native listeners. *Language and Speech*, 45, 207-228.
- Cooper, R. P., & Aslin, R. N. (1990). Preference for infant-directed speech in the first month after birth. *Child Development*, 61(5), 1584-1595.
- Cooper, W., & Paccia-Cooper, J. (1980). *Syntax and speech*. Cambridge, MA: Harvard University Press.
- Creutzfeldt, O., & Houchin, J. (1974). Neuronal basis of EEG waves. In A. Rémond (Ed.), *Handbook of Electroencephalography and Clinical Neurophysiology* (Vols. 2, Part C, p. 5-55). Amsterdam, Netherlands: Elsevier.
- Crowley, K. E., & Colrain, I. M. (2004). A review of the evidence for P2 being an independent component process: age, sleep and modality. *Clinical Neurophysiology*, 115(4), 732-744.
- Cruttenden, A. (1997). *Intonation* (2nd ed.). Cambridge, UK: Cambridge University Press.

- Crystal, D. (1997). *A dictionary of linguistics & phonetics* (4th ed.). Oxford: Blackwell.
- Csibra, G., Henty, J., Volein, A., Elwell, C., Tucker, L., Meek, J., et al. (2004). Near infrared spectroscopy reveals neural activation during face perception in infants and adults. *Journal of Pediatric Neurology*, 2, 85-89.
- Cutler, A. (1994). Segmentation problems, rhythmic solutions. *Lingua*, 92, 81-104.
- Cutler, A. (2008). Lexical stress. In D. B. Pisoni & R. E. Remez (Eds.), *The handbook of speech perception* (p. 264-289). Oxford: Blackwell.
- Cutler, A., & Carter, D. M. (1987). The predominance of strong initial syllables in the English vocabulary. *Computer Speech & Language*, 2, 133-142.
- Cutler, A., Dahan, D., & van Donselaar, W. (1997). Prosody in the comprehension of spoken language: A literature review. *Language and Speech*, 40(2), 141-201.
- Cutler, A., Mehler, J., Norris, D. G., & Segui, J. (1986). The syllable's differing role in the segmentation of French and English. *Journal of Memory and Language*, 25, 385-400.
- Cutler, A., & Norris, D. G. (1988). The role of strong syllables in segmentation for lexical access. *Journal of Experimental Psychology: Human Perception and Performance*, 14, 113-121.
- Cutler, A., & Otake. (1994). Mora or phoneme? Further evidence for language-specific listening. *Journal of Memory and Language*, 33, 824-844.
- Cutler, A., & van Donselaar, W. D. (2001). Voornaam ist not (really) a homophone: Lexical prosody and lexical access in Dutch. *Language and Speech*, 44, 171-195.
- Daffner, K. R., Scinto, L. F., Calvo, V., Faust, R., Mesulam, M. M., West, W. C., et al. (2000). The influence of stimulus deviance on electrophysiologic and behavioral responses to novel events. *Journal of Cognitive Neuroscience*, 12(3), 393-406.
- Dankovicová, J., Pigott, K., Wells, B., & Peppé, S. (2004). Temporal markers of prosodic boundaries in children's speech production. *Journal of the International Phonetic Association*, 34, 17-36.
- DeCasper, A. J., & Fifer, W. P. (1980). Of human bonding: Newborns prefer their mother's voice. *Science*, 208, 1174-1176.
- DeCasper, A. J., & Spence, M. J. (1986). Prenatal maternal speech influences newborns' perception of speech sounds. *Infant Behavior & Development*, 9, 133-150.

- Dehaene-Lambertz, G., Dehaene, S., & Hertz-Pannier, L. (2002). Functional neuroimaging of speech perception in infants. *Science*, 298(5600), 2013–2015.
- Dehaene-Lambertz, G., & Houston, D. M. (1998). Faster orientation latencies toward native language in two-month-old infants. *Language and Speech*, 41, 21-43.
- Delattre, P. (1966). A comparison of syllable length conditions across languages. *International Review of Applied Linguistics*, IV(3), 183-198.
- Di Cristo, A. (1998). Intonation in French. In D. Hirst & A. Di Cristo (Eds.), *Intonation systems: A survey of twenty languages* (p. 195-218). Cambridge, UK: Cambridge University Press.
- Dien, J. (1998). Addressing misallocation of variance in principal component analysis of event-related potentials. *Brain Topography*, 11(1), 43-55.
- Dien, J., & Frishkoff, G. A. (2004). Principal component analysis of event-related potential datasets. In T. C. Handy (Ed.), *Event-related potentials: A methods handbook* (p. 189-208). Cambridge, MA: MIT Press.
- Donchin, E., & Coles, M. (1988). Is the P300 a manifestation of context updating? *Behavioral and Brain Sciences*, 11, 357-374.
- Donchin, E., & Heffley, E. (1979). Multivariate analysis of event-related potential data: A tutorial review. In D. Otto (Ed.), *Multidisciplinary perspectives in event-related potential research* (p. 555-572). Washington, DC: US Government Printing Office.
- Donchin, E., Karis, D., Bashore, T., Coles, M., & Gratton, G. (1986). Cognitive psychology and human information processing. In M. Coles, E. Donchin, & S. Porges (Eds.), *Psychophysiology. Systems, Processes, and Applications* (p. 244-267). New York: The Guilford Press.
- Eckstein, K., & Friederici, A. D. (2005). Late interaction of syntactic and prosodic processes in sentence comprehension as revealed by ERPs. *Cognitive Brain Research*, 25, 130-143.
- 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.
- Edgar, J., Stewart, J., & Miller, G. (2005). Digital filters in ERP research. In T. C. Handy (Ed.), *Event-related potentials: A methods handbook* (p. 85-113). Cambridge, MA: MIT Press.
- Emmorey, K. D. (1987). The neurological substrates for prosodic aspects of speech. *Brain and Language*, 30(2), 305–320.

- Fernald, A. (1985). Four-month-old infants prefer to listen to motherese. *Infant Behavior & Development*, 8, 181-195.
- Fernald, A., Taeschner, T., Dunn, J., Papousek, M., De Boysson-Bardies, B., & Fukui, I. (1989). A cross-language study of prosodic modifications in mothers' and fathers' speech to preverbal infants. *Journal of Child Language*, 16, 477-501.
- Ferreira, F. (1988). *Planning and timing in sentence production: The syntax-to-phonology conversion*. Unpublished dissertation, University of Massachusetts, Amherst, MA.
- Fery, C. (1993). *German intonational patterns*. Tübingen: Niemeyer.
- Finney, S. A., Protopapas, A., & Eimas, P. D. (1996). Attentional allocation to syllables in American English. *Journal of Memory and Language*, 35, 893-909.
- Fischer, G. (2000). *Lineare Algebra: Eine Einführung für Studienanfänger* (12 ed.). Wiesbaden: Vieweg Verlag.
- Fisher, C., & Tokura, H. (1996a). Acoustic cues to grammatical structure in infant-directed speech – cross-linguistic evidence. *Child Development*, 67(6), 3192-3218.
- Fisher, C., & Tokura, H. (1996b). Prosody in speech to infants: Direct and indirect acoustic cues to syntactic structure. In J. L. Morgan & K. Demuth (Eds.), *Signal to syntax: Bootstrapping from speech to grammar in early acquisition*. (p. 343-363). Hillsdale, NJ, England: Lawrence Erlbaum Associates.
- Frazier, L. (1987). Sentence processing: A tutorial review. In M. Coltheart (Ed.), *Attention and performance XII* (p. 559-586). Hillsdale: Erlbaum.
- Friederici, A. D. (2002). Towards a neural basis of auditory sentence processing. *Trends in Cognitive Sciences*, 6, 78-84.
- Friederici, A. D. (2004). Event-related brain potential studies in language. *Current Neurology and Neuroscience Reports*, 4(6), 466-470.
- Friederici, A. D. (2005). Neurophysiological markers of early language acquisition: From syllables to sentences. *Trends in Cognitive Sciences*, 9, 481-488.
- Friederici, A. D. (2006a). The neural basis of language development and its impairment. *Neuron*, 52, 941-952.

- Friederici, A. D. (2006b). The neural basis of sentence processing: Inferior frontal and temporal contributions. In Y. Grodzinsky & K. Amunts (Eds.), *Broca's region* (p. 196-217). Oxford: Oxford University Press.
- Friederici, A. D., & Alter, K. (2004). Lateralization of auditory language functions: A dynamic dual pathway model. *Brain and Language*, 89, 267-276.
- Friederici, A. D., Friedrich, M., & Christophe, A. (2007). Brain responses in 4-month-old infants are already language specific. *Current Biology*, 17(14), 1208–1211.
- Friederici, A. D., Friedrich, M., & Weber, C. (2002). Neural manifestation of cognitive and precognitive mismatch detection in early infancy. *Neuroreport*, 13(10), 1251–1254.
- Friederici, A. D., Hahne, A., & Mecklinger, A. (1996). Temporal structure of syntactic parsing: Early and late event-related brain potential effects. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 22, 1219-1248.
- 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., Steinhauer, K., & Pfeifer, E. (2002). Brain signatures of artificial language processing: Evidence challenging the critical period hypothesis. *Proceedings of the National Academy of Sciences of the United States of America*, 99(1), 529–534.
- Friederici, A. D., & Thierry, G. (Eds.). (2008). *Early language development: Bridging brain and behaviour* (Vol. Trends in Language Acquisition Research (TiLAR) 5). Amsterdam, Netherlands: John Benjamins.
- Friederici, A. D., von Cramon, D. Y., & Kotz, S. A. (2007). Role of the corpus callosum in speech comprehension: Interfacing syntax and prosody. *Neuron*, 53(1), 135–145.
- Friederici, A. D., & Weissenborn, J. (2007). Mapping sentence form onto meaning: The syntax-semantic interface. *Brain Research*, 1146, 50-58.
- Friedrich, M., & Friederici, A. D. (2004). N400-like semantic incongruity effect in 19-month-olds: Processing known words in picture contexts. *Journal of Cognitive Neuroscience*, 16, 1465-1477.

- Gandour, J., Tong, Y. X., Wong, D., Talavage, T., Dziedzic, M., Xu, Y. S., et al. (2004). Hemispheric roles in the perception of speech prosody. *Neuroimage*, 23, 344-357.
- Gee, J. P., & Grosjean, F. (1983). Performance structure: A psycholinguistic and linguistic appraisal. *Cognitive Psychology*, 15, 411-458.
- Gerken, L. (1996). Phonological and distributional cues to syntax acquisition. In J. Morgan & K. Demuth (Eds.), *Signal to syntax* (p. 411-425). Mahwah, NJ: Erlbaum.
- Gerken, L., Jusczyk, P. W., & Mandel, D. R. (1994). When prosody fails to cue syntactic structure: 9-month-olds' sensitivity to phonological versus syntactic phrases. *Cognition*, 51(3), 237-265.
- Gertner, Y., Fisher, C., & Eisengart, J. (2006). Learning words and rules: Abstract knowledge of word order in early sentence comprehension. *Psychological Science*, 17, 684-691.
- Gibbon, D. (1998). Intonation in German. In D. Hirst & A. Di Cristo (Eds.), *Intonation systems: A survey of twenty languages* (p. 78-95). Cambridge, UK: Cambridge University Press.
- Giedd, J. N., Blumenthal, J., Jeffries, N. O., Castellanos, F. X., Liu, H., Zijdenbos, A., et al. (1999). Brain development during childhood and adolescence: A longitudinal MRI study. *Nature Neuroscience*, 2, 861-863.
- Gleitman, L. R. (1990). The structural sources of verb meaning. *Language Acquisition*, 1, 3-55.
- Gleitman, L. R., Gleitman, H., Landau, B., & Wanner, E. (1988). Where learning begins: Initial representations for language learning. In F. J. Newmeyer (Ed.), *Language: Psychological and biological aspects* (p. 150-193). New York, NY: Cambridge University Press.
- Gleitman, L. R., & Wanner, E. (1982). The state of the state of the art. In E. Wanner & L. Gleitman (Eds.), *Language acquisition: The state of the art* (p. 3-48). Cambridge, MA: Cambridge University Press.
- Goldsmith, J. (1976). *Autosegmental phonology*. Doctoral dissertation, MIT.
- Gomez, R. L., & Gerken, L. (1999). Artificial grammar learning by 1-year-olds leads to specific and abstract knowledge. *Cognition*, 70(2), 109-135.
- Gorsuch, R. L. (1983). *Factor analysis* (2nd ed.). Hillsdale, NJ: Erlbaum.
- Gout, A., Christophe, A., & Morgan, J. L. (2004). Phonological phrase boundaries constrain lexical access. II. Infant data. *Journal of Memory and Language*, 51, 548-567.

- Greenhouse, S. W., & Geisser, S. (1959). On methods in the analysis of profile data. *Psychometrika*, 24, 95-112.
- Griffiths, S. K., Brown Jr., W. S., & Gerhardt, K. J. (1994). The perception of speech sounds recorded within the uterus of a pregnant sheep. *Journal of the Acoustical Society of America*, 96(4), 2055-2063.
- Grimm, H. (2001). *Sprachentwicklungstest für drei- bis fünfjährige Kinder. Diagnose von Sprachverarbeitungs-fähigkeiten und auditiven Gedächtnisleistungen*. Göttingen: Hogrefe.
- Grosjean, F. (1983). How long is a sentence? Prediction and prosody in the on-line processing of language. *Linguistics*, 21, 501-529.
- Grosjean, F., & Hirt, C. (1996). Using prosody to predict the end of sentences in English and French: Normal and brain-damaged subjects. *Language and Cognitive Processes*, 11, 107-134.
- Guasti, M. T. (2002). *Language acquisition: The growth of grammar*. Cambridge, MA: MIT Press.
- Hagoort, P., Brown, C., & Groothusen, J. (1993). The syntactic positive shift (SPS) as an ERP measure of syntactic processing. *Language and Cognitive Processes*, 8, 439-483.
- Hahne, A., Eckstein, K., & Friederici, A. D. (2004). Brain signatures of syntactic and semantic processes during children's language development. *Journal of Cognitive Neuroscience*, 16, 1302-1318.
- 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., & Friederici, A. D. (2002). Differential task effects on semantic and syntactic processes as revealed by ERPs. *Cognitive Brain Research*, 13, 339-356.
- Hall, D., Geoffrey, S., Waxmann, S., Bredart, S., & Nicolay, A.-C. (2003). Preschoolers' use of form class cues to learn descriptive proper names. *Child Development*, 74(5), 1547-1560.
- Hall, J. W. (1992). *Handbook of auditory evoked responses*. Boston: Allyn and Bacon.
- Harman, H. H. (1976). *Modern factor analysis* (3rd ed.). Chicago: University of Chicago Press.
- Hayes, B. (1989). The prosodic hierarchy in meter. In P. Kiparsky & G. Youmans (Eds.), *Phonetics and Phonology, Vol 1: Rhythm and meter* (p. 201-260). San Diego: Academic Press.

- He, C., Hotson, L., & Trainor, L. J. (2007). Mismatch responses to pitch changes in early infancy. *Journal of Cognitive Neuroscience*, 19(5), 878–892.
- Hebden, J. C. (2003). Advances in optical imaging of the newborn infant brain. *Psychophysiology*, 40(4), 501–510.
- Herrmann, C. S., Friederici, A. D., Oertel, U., Maess, B., Hahne, A., & Alter, K. (2003). The brain generates its own sentence melody: A Gestalt phenomenon in speech perception. *Brain and Language*, 85, 396–401.
- Hesling, I., Clement, S., Bordessoules, M., & Allard, M. (2005). Cerebral mechanisms of prosodic integration: Evidence from connected speech. *Neuroimage*, 24(4), 937–947.
- Hirsh-Pasek, K., & Golinkoff, R. M. (1996). *The origins of grammar: Evidence from early language comprehension*. Cambridge, MA: MIT Press.
- Hirsh-Pasek, K., Kemler Nelson, D. G., Jusczyk, P. W., Cassidy, K. W., Druss, B., & Kennedy, L. (1987). Clauses are perceptual units for young infants. *Cognition*, 26, 269–286.
- Hirst, D. (1993). Detaching intonational phrases from syntactic structure. *Linguistic Inquiry*, 24, 781–788.
- Hirst, D., & Di Cristo, A. (Eds.). (1998). *Intonation systems: A survey of twenty languages*. Cambridge, UK: Cambridge University Press.
- Hogg, R., & McCully, C. B. (1987). *Metrical phonology*. Cambridge, UK: Cambridge University Press.
- Höhle, B., Schmitz, M., Santelmann, L. M., & Weissenborn, J. (2006). The recognition of discontinuous verbal dependencies by German 19-month-olds: Evidence for lexical and structural influences on children's early processing capacities. *Language Learning and Development*, 2(4), 277–300.
- Höhle, B., Weissenborn, J., Schmitz, M., & Ischebeck, A. (2001). Discovering word order regularities: The role of prosodic information for early parameter setting. In J. Weissenborn & B. Höhle (Eds.), *Approaches to bootstrapping. Phonological, lexical, syntactic and neurophysiological aspects of early language acquisition* (Vol. 1, p. 249–265). Amsterdam, Netherlands: John Benjamins.

- Holcomb, P. J. (1993). Semantic priming and stimulus degradation: Implications for the role of the N400 in language processing. *Psychophysiology*, 30, 47-61.
- Holcomb, P. J., & Neville, H. J. (1990). Auditory and visual semantic priming in lexical decision: A comparison using event-related brain potentials. *Language and Cognitive Processes*, 5(4), 281-312.
- Homae, F., Watanabe, H., Nakano, T., Asakawa, K., & Taga, G. (2006). The right hemisphere of sleeping infant perceives sentential prosody. *Neuroscience Research*, 54(4), 276-280.
- Inkelas, S., & Zec, D. (1990). *The phonology-syntax connection*. Chicago: The University of Chicago Press.
- Ischebeck, A. K., Friederici, A. D., & Alter, K. (2008). Processing prosodic boundaries in natural and hummed speech: an fMRI study. *Cerebral Cortex*, 18(3), 541-552.
- Jasper, H. (1958). The ten-twenty electrode system of the International Federation. *Journal of Electroencephalography and Clinical Neurophysiology*, 10, 371-375.
- Jessen, M., Marasek, K., Schneider, K., & Clahssen, K. (1995). Acoustic correlates of word stress and the tense/lax opposition in the vowel system of German. In K. Elenius & P. Branderud (Eds.), *Proceedings of the XIIIth International Congress of Phonetic Sciences* (Vol. 4, p. 428-431). Stockholm, Sweden, 13.-19. August 1995.
- Jing, H., & Benasich, A. A. (2006). Brain responses to tonal changes in the first two years of life. *Brain Development*, 28(4), 247-256.
- Johnson, E. K., & Jusczyk, P. W. (2001). Word segmentation by 8-month-olds: When speech cues count more than statistics. *Journal of Memory and Language*, 44, 1-20.
- Johnson, E. K., & Seidl, A. (2008). Clause segmentation by 6-month-old infants: A crosslinguistic perspective. *Infancy*, 13(5), 440-455.
- Jun, S.-A. (1993). *The phonetics and phonology of Korean prosody*. PhD thesis, Ohio State University.
- Jusczyk, P. W. (1985). The high-amplitude sucking technique as a methodological tool in speech perception research. In G. Gottlieb & N. A. Krasnegor (Eds.), *Measurement of audition and vision in the first year of postnatal life: A methodological overview* (p. 155-222). Norwood, NJ: Ablex.

- Jusczyk, P. W. (1997). *The discovery of spoken language*. Cambridge, MA: MIT Press.
- Jusczyk, P. W., & Aslin, R. N. (1995). Infants' detection of the sound patterns of words in fluent speech. *Cognitive Psychology*, 29(1), 1-23.
- Jusczyk, P. W., Cutler, A., & Redanz, N. (1993). Preference for the predominant stress patterns of English words. *Child Development*, 64, 675-687.
- Jusczyk, P. W., Hirsh-Pasek, K., Nelson, D. G., Kennedy, L. J., Woodward, A., & Piwoz, J. (1992). Perception of acoustic correlates of major phrasal units by young infants. *Cognitive Psychology*, 24(2), 252-293.
- Jusczyk, P. W., Hohne, E., & Mandel, D. (1995). Picking up regularities in the sound structure of the native language. In W. Strange (Ed.), *Speech perception and linguistic experience: Theoretical and methodological issues in cross-language speech research* (p. 91-119). Timonium, MD: York Press.
- Jusczyk, P. W., Houston, D. M., & Newsome, M. (1999). The beginnings of word segmentation in English-learning infants. *Cognitive Psychology*, 39(3-4), 159-207.
- Kaan, E., Harris, A., Gibson, E., & Holcomb, P. (2000). The P600 as an index of syntactic integration difficulty. *Language and Cognitive Processes*, 15, 159-201.
- Kaiser, H. F. (1958). The varimax criterion for analytic rotation in factor analysis. *Psychometrika*, 23, 187-200.
- Kaiser, H. F. (1960). The application of electronic computers to factor analysis. *Educational and Psychological Measurement*, 20, 141-151.
- Katayama, J., & Polich, J. (1998). Stimulus context determines P3a and P3b. *Psychophysiology*, 35(1), 23-33.
- Kauschke, C., & Siegmüller, J. (2002). *Patholinguistische Diagnostik bei Sprachentwicklungsstörungen*. München: Urban & Schwarzenberg.
- Kelly, M. H. (1992). Using sound to solve syntactic problems: The role of phonology in grammatical category assignment. *Psychological Review*, 99, 349-364.
- Kelly, M. H. (1996). The role of phonology in grammatical category assignments. In J. L. Morgan & K. Demuth (Eds.), *Signal to Syntax: Bootstrapping from Speech to Grammar in Early Acquisition*. Mahwah, NJ: Erlbaum.

- Kelly, M. H., & Bock, J. K. (1988). Stress in time. *Journal of Experimental Psychology: Human Perception and Performance*, 14, 389-403.
- Kemler Nelson, D. G., Jusczyk, P. W., Mandel, D. R., Myers, J., Turk, A., & Gerken, L. (1995). The head-turn preference procedure for testing auditory perception. *Infant Behavior & Development*, 18(1), 111-116.
- Kerkhofs, R., Vonk, W., Schriefers, H., & Chwilla, D. J. (2007). Discourse, syntax, and prosody: the brain reveals an immediate interaction. *Journal of Cognitive Neuroscience*, 19(9), 1421-1434.
- Kjelgaard, M. M., & Speer, S. R. (1999). Prosodic facilitation and interference in the resolution of temporary syntactic closure ambiguity. *Journal of Memory and Language*, 40, 153-194.
- Knösche, T. R., Neuhaus, C., Haueisen, J., Alter, K., Maess, B., Witte, O. W., et al. (2005). Perception of phrase structure in music. *Human Brain Mapping*, 24(4), 259-273.
- Kochanski, G., Grabe, E., Coleman, J., & Rosner, B. (2005). Loudness predicts prominence: Fundamental frequency lends little. *Journal of the Acoustical Society of America*, 118(2), 1038-1054.
- Kohler, K. J. (1995). *Einführung in die Phonetik des Deutschen*. (2nd ed.). Berlin: Schmidt Verlag.
- Kuhl, P. K. (2004). Early language acquisition: Cracking the speech code. *Nature Reviews Neuroscience*, 5(11), 831-43.
- Kushnerenko, E., Ceponiene, R., Balan, P., Fellman, V., Huotilaine, M., & Naatanen, R. (2002). Maturation of the auditory event-related potentials during the first year of life. *Neuroreport*, 13(1), 47-51.
- Kutas, M., & Federmeier, K. D. (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(5), 539-550.
- Ladd, D. R. (1986). Intonational phrasing: The case for recursive prosodic structure. *Phonology Yearbook*, 3, 311-340.
- Ladd, D. R. (1988). Declination "reset" and the hierarchical organization of utterances. *Journal of the Acoustical Society of America*, 84, 530-554.

- Ladd, D. R. (1996). *Intonational phonology*. Cambridge, UK: Cambridge University Press.
- Ladd, D. R., & Cutler, A. (1983). Introduction. Models and measurements in the study of prosody. In A. Cutler & D. R. Ladd (Eds.), *Prosody: Models and Measurements* (Vol. 14, p. 1-8). Berlin: Springer.
- Lehiste, L. (1970). *Suprasegmentals*. Cambridge, MA: MIT Press.
- Lehiste, L. (1973). Phonetic disambiguation of syntactic disambiguity. *Glossa*, 7, 107-122.
- Lieberman, M., & Prince, A. (1977). On stress and linguistic rhythm. *Linguistic Inquiry*, 8(2), 249-336.
- Lively, S. E., Pisoni, D. B., & Goldinger, S. D. (1994). Spoken word recognition: Research and theory. In M. A. Gernsbacher (Ed.), *Handbook of psycholinguistics* (p. 265-301). San Diego: Academic Press.
- Lopes da Silva, F. (1991). Neural mechanisms underlying brain waves: From neural membranes to networks. *Electroencephalography and Clinical Neurophysiology*, 79(2), 81-93.
- Magne, C., Astesano, C., Lacheret-Dujour, A., Morel, M., & Besson, M. (2005). Online processing of "pop-out" words in spoken French dialogues. *Journal of Cognitive Neuroscience*, 17, 740-756.
- Männel, C. (2008). The method of event-related brain potentials in the study of cognitive processes: A tutorial. In A. D. Friederici & G. Thierry (Eds.), *Early language development: Bridging brain and behaviour* (Vol. Trends in Language Acquisition Research (TiLAR) 5, p. 1-22). Amsterdam, Netherlands: John Benjamins.
- Männel, C., & Friederici, A. D. (2008). Event-related brain potentials as a window to children's language processing: From syllables to sentences. In I. A. Sekerina, E. M. Fernandez, & H. Clahsen (Eds.), *Developmental psycholinguistics: On-line methods in children's language processing* (Vol. Language Acquisition and Language Disorders (LALD) 44, p. 29-72). Amsterdam, Netherlands: John Benjamins.
- Männel, C., & Friederici, A. D. (in press). Pauses and intonational phrasing: ERP studies in 5-month-old German infants and adults. *Journal of Cognitive Neuroscience*.
- Maratsos, M., & Chalkley, M. A. (1980). The internal language of children's syntax: The ontogenesis and representation of syntactic categories. In K. Nelson (Ed.), *Children's language* (Vol. 2, p. 127-214). New York: Gardner Press.

- Marcar, V. L., Strassle, A. E., Loenneker, T., Schwarz, U., & Martin, E. (2004). The influence of cortical maturation on the BOLD response: An fMRI study of visual cortex in children. *Pediatric Research*, 56(6), 967–974.
- Markus, M. (2006). English and German prosody: A contrastive comparison. In Y. Kawaguchi, I. Fonagy, & T. Moriguchi (Eds.), *Prosody and syntax: Cross-linguistic perspectives* (Vol. 3, p. 103-124). Amsterdam, Netherlands: John Benjamins.
- Marslen-Wilson, W. D., Tyler, L. K., Warren, P., Grenier, P., & Lee, C. S. (1992). Prosodic effects in minimal attachment. *The Quarterly Journal of Experimental Psychology*, 45A(1), 73-87.
- Mattys, S. L., Jusczyk, P. W., Luce, P. A., & Morgan, J. L. (1999). Phonotactic and prosodic effects on word segmentation in infants. *Cognitive Psychology*, 38(4), 465-494.
- Mattys, S. L., White, S. D., & Melhorn, J. F. (2005). Integration of multiple speech segmentation cues: A hierarchical framework. *Journal of Experimental Psychology: General*, 134, 477-500.
- Mazuka, R. (1996). Can a grammatical parameter be set before the first word? Prosodic contributions to early setting of a grammatical parameter. In J. L. Morgan & K. Demuth (Eds.), *Signal to Syntax: Bootstrapping from Speech to Grammar in Early Acquisition* (p. 313-330). Mahwah, NJ: Erlbaum.
- McQueen, J. M., Norris, D. G., & Cutler, A. (1994). Competition in spoken word recognition: Spotting words in other words. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 20, 621-638.
- Meek, J. (2002). Basic principles of optical imaging and application to the study of infant development. *Developmental Science*, 5(3), 371-380.
- Mehler, J., Endress, A., Gervain, J., & Nespor, M. (2008). From perception to grammar. In A. D. Friederici & G. Thierry (Eds.), *Early language development: Bridging brain and behaviour* (p. 191-213). Amsterdam, Netherlands: John Benjamins.
- Mehler, J., Jusczyk, P., Lambertz, G., Halsted, N., Bertoncini, J., & Amiel-Tison, C. (1988). A precursor of language acquisition in young infants. *Cognition*, 29(2), 143–178.
- Meisenburg, T., & Selig, M. (1998). *Phonetik und Phonologie des Französischen*. Stuttgart: Klett.
- Meyer, M., Alter, K., & Friederici, A. D. (2003). Functional MR imaging exposes differential brain responses to syntax and prosody during auditory sentence comprehension. *Journal of*

Neurolinguistics, 16(4-5), 277-300.

- Meyer, M., Alter, K., Friederici, A. D., Lohmann, G., & von Cramon, D. Y. (2002). fMRI reveals brain regions mediating slow prosodic modulations in spoken sentences. *Human Brain Mapping*, 17(2), 73-88.
- Meyer, M., Steinhauer, K., Alter, K., Friederici, A. D., & von Cramon, D. Y. (2004). Brain activity varies with modulation of dynamic pitch variance in sentence melody. *Brain and Language*, 89(2), 277-289.
- Millotte, S., Rene, A., Wales, R., & Christophe, A. (2008). Phonological phrase boundaries constrain the online syntactic analysis of spoken sentences. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 34(4), 874-885.
- Millotte, S., Wales, R., & Christophe, A. (2007). Phrasal prosody disambiguates syntax. *Language and Cognitive Processes*, 22, 898-909.
- Möcks, J., & Verleger, R. (1991). Multivariate methods in biosignal analysis: Application of principal component analysis to event-related potentials. In R. Weitkunat (Ed.), *Digital biosignal processing* (p. 399-458). Amsterdam, Netherlands: Elsevier.
- Morgan, J. L., Meier, R. P., & Newport, E. L. (1987). Structural packaging in the input to language learning: Contributions of prosodic and morphological marking of phrases to the acquisition of language. *Cognitive Psychology*, 19(4), 498-550.
- Morgan, J. L., & Saffran, J. R. (1995). Emerging integration of sequential and suprasegmental information in preverbal speech segmentation. *Child Development*, 66(4), 911-936.
- Morr, M. L., Shafer, V. L., Kreuzer, J. A., & Kurtzberg, D. (2002). Maturation of mismatch negativity in typically developing infants and preschool children. *Ear and Hearing*, 23(2), 118-136.
- Mrzljak, J., Uylings, H. B. M., Van Eden, C. G., & Judas, M. (1990). Neuronal development in human prefrontal cortex in prenatal and postnatal stages. *Progress in Brain Research*, 85, 185-222.
- Mueller, J. L., Bahlmann, J., & Friederici, A. D. (2008). The role of pause cues in language learning: the emergence of event-related potentials related to sequence processing. *Journal of Cognitive Neuroscience*, 20(5), 892-905.
- Näätänen, R. (1990). The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function. *Behavioral and Brain Sci-*

- ences, 13, 201-288.
- 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(4), 375–425.
- Nagel, H. N., Shapiro, L. P., Tuller, B., & Nawy, R. (1996). Prosodic influences on the resolution of temporary ambiguity during on-line sentence processing. *Journal of Psycholinguistic Research*, 25, 319-344.
- Nan, Y., Knösche, T. R., & Friederici, A. D. (2006). The perception of musical phrase structure: A cross-cultural ERP study. *Brain Research*, 1094, 179-191.
- Nazzi, T., Bertoncini, J., & Mehler, J. (1998). Language discrimination by newborns: Toward an understanding of the role of rhythm. *Journal of Experimental Psychology: Human Perception and Performance*, 24(3), 756–766.
- Nazzi, T., Dilley, L. C., Jusczyk, A. M., Shattuck-Hufnagel, S., & Jusczyk, P. W. (2005). English-learning infants' segmentation of verbs from fluent speech. *Language and Speech*, 48(3), 279–298.
- Nazzi, T., Jusczyk, P. W., & Johnson, E. K. (2000). Language discrimination by English-learning 5-month-olds: Effects of rhythm and familiarity. *Journal of Memory and Language*, 43, 1-19.
- Nazzi, T., Kemler Nelson, D. G., Jusczyk, P. W., & Jusczyk, A. M. (2000). Six-month-olds' detection of clauses embedded in continuous speech: Effects of prosodic well-formedness. *Infancy*, 1(1), 123-147.
- Nazzi, T., & Ramus, F. (2003). Perception and acquisition of linguistic rhythm by infants. *Speech Communication*, 41(1), 233-243.
- Nelson, C., & Luciana, M. (1998). Electrophysiological studies II: Evoked potentials and event-related potentials. In C. E. Coffey & R. A. Brumback (Eds.), *Textbook of pediatric neuropsychiatry* (p. 331-356). Washington, DC: American Psychiatric Press.
- Nespor, M., Guasti, T., & Christophe, A. (1996). Selecting word order: The rhythmic activation principle. In U. Kleinhenz (Ed.), *Interfaces in Phonology* (p. 1-26). Berlin: Akademie Verlag.
- Nespor, M., Shukla, M., Avesani, C., van de Vijver, R., Schraudolf, H., & Donati, C. (submitted). Different phrasal prominence realizations in VO and OV languages? *Cognition*.

- Nespor, M., & Vogel, I. (1986). *Prosodic phonology*. Dordrecht: Foris.
- Neuhaus, C., Knösche, T. R., & Friederici, A. D. (2006). Effects of musical expertise and boundary markers on phrase perception in music. *Journal of Cognitive Neuroscience*, 18(3), 472–493.
- Nobre, A., & McCarthy, G. (1994). Language-related ERPs: Scalp distributions and modulation by word type and semantic priming. *Journal of Cognitive Neuroscience*, 6(33), 233-255.
- Nooteboom, S. (1997). The prosody of speech: Melody and rhythm. In W. J. Hardcastle & J. Laver (Eds.), *The handbook of phonetic sciences* (p. 640-673). Oxford: Blackwell.
- Norris, D. G., McQueen, J. M., & Cutler, A. (1995). Competition and segmentation in spoken word recognition. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 21, 1209-1228.
- Oberecker, R., & Friederici, A. D. (2006). Syntactic event-related potential components in 24-month-olds' sentence comprehension. *Neuroreport*, 17, 1017-1021.
- Oberecker, R., Friedrich, M., & Friederici, A. D. (2005). Neural correlates of syntactic processing in two-year-olds. *Journal of Cognitive Neuroscience*, 17, 1667-1678.
- Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia*, 9, 97-113.
- Opitz, B., von Cramon, D. Y., & Kruggel, F. (1999). Combining electrophysiological and hemodynamic measures of the auditory oddball. *Psychophysiology*, 36(1), 142–147.
- Osterhout, L., Holcomb, P., & Swinney, D. (1994). Brain potentials elicited by gardenpath sentences: Evidence of the application of verb information during parsing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 20, 786-803.
- Osterhout, L., & Holcomb, P. J. (1992). Event-related brain potentials elicited by syntactic anomaly. *Journal of Memory and Language*, 31, 785-806.
- Osterhout, L., & Holcomb, P. J. (1993). Event-related brain potentials and syntactic anomaly: Evidence on anomaly detection during perception of continuous speech. *Language and Cognitive Processes*, 8, 413-437.
- Osterhout, L., & Mobley, L. A. (1995). Event-related brain potentials elicited by failure to agree. *Journal of Memory and Language*, 34(6), 739-773.

- Otake, T., Hatano, G., Cutler, A., & Mehler, J. (1993). Mora or syllable? Speech segmentation in Japanese. *Journal of Memory and Language*, 32, 358-378.
- Pang, E. W., & Taylor, M. J. (2000). Tracking the development of the N1 from age 3 to adulthood: An examination of speech and non-speech stimuli. *Clinical Neurophysiology*, 111, 388-397.
- Pannekamp, A. (2005). *Prosodische Informationsverarbeitung bei normalsprachlichem und deviantem Satzmaterial: Untersuchungen mit ereigniskorrelierten Hirnpotentialen* (Vol. 63). Max-Planck-Institute für Kognitions- und Neurowissenschaften, Leipzig: MPI Series in Cognitive Neuroscience.
- Pannekamp, A., Toepel, U., Alter, K., Hahne, A., & Friederici, A. D. (2005). Prosody-driven sentence processing: An event-related brain potential study. *Journal of Cognitive Neuroscience*, 17(3), 407-421.
- Pannekamp, A., Weber, C., & Friederici, A. D. (2006). Prosodic processing at the sentence level in infants. *Neuroreport*, 17(6), 675-678.
- Pascual-Marqui, R. D. (2002). Standardized low-resolution brain electromagnetic tomography (sLORETA): technical details. *Methods and Findings in Experimental and Clinical Pharmacology*, 24 Suppl D, 5-12.
- Pascual-Marqui, R. D., Michel, C. M., & Lehmann, D. (1994). Low resolution electromagnetic tomography: A new method for localizing electrical activity in the brain. *International Journal of Psychophysiology*, 18(1), 49-65.
- Pasman, J. W., Rotteveel, J. J., Maassen, B., & Visco, Y. M. (1999). The maturation of auditory cortical evoked responses between (preterm) birth and 14 years of age. *European Journal of Paediatric Neurology*, 3, 79-82.
- Paus, T., Collins, D. L., Evans, A. C., Leonard, G., Pike, B., & Zijdenbos, A. (2001). Maturation of white matter in the human brain: A review of magnetic resonance studies. *Brain Research Bulletin*, 54(3), 255-266.
- Pell, M. D., & Baum, S. R. (1997). Unilateral brain damage, prosodic comprehension deficits, and the acoustic cues to prosody. *Brain and Language*, 57(2), 195-214.
- Pena, M., Bonatti, L. L., Nespor, M., & Mehler, J. (2002). Signal-driven computations in speech processing. *Science*, 298(5593), 604-607.

- Pena, M., Maki, A., Kovacic, D., Dehaene-Lambertz, G., Koizumi, H., Bouquet, F., et al. (2003). Sounds and silence: An optical topography study of language recognition at birth. *Proceedings of the National Academy of Sciences of the United States of America*, 100(20), 11702–11705.
- Penner, Z., & Köllicker Funk, M. (1998). *Therapie und Diagnose von Grammatikstörungen: Ein Arbeitsbuch*. Luzern: Edition SZH/SPC.
- Perkins, J. M., Baran, J. A., & Gandour, J. (1996). Hemispheric specialization in processing intonation contours. *Aphasiology*, 10, 343–362.
- Peters, A. (1983). *The units of language acquisition*. Cambridge, UK: Cambridge University Press.
- Pierrehumbert, J. (1980). *The phonology and phonetics of English intonation*. MIT Linguistics PhD thesis, Indiana University Linguistics Club, Bloomington, IN.
- Pinker, S. (1984). *Language learnability and language development*. Cambridge, MA: Harvard University Press.
- Pinker, S. (1987). The bootstrapping problem in language acquisition. In B. MacWhinney (Ed.), *Mechanisms of language acquisition* (p. 399–441). Hillsdale, NJ: Erlbaum.
- Plante, E., Creusere, M., & Sabin, C. (2002). Dissociating sentential prosody from sentence processing: Activation interacts with task demands. *Neuroimage*, 17(1), 401–410.
- Ponton, C. W., Eggermont, J. J., Kwong, B., & Don, M. (2000). Maturation of human central auditory system activity: Evidence from multi-channel evoked potentials. *Clinical Neurophysiology*, 111, 220–236.
- Price, P. J., Ostendorf, M., Shattuck-Hufnagel, S., & Fong, C. (1991). The use of prosody in syntactic disambiguation. *Journal of the Acoustical Society of America*, 90, 2956–2970.
- Pujol, J., Soriano-Mas, C., Ortiz, H., Sebastián-Gallés, N., Losiá, J. M., & Deus, J. (2006). Myelination of language-related areas in the developing brain. *Neurology*, 66, 339–343.
- Ramus, F., Nespor, M., & Mehler, J. (1999). Correlates of linguistic rhythm in the speech signal. *Cognition*, 73(3), 265–292.
- Regan, D. (1989). *Human brain electrophysiology: Evoked potentials and evoked magnetic fields in science and medicine*. New York: Elsevier.
- Rivkin, M. J., Wolraich, D., Als, H., McAnulty, G., Butler, S., Conneman, N., et al. (2004). Prolonged T*2 values in newborn versus adult brain: Implications for fMRI studies of newborns. *Magnetic*

- Resonance in Medicine*, 51(6), 1287–1291.
- Robin, D. A., Tranel, D., & Damasio, H. (1990). Auditory perception of temporal and spectral events in patients with focal left and right cerebral lesions. *Brain and Language*, 39, 539–555.
- Rossi, S., Gugler, M. F., Hahne, A., & Friederici, A. D. (2005). When word category information encounters morphosyntax: An ERP study. *Neuroscience Letters*, 384, 228–233.
- Rugg, M. D., & Coles, M. G. H. (Eds.). (1996). *Electrophysiology of mind. Event-related brain potentials and cognition*. Oxford: Oxford University Press.
- Saffran, J., Newport, E. L., & Aslin, R. (1996). Word segmentation: the role of distributional cues. *Journal of Memory and Language*, 35, 606–621.
- Sambeth, A., Ruohio, K., Alku, P., Fellman, V., & Huottilainen, M. (2008). Sleeping newborns extract prosody from continuous speech. *Clinical Neurophysiology*, 119(2), 332–341.
- Santelmann, L. M., & Jusczyk, P. W. (1998). Sensitivity to discontinuous dependencies in language learners: Evidence for limitations in processing space. *Cognition*, 69(2), 105–34.
- Savage, C., Lieven, H., Theakston, A., & Tomasello, M. (2003). Testing the abstractness of children's linguistic representations: Lexical and structural priming of syntactic constructions. *Developmental Science*, 6(557–567).
- Schafer, A. J., Speer, S. R., Warren, P., & White, S. D. (2000). Intonational disambiguation in sentence production and comprehension. *Journal of Psycholinguistic Research*, 29, 169–182.
- Schapiro, M. B., Schmithorst, V. J., Wilke, M., Byars, A. W., Strawsburg, R. H., & Holland, S. K. (2004). Bold fMRI signal increases with age in selected brain regions in children. *Neuroreport*, 15(17), 2575–2578.
- Scherg, M., Vajsaar, J., & Picton, T. (1989). A source analysis of the human auditory evoked potentials. *Journal of Cognitive Neuroscience*, 1, 336–355.
- Scherg, M., & von Cramon, D. Y. (1986). Evoked dipole source potentials of the human auditory cortex. *Electroencephalography and Clinical Neurophysiology*, 65(5), 344–360.
- Schmitz, M. (2008). *The perception of clauses in 6- and 8-month-old German-learning infants: Influence of pause duration and the natural pause hierarchy*. Unveröffentlichte Dissertationsschrift, Universität Potsdam.

- Schreuder, R., & Baayen, R. H. (1994). Prefix stripping re-revisited. *Journal of Memory and Language*, 33, 357-375.
- Schubiger, M. (1980). English Intonation and German modal particles II: A comparative study. In L. R. Waugh & C. H. van Schooneveld (Eds.), *The melody of language* (p. 279-298). Baltimore: University Park Press.
- Scott, D. (1982). Duration as a cue to the perception of a phrase boundary. *Journal of the Acoustical Society of America*, 71, 996-1007.
- Scott, S. K., & Johnsrude, I. S. (2003). The neuroanatomical and functional organization of speech perception. *Trends in Neurosciences*, 26(2), 100-107.
- Sebastián-Gallés, N., Dupoux, E., Segui, J., & Mehler, J. (1992). Contrasting syllabic effects in Catalan and Spanish. *Journal of Memory and Language*, 31, 18-32.
- Seidl, A. (2007). Infants' use and weighting of prosodic cues in clause segmentation. *Journal of Memory and Language*, 57, 24-48.
- Seidl, A., & Cristia, A. (2008). Developmental changes in the weighting of prosodic cues. *Developmental Science*, 11(4), 596-606.
- Seidl, A., & Johnson, E. K. E. (2007). Boundary alignment facilitates 11-month-olds' segmentation of vowel-initial words from speech. *Journal of Child Language*, 34, 1-24.
- Selkirk, E. (1984). *Phonology and syntax: The relation between sound and structure*. Cambridge, MA: MIT Press.
- Selkirk, E. (1996). The prosodic structure of function words. In J. L. Morgan & K. Demuth (Eds.), *Signal to Syntax: Bootstrapping from Speech to Grammar in Early Acquisition* (p. 187-214). Mahwah, NJ: Lawrence Erlbaum Associates.
- Selkirk, E. (2000). The interaction of constraints on prosodic phrasing. In M. Horne (Ed.), *Prosody: Theory and experiment* (p. 231-262). Dordrecht: Kluwer.
- 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, 200-2.
- Share, D. L. (1999). Phonological recoding and orthographic learning: A direct test of the self-teaching hypothesis. *Journal of Experimental Child Psychology*, 72, 95-129.

- Shattuck-Hufnagel, S., & Turk, A. E. (1996). A prosody tutorial for investigators of auditory sentence processing. *Journal of Psycholinguistic Research*, 25(2), 193-247.
- Shi, R., Werker, J. F., & Cutler, A. (2006). Recognition and representation of function words in English-learning infants. *Infancy*, 10(2), 187-198.
- Siegmüller, J., Kauschke, C., Bartke, S., & Bittner, D. (in prep). *Satzverständnistest für Kinder von zwei bis acht Jahren*. Amsterdam, Netherlands: Elsevier.
- Slowiaczek, L. M. (2000). Effects of lexical stress in auditory word recognition. *Language and Speech*, 33, 47-68.
- Soderstrom, M. (2003). The acquisition of inflection morphology in early perceptual knowledge of syntax. *Dissertation Abstracts International: Section B: The Sciences and Engineering*, 63(10-B), 4944.
- Soderstrom, M., Nelson, D. G. K., & Jusczyk, P. W. (2005). Six-month-olds recognize clauses embedded in different passages of fluent speech. *Infant Behavior & Development*, 28, 87-94.
- Soderstrom, M., Seidl, A., Nelson, D. G. K., & Jusczyk, P. W. (2003). The prosodic bootstrapping of phrases: Evidence from prelinguistic infants. *Journal of Memory and Language*, 49(2), 249-67.
- Speckmann, E.-J., & Elger, C. E. (1993). Neurophysiological basis of the EEG and of DC potentials. In E. Niedermeyer & F. Lopes da Silva (Eds.), *Electroencephalography. Basic principles, clinical applications and related fields* (p. 15-26). Baltimore: Urban & Schwarzenberg.
- Steedman, M. (1990). Syntax and intonational structure in a combinatory grammar. In G. T. M. Altmann (Ed.), *Cognitive models of speech processing: Psycholinguistic and computational perspectives* (p. 457-482). Cambridge, MA: MIT Press.
- Steinhauer, K. (2003). Electrophysiological correlates of prosody and punctuation. *Brain and Language*, 86(1), 142-164.
- Steinhauer, K., Alter, K., & Friederici, A. D. (1999). Brain potentials indicate immediate use of prosodic cues in natural speech processing. *Nature Neuroscience*, 2(2), 191-6.
- Steinhauer, K., & Friederici, A. D. (2001). Prosodic boundaries, comma rules, and brain responses: The Closure Positive Shift in ERPs as a universal marker for prosodic phrasing in listeners and readers. *Journal of Psycholinguistic Research*, 30(3), 267-295.

- Stirling, L., & Wales, R. (1996). Does prosody support or direct sentence processing? *Language and Cognitive Processes*, 11, 193-212.
- Streeter, L. A. (1978). Acoustic determinants of phrase boundary location. *Journal of the Acoustical Society of America*, 64, 1582-1592.
- Strelnikov, K. N., Vorobyev, V. A., Chernigovskaya, T. V., & Medvedev, S. V. (2006). Prosodic clues to syntactic processing – a PET and ERP study. *Neuroimage*, 29(4), 1127–1134.
- Szagun, G. (2006). *Sprachentwicklung beim Kind*. Weinheim: Beltz.
- Talsma, D., & Woldorff, M. (2005). Methods for the estimation and removal of artifacts and overlap in ERP waveforms. In T. C. Handy (Ed.), *Event-related potentials: A methods handbook* (p. 115-148). Cambridge, MA: MIT Press.
- Thiessen, E. D., Hill, E. A., & Saffran, J. R. (2005). Infant-directed speech facilitates word segmentation. *Infancy*, 7(1), 53-71.
- Tong, Y., Gandour, J., Talavage, T., Wong, D., Dziedzic, M., Xu, Y., et al. (2005). Neural circuitry underlying sentence-level linguistic prosody. *Neuroimage*, 28(2), 417–428.
- Toro, R., & Burnod, Y. (2005). A morphogenetic model for the development of cortical convolutions. *Cerebral Cortex*, 15, 1900-1913.
- Trainor, L., McFadden, M., Hodgson, L., Darragh, L., Barlow, J., Matsos, L., et al. (2003). Changes in auditory cortex and the development of mismatch negativity between 2 and 6 months of age. *International Journal of Psychophysiology*, 51(1), 5–15.
- Trauner, D. A., Ballantyne, A., Friedland, S., & Chase, C. (1996). Disorders of affective and linguistic prosody in children after early unilateral brain damage. *Annals of Neurology*, 39(3), 361-367.
- Truckenbrodt, H. (1999). On the relation between syntactic phrases and phonological phrases. *Linguistic Inquiry*, 30, 219-255.
- Turk, A. E., Jusczyk, P. W., & Gerken, L. (1995). Do English-learning infants use syllable-weight to determine stress? *Language and Speech*, 38, 143-158.
- Uylings, H. B. M. (2006). Development of the human cortex and the concept of 'critical' or 'sensitive' periods. *Language Learning*, 56(s1), 59-60.
- Van Donselaar, W., Koster, M., & Cutler, A. (2005). Exploring the role of lexical stress in lexical recognition. *Quarterly Journal of Experimental Psychology*, 58A(2), 251-273.

- Van Lancker, D. (1980). Cerebral lateralization of pitch cues in the linguistic signal. *International Journal of Human Communication*, 13(2), 101-109.
- Van Lancker, D., & Sidtis, J. J. (1992). The identification of affective-prosodic stimuli by left- and right-hemisphere-damaged subjects: All errors are not equal. *Journal of Speech and Hearing*, 35, 963-970.
- Vroomen, J., van Zon, M., & van Gelder, B. (1996). Cues to speech segmentation: Evidence from juncture misperceptions and word spotting. *Memory & Cognition*, 24, 744-755.
- Warren, P. (1999). Prosody and language processing. In S. Garrod & M. J. Pickering (Eds.), *Language processing* (p. 155-188). Hove: Psychology Press.
- Warren, P., Grabe, E., & Nolan, F. (1995). Prosody, phonology and parsing closure ambiguities. *Language and Cognitive Processes*, 10, 457-486.
- Wartenburger, I., Steinbrink, J., Telkemeyer, S., Friedrich, M., Friederici, A. D., & Obrig, H. (2007). The processing of prosody: Evidence of interhemispheric specialization at the age of four. *Neuroimage*, 34(1), 416-425.
- Watt, S., & Murray, W. S. (1996). Prosodic form and parsing commitments. *Journal of Psycholinguistic Research*, 25, 291-318.
- Weber, A., Grice, M., & Grocker, M. W. (2006). The role of prosody in the interpretation of structural ambiguities: A study of anticipatory eye movements. *Cognition*, 99(2), B63-B72.
- Weintraub, S., Mesulam, M. M., & Kramer, L. (1981). Disturbances in prosody: A right-hemisphere contribution to language. *Archives of Neurology*, 38(12), 742-744.
- Werker, J. F., Polka, L., & Pegg, J. E. (1997). The conditioned head turn procedure as a method for testing infant speech perception. *Early Development and Parenting*, 6, 171-178.
- West, W. C., & Holcomb, P. J. (2002). Event-related potentials during discourse-level semantic integration of complex pictures. *Cognitive Brain Research*, 13(3), 363-375.
- Wiese, R. (1996). *The phonology of German*. Oxford: Oxford University Press.
- Wightman, C. W., Shattuck-Hufnagel, S., Ostendorf, M., & Price, P. J. (1992). Segmental durations in the vicinity of prosodic phrase boundaries. *Journal of the Acoustical Society of America*, 91(3), 1707-1717.
- Willems, N. (1982). *English intonation from a Dutch point of view*. Dordrecht: Foris.

- Wingfield, A., Lindfield, K., & Goodglass, H. (2000). Effects of age and hearing sensitivity on the use of prosodic information in spoken word recognition. *Journal of Speech & Hearing Research*, 43, 915-925.
- Winkler, I., Kujala, T., Tiitinen, H., Sivonen, P., Alku, P., Lehtokoski, A., et al. (1999). Brain responses reveal the learning of foreign language phonemes. *Psychophysiology*, 36(5), 638–642.
- Wode, H. (1993). *Psycholinguistik – Eine Einführung in die Lehr- und Lernbarkeit von Sprachen*. Ismaning: Hueber.
- Wunderlich, J. L., Cone-Wesson, B. K., & Shepherd, R. (2006). Maturation of the cortical auditory evoked potential in infants and young children. *Hearing Research*, 212(1-2), 185–202.
- Zatorre, R. J., Belin, P., & Penhune, V. B. (2002). Structure and function of auditory cortex: Music and speech. *Trends in Cognitive Sciences*, 1(6), 37-46.
- Zwitserslood, P., Schriefers, H., Lahiri, A., & Donselaar, W. (1993). The role of syllables in the perception of spoken Dutch. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 19, 260-271.

List of Figures

1.1	Prosody with acoustic information on the production side and phonetic-phonological information on the perception side	4
1.2	Hierarchy of prosodic constituents (Selkirk, 1984)	10
3.1	Closure Positive Shift (Steinhauer, Alter, & Friederici, 1999)	32
3.2	Neurocognitive Model of Sentence Processing (Friederici, 2002)	37
5.1	From EEG to ERP: Electroencephalographic recordings and subsequent data processing reveal event-related brain potentials	46
5.2	International 10-10 System of Electrode Placement (Chatrian, Lettich, & Nelson, 1988)	49
7.1	Naturally spoken sentences: Duration parameters	68
7.2	Naturally spoken sentences: Waveform and pitch track	69
7.3	Sentences with neutralized pause: Duration parameters	69
7.4	Sentences with neutralized pause: Waveform and pitch track	70
8.1	Adults: Naturally spoken sentences relative to sentence onset	79
8.2	5-month-olds: Naturally spoken sentences relative to sentence onset	81
8.3	Adults: Sentences with neutralized pause relative to sentence onset	82
8.4	5-month-olds: Sentences with neutralized pause relative to sentence onset	84
8.5	5-month-olds: Sentences with IPB relative to sentence onset and NP2 onset	86
8.6	5-month-olds: Naturally spoken sentences and Sentences with neutralized pause relative to NP2 onset	88
8.7	Adults: Sentences with IPB relative to sentence onset and NP2 onset	89

8.8	Adults and 5-month-olds: NP2 onsets of Naturally spoken sentences and Sentences with neutralized pause	92
9.1	21-month-olds: Naturally spoken sentences relative to sentence onset	105
9.2	3-year-olds: Naturally spoken sentences relative to sentence onset	106
9.3	21-month-olds & 3-year-olds: Naturally spoken sentences relative to NP2 onset . . .	108
9.4	6-year-olds: Naturally spoken sentences relative to sentence onset	112
9.5	6-year-olds & 3-year-olds: Naturally spoken sentences relative to NP2 onset	114
9.6	6-year-olds: Topographic maps of spatial factor loadings for sentences with IPB relative to NP2 onset	117
9.7	6-year-olds: Spatial factor scores for sentences with IPB relative to NP2 onset	118
9.8	6-year-olds: Topographic maps of Factor-EEGs for sentences with IPB relative to NP2 onset	119
9.9	6-year-olds: Factor-EEGs at FZ and PZ for sentences with IPB relative to NP2 onset	119
9.10	Subgroup of 6-year-olds: Topographic maps of Factor-EEGs for sentences with IPB relative to NP2 onset	120
9.11	Subgroup of 6-year-olds: Factor-EEGs at FZ and PZ for sentences with IPB relative to NP2 onset	121

List of Tables

1.1	Different prosodic realization of an example sentence (example from Selkirk, 1984) .	8
1.2	Prosodic disambiguation of an example sentence with global syntactic structure ambiguity (example from Lehiste, 1973)	15
1.3	Example sentences with local syntactic ambiguities (example from Marslen-Wilson et al., 1992)	16
1.4	Example sentences without and with optional prepositional phrases of different lengths (example from Grosjean, 1993)	17
7.1	Stimulus examples for Naturally spoken sentences	66
7.2	Stimulus examples for the long version of Naturally spoken sentences	67
8.1	Hypotheses of Study I on IP processing in 5-month-old German infants and adults . .	76
8.2	Adults: Significant effects of ANOVAs for Naturally spoken sentences for the 0-2500 ms latency range relative to sentence onset	80
8.3	Adults: Significant effects of ANOVAs for Sentences with neutralized pause for the 0-2500 ms latency range relative to sentence onset	83
8.4	Adults: Significant effects of ANOVAs for N1 and P2 peak amplitudes and latencies of Naturally spoken sentences with IPB	90
8.5	Adults: Significant effects of ANOVAs for N1 and P2 peak amplitudes and latencies of Sentences with neutralized pause (with IBP)	91
9.1	Hypotheses of Study II on IP processing in 21-month-old, 3-year-old and 6-year-old children	103

9.2	3-year-olds: Mean amplitudes in the TW 0-300 ms following the NP2 onset of Sentences with IBP	109
9.3	6-year-olds: Significant effects of ANOVAs for Naturally spoken sentences for the 0-2500 ms latency range relative to sentence onset	113
9.4	6-year-olds: Mean amplitudes in TWs preceding and following the NP2 onset of Sentences with IBP	115
10.1	5-month-olds: Significant effects of ANOVAs for Naturally spoken sentences with IPB for the 0-500 ms latency range relative to sentence onset and NP2 onset	173
10.2	5-month-olds: Significant effects of ANOVAs for Sentences with neutralized pause (with IPB) for the 0-1500 ms latency range relative to sentence onset and NP2 onset	174
10.3	Adults: N1 and P2 peak amplitudes and latencies of Naturally spoken sentences with IBP	175
10.4	Adults: N1 and P2 peak amplitudes and latencies of Sentences with neutralized pause (with IBP)	176

Appendices

Appendix A: Statistics

Table 10.1: 5-MONTH-OLDS Naturally spoken sentences with IPB: Significant effects of ANOVAs for the 0-500 ms latency range relative to sentence onset and NP2 onset (Onset = Onset Type; Reg = Region; Hem = Hemisphere; Ant = anterior; Cen = central).

TW (ms)	Lateral ROIs			Midline sites		
	<i>Effect</i>	<i>df</i>	<i>F</i>	<i>Effect</i>	<i>df</i>	<i>F</i>
100-200	Onset x Reg	2,66	5.06*			
200-300	Onset	1,33	5.43*	Onset x Reg	2,66	3.44*
	Onset x Reg	2,66	12.74**	FZ	1,33	4.15*
	Ant	1,33	10.57**			
	Cen	1,33	8.18**			
300-400	Onset	1,33	4.36*			
	Onset x Reg	2,66	8.2**			
	Ant	1,33	9.74**			
	Cen	1,33	4.75*			
	Onset x Hem	1,33	5.36*			
	Right	1,33	7.55**			

* $p \leq .05$; ** $p \leq .01$

Table 10.2: 5-MONTH-OLDS Sentences with neutralized pause (with IPB): Significant effects of ANOVAs for the 0-1500 ms latency range relative to sentence onset and NP2 onset (Onset = Onset Type; Reg = Region; Ant = anterior; Cen = central; Post = posterior).

TW (ms)	Lateral ROIs			Midline sites		
	<i>Effect</i>	<i>df</i>	<i>F</i>	<i>Effect</i>	<i>df</i>	<i>F</i>
0-500	Onset	1,33	36.07**	Onset	1,33	16.12**
	Onset x Reg	2,66	31.69**	Onset x Reg	2,66	3.44*
	Ant	1,33	51.47**	FZ	1,33	22.75**
	Cen	1,33	43.81**	CZ	1,33	14.24**
500-1000	Onset	1,33	17.17**	Onset	1,33	21.92**
	Onset x Reg	2,66	6.31**			
	Ant	1,33	19.64**			
	Cen	1,33	19.98**			
	Post	1,33	4.81*			
1000-1500	Onset	1,33	7.22*	Onset	1,33	6.0*

* $p \leq .05$; ** $p \leq .01$

Table 10.3: ADULTS Naturally spoken sentences with IPB: N1 and P2 peak amplitudes and latencies (SD indicated) (Amp = amplitude; Lat = latency; Ant = anterior; Cen = central; Post = posterior).

TW	ROIs/ sites	Sentence onset		NP2 onset	
		Amp (μV)	Lat (ms)	Amp (μV)	Lat (ms)
N1	Right ant	-1.40 (2.18)	77 (9)	-1.28 (1.27)**	74 (12)
	Left ant	-1.58 (2.24)	76 (10)	-1.43 (1.03)**	74 (13)
	Right cen	-2.00 (1.84)	80 (8)	-1.38 (0.95)**	78 (12)
	Left cen	-2.33 (2.11)	78 (9)	-1.68 (1.06)**	74 (12)
	Right post	-2.71 (1.73)	82 (12)	-1.37 (0.98)**	78 (13)
	Left post	-3.06 (1.76)	82 (13)	-1.63 (1.16)**	75 (13)
	FZ	-2.18 (2.80)	77 (12)	-1.75 (1.38)**	75 (14)
	CZ	-3.68 (3.22)	77 (9)	-2.24 (1.41)**	73 (14)
	PZ	-3.77 (2.42)	80 (11)	-2.11 (1.36)**	73 (15)
P2	Right ant	5.78 (2.81)	172 (16)	2.93 (2.28)**	174 (20)
	Left ant	5.47 (2.63)	171 (16)	2.72 (2.13)**	172 (21)
	Right cen	4.88 (2.01)	174 (16)	2.85 (1.69)**	170 (21)
	Left cen	4.53 (2.31)	180 (16)	2.32 (1.68)**	175 (17)
	Right post	1.90 (1.54)	176 (18)	1.33 (1.42)**	168 (21)
	Left post	1.72 (1.78)	180 (19)	0.96 (1.55)**	169 (18)
	FZ	6.13 (3.36)	173 (17)	2.90 (2.64)**	168 (25)
	CZ	6.73 (3.79)	169 (16)	3.51 (2.83)**	166 (25)
	PZ	3.55 (2.79)	175 (22)	1.90 (2.27)**	170 (23)

** $p \leq .01$; one sample t-test against the test value 0

Table 10.4: ADULTS Sentences with neutralized pause (with IPB): N1 and P2 peak amplitudes and latencies (SD indicated) (Amp = amplitude; Lat = latency; Ant = anterior; Cen = central; Post = posterior).

TW	ROIs/ sites	Sentence onset		NP2 onset	
		Amp (μV)	Lat (ms)	Amp (μV)	Lat (ms)
N1	Right ant	-1.61 (1.84)	72 (10)	-2.07 (1.39)**	82 (12)
	Left ant	-1.64 (1.83)	72 (8)	-2.22 (1.31)**	82 (12)
	Right cen	-1.93 (1.71)	75 (11)	-1.53 (1.31)**	80 (13)
	Left cen	-2.35 (1.51)	74 (12)	-1.82 (1.28)**	83 (11)
	Right post	-2.48 (1.42)	76 (12)	-1.40 (1.19)**	81 (14)
	Left post	-2.69 (1.41)	77 (11)	-1.60 (1.07)**	84 (15)
	FZ	-2.20 (2.19)	73 (9)	-2.72 (1.62)**	83 (16)
	CZ	-3.39 (2.28)	74 (9)	-2.67 (1.75)**	84 (15)
	PZ	-3.16 (1.85)	75 (13)	-1.98 (1.48)**	83 (15)
P2	Right ant	6.44 (2.36)	174 (17)	1.88 (1.34)**	186 (18)
	Left ant	5.99 (2.33)	175 (20)	1.85 (1.62)**	181 (17)
	Right cen	5.21 (1.79)	176 (15)	1.89 (1.19)**	181 (18)
	Left cen	4.74 (2.37)	177 (12)	1.72 (1.39)**	181 (17)
	Right post	2.29 (1.89)	176 (17)	1.12 (1.41)**	173 (18)
	Left post	2.01 (2.31)	175 (17)	1.03 (1.47)**	172 (20)
	FZ	7.00 (3.10)	175 (20)	1.87 (1.95)**	185 (21)
	CZ	6.77 (3.46)	169 (17)	2.02 (1.86)**	178 (20)
	PZ	3.76 (2.60)	172 (20)	1.22 (1.88)**	172 (22)

** $p \leq .01$; one sample t-test against the test value 0

Appendix B: Stimulus material – Sentence pairs of sentences without and with IPB

Tommi verspricht Papa zu schlafen.

Tommi verspricht, Papa zu helfen.

Lena verspricht Opa zu laufen.

Lena verspricht, Opa zu schreiben.

Oma verspricht Lena zu stricken.

Oma verspricht, Lena zu küssen.

Papa verspricht Kevin zu rennen.

Papa verspricht, Kevin zu glauben.

Mama verspricht Tina zu singen.

Mama verspricht, Tina zu streicheln.

Kevin verspricht Tina zu puzzeln.

Kevin verspricht, Tina zu mögen.

Opa verspricht Tommi zu warten.

Opa verspricht, Tommi zu retten.

Kevin verspricht Oma zu wischen.

Kevin verspricht, Oma zu folgen.

Tina verspricht Papa zu raten.

Tina verspricht, Papa zu halten.

Lena verspricht Mama zu kehren.

Lena verspricht, Mama zu drücken.

Tommi bittet Mama zu kommen.

Tommi bittet, Mama zu holen.

Oma bittet Opa zu lachen.

Oma bittet, Opa zu danken.

Lena bittet Papa zu flüstern.

Lena bittet, Papa zu fragen.

Kevin bittet Opa zu würfeln.

Kevin bittet, Opa zu grüßen.

Opa bittet Papa zu bleiben.

Opa bittet, Papa zu rufen.

Mama bittet Kevin zu essen.

Mama bittet, Kevin zu finden.

Papa bittet Tommi zu trinken.

Papa bittet, Tommi zu wecken.

Tina bittet Lena zu lächeln.

Tina bittet, Lena zu schicken.

Tommi bittet Tina zu lesen.

Tommi bittet, Tina zu warnen.

Tina bittet Oma zu klingeln.

Tina bittet, Oma zu stützen.

Papa verbietet Tina zu hüpfen.

Papa verbietet, Tina zu kneifen.

Lena verbietet Kevin zu streiten.

Lena verbietet, Kevin zu schubsen.

Mama verbietet Tommi zu zappeln.

Mama verbietet, Tommi zu jagen.

Opa verbietet Kevin zu quengeln.

Opa verbietet, Kevin zu hänseln.

Oma verbietet Lena zu bummeln.

Oma verbietet, Lena zu stoßen.

Opa verbietet Oma zu jammern.

Opa verbietet, Oma zu stören.

Oma verbietet Tina zu schreien.

Oma verbietet, Tina zu knuffen.

Tommi verbietet Opa zu schummeln.

Tommi verbietet, Opa zu ärgern.

Kevin verbietet Tommi zu kichern.

Kevin verbietet, Tommi zu zwicken.

Mama verbietet Lena zu schmatzen.

Mama verbietet, Lena zu hauen.

Kevin hilft Papa zu malen.

Kevin hilft, Papa zu fangen.

Lena hilft Oma zu backen.

Lena hilft, Oma zu kämmen.

Kevin hilft Lena zu springen.

Kevin hilft, Lena zu fönen.

Tina hilft Opa zu gehen.

Tina hilft, Opa zu suchen.

Papa hilft Mama zu schwimmen.

Papa hilft, Mama zu schützen.

Tommi hilft Kevin zu werfen.

Tommi hilft, Kevin zu kitzeln.

Opa hilft Tina zu basteln.

Opa hilft, Tina zu wickeln.

Oma hilft Mama zu kochen.

Oma hilft, Mama zu schminken.

Papa hilft Tommi zu pfeifen.

Papa hilft, Tommi zu baden.

Mama hilft Oma zu putzen.

Mama hilft, Oma zu trösten.

Papa erlaubt Lena zu rutschen.

Papa erlaubt, Lena zu schaukeln.

Tina erlaubt Tommi zu flitzen.

Tina erlaubt, Tommi zu piksen.

Opa erlaubt Tina zu spielen.

Opa erlaubt, Tina zu loben.

Oma erlaubt Tommi zu klettern.

Oma erlaubt, Tommi zu ziehen.

Oma erlaubt Mama zu feiern.

Oma erlaubt, Mama zu winken.

Tommi erlaubt Lena zu reden.

Tommi erlaubt, Lena zu bringen.

Mama erlaubt Kevin zu plantschen.

Mama erlaubt, Kevin zu knuddeln.

Papa erlaubt Tina zu tanzen.

Papa erlaubt, Tina zu waschen.

Mama erlaubt Papa zu schnarchen.

Mama erlaubt, Papa zu treffen.

Opa erlaubt Kevin zu naschen.

Opa erlaubt, Kevin zu tragen.

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 Aufgabenwechseparadigmas 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 Rüschmeyer
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
Aufgabeninhibition 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 ereigniskorrelierter Hirmpotentiale
- 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: Neuropsychologische 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
- 97 Anna S. Hasting
Syntax in a blink: Early and automatic processing of syntactic rules as revealed by event-related brain potentials
- 98 Sebastian Jentschke
Neural Correlates of Processing Syntax in Music and Language – Influences of Development, Musical Training and Language Impairment
- 99 Amelie Mahlstedt
*The Acquisition of Case marking Information as a Cue to Argument Interpretation in German
An Electrophysiological Investigation with Pre-school Children*
- 100 Nikolaus Steinbeis
Investigating the meaning of music using EEG and fMRI
- 101 Tilmann A. Klein
Learning from errors: Genetic evidence for a central role of dopamine in human performance monitoring
- 102 Franziska Maria Korb
Die funktionelle Spezialisierung des lateralen präfrontalen Cortex: Untersuchungen mittels funktioneller Magnetresonanztomographie
- 103 Sonja Fleischhauer
Neuronale Verarbeitung emotionaler Prosodie und Syntax: die Rolle des verbalen Arbeitsgedächtnisses
- 104 Friederike Sophie Haupt
The component mapping problem: An investigation of grammatical function reanalysis in differing experimental contexts using event-related brain potentials
- 105 Jens Brauer
Functional development and structural maturation in the brain's neural network underlying language comprehension
- 106 Philipp Kanske
Exploring executive attention in emotion: ERP and fMRI evidence
- 107 Julia Grieser Painter
Music, meaning, and a semantic space for musical sounds

- 108 Daniela Sammler
The Neuroanatomical Overlap of Syntax Processing in Music and Language - Evidence from Lesion and Intracranial ERP Studies
- 109 Norbert Zmyj
Selective Imitation in One-Year-Olds: How a Model's Characteristics Influence Imitation
- 110 Thomas Fritz
Emotion investigated with music of variable valence – neurophysiology and cultural influence
- 111 Stefanie Regel
The comprehension of figurative language: Electrophysiological evidence on the processing of irony
- 112 Miriam Beisert
Transformation Rules in Tool Use
- 113 Veronika Krieghoff
Neural correlates of Intentional Actions
- 114 Andreja Bubić
Violation of expectations in sequence processing