The central contribution of prosody to sentence processing
Evidence from behavioural and neuroimaging studies

Von der Fakultät für Lebenswissenschaften

der Universität Leipzig

genehmigte

DISSERTATION

zur Erlangung des akademischen Grades

Doctor rerum naturalium
(Dr. rer. nat.)

vorgelegt

von
Constantijn Laurens van der Burght, MSc

geboren am 02.11.1990 in Rotterdam

Dekan: Prof. Dr. M. Schönwiesner

Gutachter: Prof. Dr. A.D. Friederici
Prof. Dr. F. Isel

Tag der Verteidigung 11.02.2021

BIBLIOGRAPHISCHE DARSTELLUNG

Constantijn Laurens van der Burght

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219 Seiten, 302 Literaturangaben, 19 Abbildungen, 3 Tabellen

During everyday conversation, listeners rely on several language cues to understand what is being said. Besides syntax (grammar) and semantics (content), important information is conveyed by the way in which a sentence is spoken. Variations in speech melody, rhythm, and intensity, together called *prosody*, can play a decisive role in the interpretation of a sentence. This thesis investigated the ways in which prosody influences sentence processing and studied the neural implementation of these effects. **Study 1** used a sentence comprehension task, in which participants relied on either a grammatical or a prosodic cue—the intonational phrase boundary—to understand the sentence. Using functional magnetic resonance imaging, the study showed that the left inferior frontal gyrus is engaged in processing of sentences in which the structure is established by a prosodic cue. Furthermore, lateralisation of activity was determined by the relevance of the prosodic cue for the interpretation of the sentence. **Study 2** explored the interaction between a different type of prosodic cue—the pitch accent—and both syntactic and semantic processing. This study investigated if pitch accents can establish dissociable expectations in the syntactic and semantic domains, using a sentence comprehension task and a sentence completion task. Results pointed to expectations established by pitch accents in both syntactic and semantic domains. Yet, only violated syntactic expectations were strong enough to interfere with sentence comprehension. Results of both studies were brought together in **Study 3**, investigating the causal role of the left inferior frontal gyrus in processing syntactic, semantic, as well as prosodic cues. This transcranial magnetic stimulation study showed that after disruption of the posterior inferior frontal gyrus, grammatical role processing was impaired, providing evidence for the causal role of this region in sentence comprehension prompted by a prosodic cue. Together, the studies emphasise the influence of prosody on sentence comprehension and reveal core languages areas underlying these effects. In the paradigms presented here, prosodic cues were essential for sentence comprehension. In both paradigms, results suggested a key role for the left inferior frontal gyrus, a core area for sentence processing. The thesis concludes that prosody makes a central contribution the sentence processing system, as is reflected both on the behavioural and neural level.

My ear should catch your voice, my eye your eye,
My tongue should catch your tongue's sweet melody.

William Shakespeare - A Midsummer Night's Dream

When that strange expression of indiscretion
Begins to show in your stare
There's a hocus-pocus about your focus
That gives me a terrible scare

Cole Porter - Don't look at me that way

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Chapter 1

Introduction

As a way to convey thoughts from one person to another, humans have developed communication through complex sequences of sounds. The task of the listener is to deconstruct these sequences into consonants and vowels, then to reconstruct syllables and words, and ultimately, a sentence. To arrive at this end product—a mental representation in the form of a sentence—a wealth of processes is required. Successful and efficient processing draws on several levels of information that are contained in the speech stream, as well as in the abstract representations derived from it. These levels of information can be better understood by separating them in different linguistic disciplines, such as phonology (the study of sounds), syntax (grammar), and semantics (meaning).

Integral to sentence processing is not merely the analysis of *what* is being said, but also of *how* it is said. Prosody concerns those parts of the speech stream that are influenced by the *realisation of speech*, rather than the speech content. This includes the use of acoustic features such as intensity, pitch, and rhythm. As it concerns the sounds of speech and the rules that govern them, prosody is a field of study within phonology. Specifically, prosody can be described as *suprasegmental phonology*, given that its acoustic features are both superimposed on and spanning across the segmental phonology, that is, consonants and vowels (Féry, 2016). Although prosody concerns acoustic features applied to the words of an utterance, prosody can exert strong effects on the way a sentence is processed, similar to the effects that words themselves can have on the sentence interpretation. This will become apparent in the course of this introduction.

The effects of prosody on linguistic processing are manifold[1]. Broadly, effects of prosody can be distinguished in three main areas: on spoken word recognition, on syntactic structure, and on structuring of the discourse (Cutler, Dahan, & van Donselaar, 1997). On the word level, different placement of stress can create lexical distinctions (*INsight* vs *inCITE*) and steer the way compound words are

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[1] *Emotional prosody* concerns acoustic features reflecting a speaker's emotional attitude without carrying out a linguistic function, and is therefore disregarded here.

accessed (Isel, Gunter, & Friederici, 2003) and interpreted (e.g., *kitchen TOWEL rack* [a towel rack in the kitchen] vs *KITCHEN towel rack* [a rack for kitchen towels], from Everaert, Huybregts, Chomsky, Berwick, & Bolhuis, 2015)). Due to its acoustic saliency, prosody plays an important role during development. Infants are sensitive to the stress patterns of their native language, supporting their ability to segment words (Curtin, Mintz, & Christiansen, 2005), as well as to the intonational contours, supporting the distinction between phrases (Christophe, Mehler, & Sebastián Gallés, 2001). Indeed, already at the new-born stage, a child's cry mimics the stress patterns of their native language (Mampe, Friederici, Christophe, & Wermke, 2009).

Most prominently, prosody can have an influence on the sentence level, which will be the focus of the research presented here. Sentence-level prosody can influence how sentences are grammatically interpreted, as well as how information in the discourse is structured. To illustrate this, I will introduce two prosodic phenomena that are at the centre of the experimental work in this thesis: the intonational phrase boundary (IPB; Section 1.2) and the pitch accent (Section 1.3), two prosodic cues well-described in the linguistic and psycholinguistic literature. A third phenomenon, the question-marking pitch rise (not discussed in-depth in this introduction), will feature in the discussions of other studies.

Ultimately, the aim of this thesis is to investigate the ways in which prosody influences sentence processing and to study the neural implementation of these effects. To this end, novel paradigms were designed that investigated how the IPB and the pitch accent affect the listener's interpretation of a sentence. Finally, these paradigms were combined with neuroimaging methods to study the neuroanatomical regions supporting prosodic effects on sentence comprehension.

To fully appreciate sentence-level effects of prosody, it is worthwhile to first consider sentence processing in more detail.

1. Prosodic effects on sentence processing: a psycholinguistic perspective

1.1. Sentence processing

One of the main challenges for the language processing system is how to group words together, that is, how to *parse* the sentence. This is because words in a sentence do not merely form a string that can be processed linearly. Indeed, words frequently relate to elements in distant positions in the sentence, and their relationships can best be represented in a hierarchical structure (Everaert et al., 2015). Because during speech production, words are necessarily delivered linearly (i.e., one after another), the hierarchical structure is covered and not apparent at the surface. Therefore, during sentence processing, the relationships between words and the hierarchical structure they form need to be reconstructed. However, sometimes the same string of words can be structured in multiple ways, yielding different interpretations. Sentence processing research often makes use of these so-called structural ambiguities to investigate the way parsing is done (Bever, 1970). By investigating how ambiguous structures are interpreted, the preferred parsing of a string of words can be determined. Likewise, by introducing cues that disambiguate such structures, it can be analysed how influential a given cue is in driving the processing system towards a specific analysis of the sentence. Consider the following example sentences (1) to (3).

1 the reviewers claim the authors are mistaken
2 [the reviewers claim that [the authors are mistaken]]
3 [the reviewers [claims the author] [are mistaken]]

The structural ambiguity in (1) leaves two possible interpretations: either the reviewers accuse the authors of being wrong, or vice versa. To establish an unambiguous interpretation, morphosyntactic cues (from Greek *morphē* ‘form’) are required to disambiguate the structure. In (2), this is done by the complementiser “that”, and in (3), the word form indicating singular or plural allocates the nouns to their corresponding verbs (in these sentences, the brackets indicate the unambiguous structuring of the sentence).

The way the nouns and verbs of the sentence relate to one another is determined by the verb argument structure of a sentence. The verb argument structure lies at the core of sentence processing, as it governs our understanding of *who did what to whom*. Apart from syntactic cues, semantic cues can be helpful in conveying the verb argument structure. This becomes apparent in the list of words provided in (4).

4 arrests; police officer; thief

Even though this word list contains no syntactic cues, the most plausible interpretation is that of a police officer arresting a thief, not vice versa. This is because in relation to the verb “to arrest”, police officers are typical Agents (*doers*), and thieves typical Patients (*undergoers*) of the action. These properties of nouns are called thematic roles (Jackendoff, 1972) and have been shown to put semantic constraints on the syntactic analysis of a sentence (Ferreira & Clifton, 1986; Garnsey, Pearlmutter, Myers, & Lotocky, 1997; Trueswell, Tanenhaus, & Garnsey, 1994).

Classical sentence processing models differ in terms of the order in which these cues are used by the processing system. In serial models, an initial phrase structure is built based on the word category information of the input (noun, verb, adjective), without access to lexical information (Frazier & Fodor, 1978). In interactive or constraint-based models, syntactic and semantic cues are used in parallel to construct a sentence representation (Marslen-Wilson, 1975; Tanenhaus & Trueswell, 1995). Finally, some theories propose that neither cue type requires detailed or complete processing, and that an analysis based on simple heuristics may suffice to yield a so-called good-enough sentence representation (Ferreira, 2003; Ferreira, Bailey, & Ferraro, 2002).

Although these models differently describe the order in which syntactic and semantic cue types are processed, it is undisputed that prosody influences both of these domains. To illustrate this, two prosodic phenomena (see Figure 1A and 1B) will be introduced that are known to form a tight connection with syntactic structure and semantic information.

1.2. Intonational phrase boundaries

Intonational phrase boundaries (IPBs) form a direct interface with syntactic processing by signaling syntactic boundaries. This can be appreciated in (5) and (6) and in Figure 1A.

5 The reviewers claim # the authors are mistaken

6 The reviewers # claim the authors # are mistaken

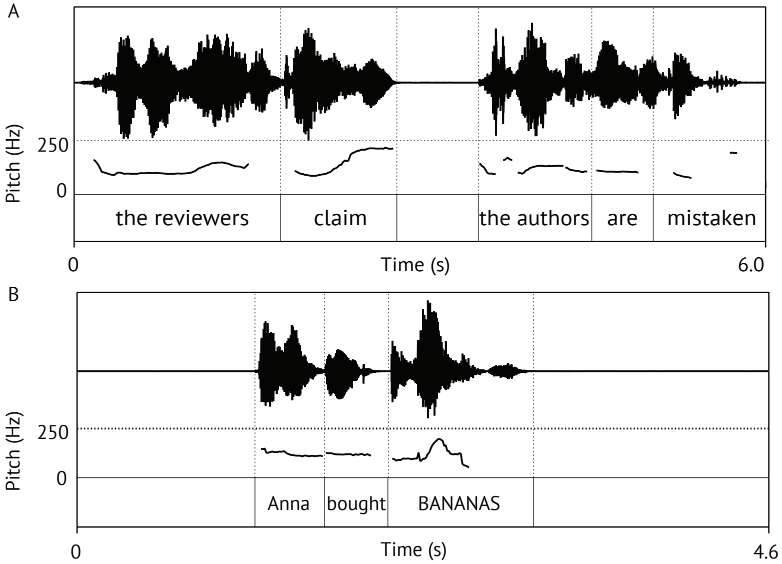

Figure 1. Speech waveforms and pitch contours of two prosodic phenomena, the intonational phrase boundary (A) and pitch accent (B). Note the pitch rise and syllable lengthening on *claim.* followed by a pause (A) and the rise in pitch and intensity on *bananas* (B).

Here, disambiguation is done not by morphosyntax as in the aforementioned (2) and (3), but by acoustic boundaries in the form of an IPB (indicated with #): the prosodic realisation of the sentence resolves the structurally ambiguous string in (1). IPBs are acoustically comprised of a pitch rise and syllable lengthening, followed by a pause

(Selkirk, 1984). The close connection between prosody and syntactic structure has been described in linguistic theory: IPBs often signal a syntactic boundary, yet, not all syntactic boundaries are marked by an IPB (Nespor & Vogel, 1983; Selkirk, 1984). Subsequent psycholinguistic studies showed that the interpretation of various types of syntactic ambiguities can be influenced by prosodic structure (Beach, 1991; P. J. Price, Ostendorf, Shattuck-Hufnagel, & Fong, 1991).

One of the first studies to demonstrate that prosodic cues could affect parsing of syntactic structure in an online fashion was performed by Marslen-Wilson and colleagues (1992). They studied processing of sentences of the type given in (7).

7 The workers considered the last offer from the management was a real insult[2]

Without prosodic information, this sentence is ambiguous up to “was”: “the last offer” can be either the direct object of “considered”, or the subject of a complement clause (the last offer was a real insult). The ability of listeners to integrate upcoming sentence material in the sentence depended directly on which type of syntactic structure was signalled by the prosodic realisation of the utterance. This showed that during online processing, prosody directly affected syntactic analysis. Importantly, including the morphosyntactic cue “that” to separate main clause and complement clause, as in (8), did not lead to further facilitation of responses over and above the prosodic boundary.

8 The workers considered that the last offer from the management was a real insult[2]

This suggested that prosodic boundaries have strong effects on the parsing of a sentence, such that morphosyntactic cues do not provide an additional disambiguation influence.

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[2] From Marslen-Wilson et al. (1992)

Prosodic effects on syntactic processing have subsequently been shown in various sentence comprehension tasks, showing both facilitatory effects when syntactic and prosodic structure correspond, and interference effects when syntax and prosody mismatch (Kjelgaard & Speer, 1999; Speer, Kjelgaard, & Dobroth, 1996). Subsequent work on the acoustics of IPBs showed that not the absolute, but the relative size of local and distal boundaries matter for the way a sentence is parsed (Carlson, Clifton, & Frazier, 2001; Clifton, Carlson, & Frazier, 2002). Furthermore, in addition to the size of the prosodic boundaries, the size of the constituents that they separate play a role (Clifton, Carlson, & Frazier, 2006).

Finally, Buxo-Lúgo and colleagues (2016) recently showed that prosodic boundaries are more likely to be perceived at locations in the sentence where they are syntactically plausible, suggesting an influence of syntax on prosody perception, in addition to the well-established effects of prosody on syntactic processing.

1.3. Pitch accents

Research on pitch accents has concentrated on the interaction between prosody and information structure. Information structure can be described as the *packaging* of information, such that it fits the communicative requirements of a conversation (Féry & Krifka, 2008). It can be intuitively appreciated in question-answer pairs such as (9a) and (9b).

9

a. What did Anna buy?
b. Anna bought BANANAS

Here, *bananas* is highlighted by means of a pitch accent to efficiently provide the information that was requested. This highlighting of information is called *focus,* a feature of information structure that marks new or important information (Rooth, 1992). Pitch accents are realised acoustically by an increase in intensity and pitch, and play a central role in establishing the information structure in intonational languages, such as English and German (Breen, Fedorenko, Wagner, & Gibson, 2010;

Féry & Kügler, 2008). Sentence information that is new or important is usually pitch accented, as opposed to that what is given or unimportant[3].

Focus forms a close connection to semantic processing by activating a set of semantic alternatives to the focused constituent: after hearing (9b), a listener may automatically wonder what other types of groceries Anna could have bought. Cross-modal priming studies showed a facilitation for items of related or previously activated set belonging to the same category of the focused item (Braun & Tagliapietra, 2010; Husband & Ferreira, 2016; Watson, Tanenhaus, & Gunlogson, 2008; see Gotzner & Spalek (2019) for a discussion on the scope of these categories).

These semantic pre-activations led to the hypothesis that pitch accents contribute to semantic processing in a predictive manner. This was subsequently tested using visual world paradigms and eye-tracking (Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995), in which participants typically watch a scene with objects while listening to a sentence, with simultaneous measurement of their eye movements and fixations. In these experiments, participants start fixating at elements in the visual scene based on semantic context and pitch accent cues, demonstrating that pitch accents can help to infer semantic properties of upcoming words (Dahan, Tanenhaus, & Chambers, 2002; Weber, Braun, & Crocker, 2006; Ito & Speer, 2008; Karimi, Brothers, & Ferreira, 2019; Kurumada, Brown, Bibyk, Pontillo, & Tanenhaus, 2014).

Although the role of pitch accents in processing information structure and the semantic domain has been studied most extensively, pitch accents interact with the syntactic domain as well. An example of this can be found in (10).

10 …the propeller of the plane, that the mechanic was so carefully examining[4]

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[3] A non-prosodic manner of assigning focus could be syntactic: *It was bananas that Anna bought.*

[4] From Schafer et al. (1996).

In (10), a pitch accent on either *propeller* or *plane* determines if the mechanic is interpreted to examine the former or the latter (Carlson & Tyler, 2017; Schafer et al., 1996). The accented and focused constituent seems to attract the relative clause (but see E.-K. Lee & Watson (2010) for an alternative explanation). Furthermore, and analogous to the semantic domain, eye-tracking studies have shown that this syntactic role of pitch accents has been shown to be predictive (Nakamura, Arai, & Mazuka, 2012; Weber, Grice, & Crocker, 2006b).

Together, the psycholinguistics literature shows a clear influence of pitch accents on both syntactic and semantic processing. Furthermore, pitch accents exert their effects on sentences in an anticipatory way, supporting recent models that emphasise the predictive nature of language processing (Federmeier, 2007; Ferreira & Chantavarin, 2018; Kuperberg & Jaeger, 2016; Pickering & Gambi, 2018). In all of these previous studies, however, effects of pitch accents on the syntactic and semantic domains were studied in isolation. What is unclear, is if a pitch accent can establish expectations simultaneously in both domains. Furthermore, because research on the interaction of all three cues (prosodic, syntactic, and semantic) is limited, an important open question remains which cues are most influential in guiding sentence processing when multiple, competing cues are available.

1.4. Summary part I

Prosody forms an interface with various components of a sentence and can influence comprehension in various ways. The IPB is a prosodic cue that forms a particularly close connection to syntactic structure, coinciding with syntactic boundaries and disambiguating syntactic structure during online processing. After a brief methodological overview in **Chapter 2**, the IPB will be used in **Chapter 3** to study the neuroanatomical basis of syntactic structure building guided by prosody. The pitch accent has been found to inform either sentential syntax or semantics. One question that remains outstanding is if a single pitch accent can establish expectations simultaneously in both domains. Furthermore, it is unclear which type of cue takes precedence if multiple contradicting cues exist in the sentence. These questions will be addressed in **Chapter 4**. Both phenomena, the IPB and the pitch accent, have been used in prosody research on the neurocognitive level, which is what I will turn to in the second part of this introduction.

2. Prosody in neurocognitive research

The development of neuroimaging techniques has enabled investigation of how the rapid integration of prosodic cues during sentence comprehension is implemented in the brain. This section will concentrate on neuroimaging work on sentence-level prosody, using methods that investigate the temporal aspects (electroencephalography (EEG) studies) and cortical distribution of prosody processing (functional magnetic resonance imaging (fMRI) and positron emission topography (PET) studies). In addition, attention will be paid to the lesion literature. To provide a background for this, what follows is a brief overview of the brain structures supporting auditory sentence comprehension in general. This section will draw on studies using a range of methods, such as fMRI, EEG, electrocorticoraphy (ECoG), and transcranial magnetic stimulation (TMS).

2.1. The language network

The translation of sound pressure waves into a mental representation requires many processing steps, supported by the interaction between widely distributed structures in the human brain. A number of influential models exist today that describe these pathways in detail (Bornkessel-Schlesewsky & Schlesewsky, 2013; Duffau, Moritz-Gasser, & Mandonnet, 2014; Fedorenko & Thompson-Schill, 2014; Friederici, 2012; Hagoort, 2017; Poeppel, Emmorey, Hickok, & Pylkkänen, 2012; Ullman, 2016), based on a rich body of neuroimaging literature (reviewed in Friederici (2011); C. J. Price (2012); Vigneau et al. (2006)). An illustration of the main neuroanatomical regions within the language network can be found in Figure 2.

After several filtering steps in the inner ear, the speech signal travels down the cochlear nerve, via nuclei in the brainstem, pons, and thalamus, to Heschl's gyrus

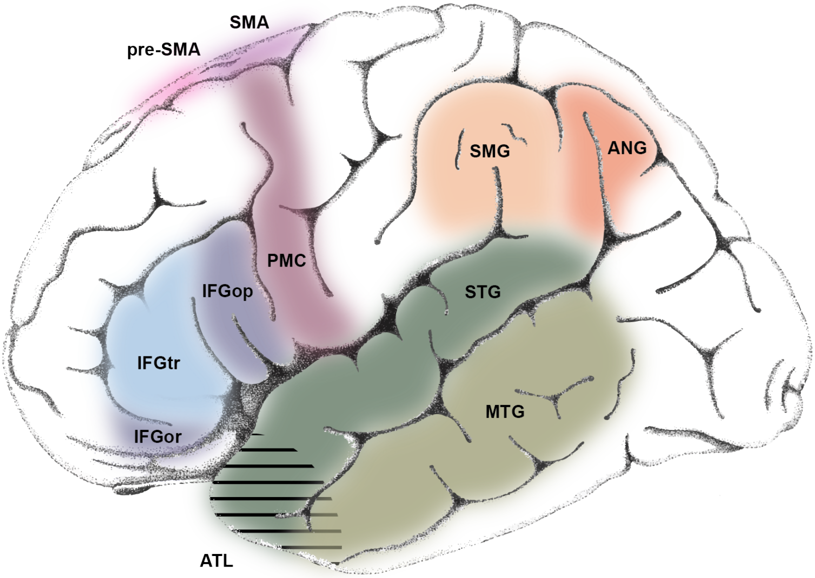

Figure 2. Illustration of the left hemisphere with the main neuroanatomical regions supporting language processing. IFGor/IFGtr/IFGop: inferior frontal gyrus pars orbitalis/triangularis/opercularis. PMC: premotor cortex. SMA: supplementary motor area. ATL: anterior temporal lobe. MTG: middle temporal gyrus. STG: superior temporal gyrus. SMG: supramarginal gyrus. ANG: angular gyrus.

in primary auditory cortex (Pickles, 2015). During the earliest stages, a hemispheric asymmetry in speech processing exists, thought to arise from a differential sensitivity of left and right temporal cortex to temporal and spectral properties, respectively (Poeppel, 2003; Zatorre, Belin, & Penhune, 2002; but see McGettigan & Scott (2012) for a more nuanced account). The superior temporal gyrus (STG) is fundamental for abstraction into the smallest linguistic units, such as phonetic features (Mesgarani, Cheung, Johnson, & Chang, 2014), phonetic categories (Chang et al., 2010), and morphemes (D. K. Lee et al., 2018).

Following these initial acoustic processing steps, syntactic and lexical information becomes available. This occurs extremely fast, as has been shown by a number of seminal electrophysiology studies. Syntactic information becomes available as early as 120-200ms, as shown by an early left anterior negativity (ELAN) (Friederici, Pfeifer, & Hahne, 1993; Neville, Nicol, Barss, Forster, & Garrett, 1991) elicited by word category misfit in syntactically obligatory situations. Semantic processing has been reliably shown by a negativity around 400 ms (N400), representing lexical retrieval or integration effort (DeLong, Urbach, & Kutas, 2005; Kutas & Hillyard, 1980; Lau, Phillips, & Poeppel, 2008). Finally, a positivity around 600 ms (P600) is taken to reflect a late integration phase, as indicated by syntactic reanalysis processes (Gunter, Friederici, & Schriefers, 2000; Kaan, Harris, Gibson, & Holcomb, 2010). These electrophysiological components have provided a fruitful temporal framework in studying the sequence of events during sentence processing (see for a more recent discussion Kuperberg et al. (2020)). Furthermore, aside from the acoustic input (so-called *bottom-up* input), contextual effects have been shown to play a role in sentence processing, such as discourse (Nieuwland & Van Berkum, 2006; Van Berkum, Brown, & Hagoort, 1999) or speaker information (Van Berkum, van den Brink, Tesink, Kos, & Hagoort, 2008).

The division between syntactic and semantic processing has been extended to the neuroanatomical level, as both have been shown to rely on mostly separable structures. Most prominently, within the left inferior frontal gyrus (IFG), syntactic processing has consistently been associated to the more posterior pars opercularis and semantic processing to the more anterior pars triangularis (Dapretto & Bookheimer, 1999; Goucha & Friederici, 2015; Hagoort & Indefrey, 2014; Rodd, Vitello, Woollams, & Adank, 2015). These anatomically defined subregions roughly correspond to a subdivision of the IFG in terms of cytoarchitectonic areas: Brodmann area (BA) 44 (pars opercularis) and BA45 (pars triangularis) (Amunts et al., 1999). The posterior superior temporal gyrus and sulcus (pSTG/S) is an additional key syntactic region, involved in the integration of syntactic information and verb argument structure (Bornkessel, Zysset, Friederici, Cramon, & Schlesewsky, 2005; Grodzinsky & Friederici, 2006). Further core semantic regions are thought to be the angular gyrus (Binder, Desai, Graves, & Conant, 2009) and the anterior temporal lobe (ATL), likely as hubs in a more distributed semantic network (Ralph, Jefferies, Patterson, & Rogers, 2017). In some accounts, the ATL rather supports combinatorial processing in general (Pylkkänen, 2019).

Core syntactic and semantic computations are supported by a number of major fibre tracts connecting the left temporal and frontal lobes: a dorsal connection formed by the arcuate fascicle and the superior longitudinal fascicle has been associated with sound-to-articulation mapping, whereas a ventral connection was shown to subserve sound-to-meaning mapping (Saur et al., 2008). These data support a dual stream model of speech perception (Hickok & Poeppel, 2007; Rauschecker & Scott, 2009), analogous to the visual system (Goodale & Milner, 1992). These frameworks were later extended to a model ascribing complex syntactic processing to a dorsal connection between posterior IFG and posterior STG (Friederici, 2015).

Sentence comprehension requires several support processes, such as working memory, which are thought to be functionally and to some extent anatomically separable from core language functions (Fedorenko, Duncan, & Kanwisher, 2012; Makuuchi, Bahlmann, Anwander, & Friederici, 2009). Around language-specific structures at the heart of sentence processing, a number of structures can be found which are involved in processes that contribute to sentence comprehension. In the frontal lobe, these include premotor cortex, which has been suggested to contribute to articulatory processes in both perception and production (Möttönen & Watkins, 2009; Müsch, Himberger, Tan, Valiante, & Honey, 2020), the supplementary motor area (SMA) for motor related auditory processing, and the pre-SMA for planning of speech acts (Hertrich, Dietrich, & Ackermann, 2016; Lima, Krishnan, & Scott, 2016; Schwartze, Rothermich, & Kotz, 2012). In the parietal lobe, inferior parietal cortex has been associated to both higher level and lower level aspects of language processing (Bzdok et al., 2016), with supramarginal gyrus (SMG) often associated with phonological processing (Hartwigsen, Baumgaertner, et al., 2010a; Oberhuber et al., 2016; Raizada & Poldrack, 2007) and angular gyrus with semantic processing (Bemis & Pylkkänen, 2013; Binder et al., 2009; Hartwigsen et al., 2016).

In sum, language processing is mainly supported by regions in the temporal and frontal lobes, predominantly in the left hemisphere. Which parts of this language network are involved in prosody processing is an intriguing research question, given the intertwined role which prosody plays with respect to syntax and semantics.

Within neuroimaging research on language, however, prosody has held a relatively underappreciated position. Where syntax and semantics have been widely studied, generating extensively debated models (Binder et al., 2009; Friederici, 2011; Kaan & Swaab, 2002; Matchin & Hickok, 2019; Ralph et al., 2017), prosody has notably received less attention. Moreover, although the effects of prosody on sentence structure are non-negligible, neuroimaging studies investigating these effects are relatively rare. An exception to this are electrophysiological studies on the syntax-prosody interface. These studies will be addressed first.

2.2. Prosody: EEG studies

Given its high temporal resolution, EEG has proven to be a powerful method in scrutinising prosody-syntax interaction effects. A landmark study on prosodic effects during sentence processing was performed by Steinhauer et al. (1999). Using EEG, the authors were able to show that depending on the position of an IPB, a certain verb-argument configuration was expected. A mismatch between the prosodic structure and the incoming verb led to an event related potential (ERP) response indicating processing effort (N400) and reanalysis of the sentence (P600). Furthermore, detection of an IPB elicited a positivity in the EEG signal, coined closure positive shift (CPS), providing a direct electrophysiological readout of a prosodic phenomenon. Importantly, the CPS was evoked even when the pause was removed from the IPB, suggesting that in adults, pitch rise and syllable lengthening are the fundamental acoustic cues that constitute an IPB. In turn, the combination of these cues (syllable lengthening and pitch rise) is required for the perception of an IPB (Holzgrefe-Lang et al., 2016). Later work showed that the CPS effect is elicited also in jabberwocky (language without semantic meaning) and hummed speech (Pannekamp, Toepel, Alter, Hahne, & Friederici, 2005), supporting its purely prosodic effect, and the effect has been replicated in various languages (Bögels, Schriefers, Vonk, Chwilla, & Kerkhofs, 2010; Isel, Alter, & Friederici, 2005; Pauker, Itzhak, Baum, & Steinhauer, 2011; Roll & Horne, 2011). Finally, developmental studies have highlighted the sensitivity to prosodic boundaries during language development, with a CPS arising around 2,3 years of age, and at 6-years-of-age in response to IPBs without pause

(Männel & Friederici, 2009; 2011; Männel, Schipke, & Friederici, 2013). A detailed discussion of EEG studies on prosodic boundary perception can be found in Bögels et al. (2011).

The experimental paradigm from Steinhauer et al. (1999) formed the basis for a lesion study that provided key evidence on the hemispheric interaction involved in processing of the prosody-syntax interface. In patients with lesions in the posterior part of the corpus callosum, prosodic-syntactic violations did not elicit an N400-effect, providing strong evidence for the necessity of interhemispheric transfer between the temporal lobes in order for syntactic and prosodic structure to be matched (Friederici, Cramon, & Kotz, 2007). These findings were later extended by Sammler et al. (2010) using a paradigm in which the syntactic structure informed prosodic structure (rather than vice versa), underlining the importance of interhemispheric transfer for the interaction between prosodic and syntactic information during sentence processing.

Finally, experiments on pitch accent processing have shown early EEG responses as well, both when pitch accents correspond to focus structure (Heim & Alter, 2006; Hruska & Alter, 2004) and when prosodic and focus structure mismatch (Wang, Bastiaansen, Yang, & Hagoort, 2011). Furthermore, a reading study, investigating so-called implicit prosody, suggested that reanalysis of the focus structure and of its (implicit) prosodic structure lead to distinct electrophysiological correlates (Stolterfoht, Friederici, Alter, & Steube, 2007).

Together, these studies have shown that prosodic effects on sentence processing are rapid (in the range of 100-400ms) and, importantly, that they have a neural correlate that can be reliably measured using EEG.

2.3. Prosody: fMRI and PET studies

For the appraisal of the fMRI literature on prosody processing, it is both helpful and important to organise previous work based on the type of stimulus studied, the paradigm used, and the overall study design. The stimulus material has varied from natural sentences to acoustically manipulated speech (filtering out either segmental information, resulting in a sound comparable to hummed speech, or the suprasegmental information, yielding flattened speech). Experimental paradigms have varied from sub-vocal repetition of intonational contours to answering of comprehension questions. Finally, the study design or experimental approach matters: comparisons can be made between an experimental and a control task or between different stimulus manipulations (e.g., manipulating the acoustics or the congruency between prosodic structure and either syntactic or information structure). Consequently, the results found in the prosody literature vary considerably.

In studies with an emphasis on acoustic features, which effectively isolate either higher- or lower-frequency information in speech, primary and secondary auditory areas are consistently found. Importantly, it is the higher-frequency part of the signal that contains phonemic and lexical information, and the lower-frequency part that contains information pitch – the information relevant for prosodic phenomena. Analysis contrasts that emphasise the segmental information result in predominantly left hemispheric activity (including the IFG) (M. Meyer, Alter, Friederici, Lohmann, & Cramon, 2002; M. Meyer, Steinhauer, Alter, Friederici, & Cramon, 2004). Comparisons on flattened speech or speech in which only supra-segmental information is available involve the superior temporal cortices, often with a dominance for the right hemisphere (Kyong et al., 2014; M. Meyer et al., 2004). A task that requires rehearsal of the pitch contour additionally yields activation of the right IFG (Hesling, Clément, Bordessoules, & Allard, 2005; Kyong et al., 2014; M. Meyer et al., 2004; Plante, Creusere, & Sabin, 2002), which corroborates results from question/statement intonation discrimination tasks (Kreitewolf, Friederici, & Kriegstein, 2014; Sammler, Grosbras, Anwander, Bestelmeyer, & Belin, 2015). It seems that the right IFG comes into play when the pitch information requires further processing, such as keeping in working memory, or decision-making based on the pitch contour.

Investigations of prosodic effects on the sentence level include comparisons between sentence and list-like prosodic contours, recruiting areas in bilateral (superior) temporal cortex (Fedorenko, Hsieh, & Balewski, 2014; Humphries, Love, Swinney, & Hickok, 2005). Activations along the STG are also found in studies on rhythmical patterns such as word stress and rhythmical well-formedness (Honbolygó et al., 2020; Kandylaki et al., 2017).

Few studies have investigated prosodic effects on structural processing using the IPB. Contrasting sentences with and without IPB, right frontal and cerebellar activation was found (Strelnikov, Vorobyev, Chernigovskaya, & Medvedev, 2006). However, this functional contrast confounded prosodic aspects with syntactic and semantic aspects in both stimuli and task. A study contrasting sentences containing 2 vs 1 IPBs showed bilateral superior temporal regions (Ischebeck, Friederici, & Alter, 2008). This study reported additional involvement of left premotor and inferior frontal regions when contrasting natural vs hummed speech, likely reflecting additional phonological, syntactic, and semantic processing.

Studies on pitch accent processing frequently investigated the compatibility of prosody with information structure. Among other regions, these studies report involvement of the left IFG when the position of pitch accents is incongruent vs. congruent with sentence semantics or pragmatics (Kristensen, Wang, Petersson, & Hagoort, 2013; van Leeuwen et al., 2014). The left IFG is also involved in contrasts between focused vs. neutral phrases (Perrone-Bertolotti et al., 2013) and linguistic vs. emotional prosody discrimination (Wildgruber et al., 2004).

In sum, functional imaging studies show that prosody processing is supported by a mostly bilateral fronto-temporal network, with the exact distribution of activity highly dependent on experimental approach and study design. Activity in temporal cortex is found, predominantly in the right hemisphere, when stimulus or task contrasts emphasise the acoustic features of prosodic phenomena. In the frontal lobe, the right IFG seems to be involved when the pitch contour is used in memory-related or decision-making processes. In the left hemisphere, IFG has been reported in interactions of prosody with information structure, however, since many of these contrasts involved violations or incongruencies, an explanation of these results in terms of more general attentional or error processing cannot be excluded.

2.4. Lateralisation debate

Within studies on prosody, lateralisation of processing has been a prominent topic of research. Although mammals have a symmetrically organised body, their brains show many asymmetries. This is thought to be beneficial in various ways. Hemispheric distribution of brain functions is computationally efficient; it increases processing capacity and enables parallel processing (Ocklenburg & Güntürkün, 2018). Furthermore, it allows for specialisation of functions in either hemisphere. At the origin of lateralisation research is thought to be Paul Broca, who in the early 19th century was one of the first to note that the post-mortem brains of patients suffering from language production deficits had lesions in the left, and not the right hemisphere (Broca, 1861a; 1861b)[5].

Prosody has taken an interesting position in lateralisation research, since it is classically seen as being predominantly right-lateralised, in contrast to other components of language such as syntax, semantics, and segmental phonology. This view was originally based on lesion studies and data from dichotic listening studies. Dichotic listening studies, in which both ears are simultaneously presented with different stimuli, initially showed a left-ear (right-hemispheric) advantage for intonational contour processing (Blumstein & Cooper, 1974). This lateralisation was later shown to be task-specific, with a right-ear advantage for discrimination of linguistic prosody (question/statement intonation), and left-ear advantage for emotional prosody (angry/sad intonation) (Luks, Nusbaum, & Levy, 1998). Lesion studies have shown a similar asymmetry, although a recent meta-analysis of lesions studies put forward a more nuanced, bi-hemispheric picture (Witteman, van IJzendoorn, van de Velde, van Heuven, & Schiller, 2011). Together, this has led to models suggesting that lateralised processing of pitch information occurs in function of the linguistic purpose of pitch contour processing: the more linguistic information

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[5] It should be noted that Marc Dax and his son Gustave were making similar observations around the same time or possibly earlier. See for an example of this discussion Finger & Roe (1999).

is conveyed, the more the left hemisphere is engaged (Friederici & Alter, 2004; van Lancker, 1980).

Using fMRI, the lateralisation question has been studied using lateralisation analyses that directly compare activation in both hemispheres via a normalisation to a symmetrical brain template. Using contrasts between an intonation judgement to both a linguistic task (phoneme judgement) and a non-linguistic control task (speaker identity judgement), it was shown that the contributions of each hemisphere depended on the control task used. Activity in the intonation task is left-lateralised when contrasted to the non-linguistic task, and right-lateralised when contrasted to the linguistic task (Kreitewolf et al., 2014), regardless of whether listeners are native speakers of tonal or non-tonal languages (Chien, Friederici, Hartwigsen, & Sammler, 2020). These results are in line with Sammler et al. (2015), who similarly contrasted question/statement judgement with phoneme judgement, resulting in functional activity in the right hemisphere. These results were complemented using a non-invasive brain stimulation method, TMS: transient disruption of the right, but not left premotor cortex inhibited performance in the prosody task, leaving the phoneme task unaffected (Sammler et al., 2015). Task-dependent results have further been found in experiments contrasting a linguistic prosody task to an emotional prosody task (Wildgruber et al., 2004). Finally, cross-linguistic studies have frequently reported left-lateralised activations for lexical tone perception (Gandour et al., 2004; 2000).

It can be concluded that linguistic prosody is processed in both hemispheres, and that a possible lateralisation of processing depends partly on the task: if the cognitive subtraction of two tasks types isolates linguistic processing, increased engagement of the left hemisphere is found. However, given the considerable influence of the control task used on the pattern of results, the literature lacks a study investigating the lateralisation hypothesis by comparing different usage of a prosodic cue within the same task.

2.5. Summary part II

Neurocognitive research on prosody processing has seen a wide number of approaches. Accordingly, the results of these studies have painted a varied picture in terms of the brain networks that support prosody processing, with the exact pattern of frontal and temporal areas involved depending on variables such as task, stimulus material, and experimental approach used. Moreover, few fMRI studies have been carried out on the interaction between prosodic cues on syntactic processing. We therefore set out to study prosody processing using the prosodic cue that arguably has the closest connection to sentence structure: the IPB. Importantly, given the described effects of study design in previous neuroimaging studies, the brain basis of sentence processing guided by the IPB will be investigated using natural, ecologically valid, grammatical stimuli, using a single task. Varying the necessity of the IPB for syntactic structure building, the effect of the IPB's linguistic role on the lateralisation of brain functions will be assessed. These are the questions that **Chapter 3** is concerned with.

3. Scope of this thesis

In three studies, this thesis will address different ways in which prosodic phenomena affect other domains of linguistic processing and consider the brain areas involved in this interaction.

Chapter 2 provides a brief overview of the methodology used in this thesis.

In **Chapter 3** I investigate the neural correlates of sentence processing guided by prosodic cues. In a sentence comprehension task, participants relied on either a prosodic or a morphosyntactic cue, or a combination of both, to understand the sentence structure. Using fMRI, this study showed that the left inferior frontal gyrus is engaged in processing of sentences in which the structure is established by a prosodic cue. Furthermore, lateralisation of activity in the left inferior frontal gyrus was driven by the relevance of the prosodic cue for the interpretation of the sentence structure.

Chapter 4 explores the interaction between prosody and both syntactic and semantic processing. I ask the question if a processing hierarchy exists between cues from these three domains, and if so, which cue takes prevalence when competing cues co-occur. This study investigated if pitch accents can establish dissociable expectations in the syntactic and semantic domains, using two behavioural experiments: a sentence comprehension task and a sentence completion task. Results pointed to expectations established by pitch accents in both syntactic and semantic domains. However, only violated syntactic expectations were strong enough to interfere with sentence comprehension.

Results of both studies are brought together in **Chapter 5**, which concentrates on the role of the left inferior frontal gyrus in processing of syntactic, semantic, as well as prosodic cues. The aim of this TMS experiment was to explore the causal role of the left inferior frontal gyrus for sentence processing guided by prosodic cues. A further objective was to demonstrate the causal role of subregions of the inferior frontal gyrus in the syntactic and semantic processes prompted by pitch accents. Results showed impaired syntactic as well as semantic decisions after disruption of the posterior inferior frontal gyrus, providing evidence for the causal role of this region in processing of grammatical roles in the sentence prompted by a prosodic cue.

In **Chapter 6,** I place the findings of these three studies in wider perspective, addressing limitations of my work as well as suggesting a number of future directions for the cognitive neuroscience of prosody processing.

Chapter 2

Methodology

1. Modelling behaviour

Behavioural data of response time experiments, such as the ones described in this thesis, typically yield two behavioural outcome measures: response times and accuracy rates. These types of studies are founded on a core principle of experimental psychology dating back to Franciscus Cornelisz Donders, which posits that psychological processes are in part serial and that their duration can be measured (Donders, 1969). From this stems the concept of *cognitive subtraction*: the processing time of a given cognitive process will be reflected in the response time difference between two experimental conditions that are designed to differ in that particular cognitive process (Sternberg, 1969). This rationale is used throughout the current thesis. In **Chapter 3**, comparisons are made between processing times required to disambiguate sentence structure using one or multiple disambiguating cues. In **Chapter 4**, response times to comprehension questions are compared, contrasting sentences that contain violations between syntactic or semantic information and baseline sentences containing solely congruent information.

A common statistical method used to analyse response time and accuracy data is analysis of variance (ANOVA). In an ANOVA, group means and variances are computed and compared to assess possible differences between groups. A key assumption of the ANOVA is that the residuals of the computed estimates are normally distributed, homogeneous, and independent, an assumption that is almost never met in response time data (Rousselet & Wilcox, 2020). Log-transformation of response times may improve their normality distribution. Alternatively, non-parametric tests can be used, such as the Friedman test.

As an alternative to the ANOVA, recent years have seen a rise in the use of linear mixed effects models (LMMs; also Generalised LMMs, or GLMMs) (Singmann & Kellen, 2019). What LMMs and ANOVAs have in common, is that they try to estimate a response parameter in function of a set of predictors or experimental factors (Baayen, Davidson, & Bates, 2008). However, LMMs provide a more flexible alternative to the classical ANOVA approach for a number of reasons. Most importantly, LMMs try to fit a distribution to the contribution of factors that the experimenter is usually not interested in, the *random effects* (Barr, Levy, Scheepers, & Tily, 2013). In this way, they can account for differences between responses given by different participants or given to different experimental items. Furthermore, in LMMs, single-trial responses can be modelled, avoiding the need for computing a grand average (as commonly done in the ANOVA). Finally, by means of so-called link functions, GLMMs can be used to analyse data with various statistical distributions besides the normal distribution that is mandatory for an ANOVA. Disadvantages of LMMs are that the most appropriate way to perform statistical inference is debated (Singmann & Kellen, 2019), and that inference is highly dependent on the way the random effects are modelled, necessitating transparent reporting of both the models used and corresponding results (Meteyard & Davies, 2020).

(G)LMMs are used for analysis of the behavioural results in **Chapters 2** and **3** of this thesis, with the behavioural data in **Chapter 1** being analysed with a non-parametric alternative to the ANOVA.

2. Functional Magnetic Resonance Imaging

Since the 1990s, functional Magnetic Resonance Imaging (fMRI) has been a successful method for non-invasive mapping of functional brain responses and has developed into a widely used tool in cognitive neuroscience research. fMRI is based on the principle of nuclear magnetic resonance (NMR) imaging, which uses a strong magnetic field in combination with a radiofrequency pulse to measure energy emitted by resonating protons. Given the different nuclear properties of different tissue types, this can be used to create an image of the body. Depending on the configuration of the pulse sequence, tissues with different molecular makeup can be visualised.

In fMRI, this principle is used to visualise levels of blood oxygenation. Specifically, in fMRI the magnetic properties of deoxyhaemoglobin are used to compute a signal called the blood oxygenation level dependent (BOLD) signal (Ogawa, Lee, Kay, & Tank, 1990). The BOLD signal is thought to reflect the local field potential at a given area and it is assumed that neurovascular coupling (the relationship between blood flow and neural activity) is more or less linear (Logothetis, Pauls, Augath, Trinath, & Oeltermann, 2001)). This latter principle is then used to model the neural response: the BOLD response is convolved with a haemodynamic response function that describes the way BOLD response relates to the neural response (Buxton, Uludağ, Dubowitz, & Liu, 2004). Before this step can be done, however, the acquired images require pre-processing.

An fMRI measurement typically consists of a time series that contains the BOLD signal acquired at regular intervals. First, the images require spatial realignment to a reference image, to correct for any motion that may have occurred inside the scanner. Additionally, the images are unwarped to correct for any inhomogeneities in the magnetic field. To enable inference on functional activity across participants, the images are normalised to an average brain, commonly the Montreal Neurological institute (MNI) template. Finally, the images are smoothed in order to reduce inter-individual variability and to improve the gaussian distribution of the data, meeting a critical assumption for the statistical analysis used on the fMRI images (Friston, Worsley, Frackowiak, Mazziotta, & Evans, 1994b).

The statistical analysis of the BOLD images occurs in two steps. On the single-subject level, the experimenter constructs a generalised linear model (GLM) that describes all events during the fMRI session. This model is then convolved with a hemodynamic response function, which describes the neurovascular coupling (Buxton et al., 2004). Subsequently, a model fit is computed comparing the GLM with the measured BOLD response in each voxel. In a second step, statistical inference on the group level is performed (Friston, Holmes, Worsley, Poline, Frith, & Frackowiak, 1994a). Finally, based on the cognitive subtraction principle, BOLD responses to different conditions are contrasted to each other to yield a brain activation map that reflects the cognitive process under investigation (Karni et al., 1995; Lueck et al., 1989).

The study presented in **Chapter 3** is a sentence comprehension task performed in the MRI scanner. This method of investigation, although limited in temporal resolution, allowed for detailed spatial information on the brain regions that support processing of prosodic cues and sentence structure. The high spatial resolution of fMRI makes it an appropriate method for a localisationist approach to prosody processing in the brain and is therefore the method of choice in this study. In addition to a standard univariate, whole-brain method of analysis, a lateralisation analysis is presented that directly compares the contribution of both hemispheres in processing of prosodic cues.

3. Transcranial Magnetic Stimulation

Transcranial magnetic stimulation (TMS) emerged in the 1980s as a method that could noninvasively stimulate the brain (Barker, Jalinous, & Freeston, 1985). TMS employs a copper-wire coil that is held against the scalp. A brief pulse is generated, translating into a magnetic field around the coil which traverses the skull in a painless manner, evoking an electrical current in the underlying tissue. Initially developed in research on the motor system, the evoked neural response in motor cortex could be measured as a muscle response at the corresponding muscle (Day et al., 1989). Both the high temporal and spatial resolution, in the order of milliseconds and centimetres, respectively, has made TMS a useful method in mapping cortical functions (Parkin, Ekhtiari, & Walsh, 2015).

This utility was increased further when discovered to be able to induce changes in motor response, in some cases outlasting the time of stimulation. Using repeated application of TMS pulses, repetitive TMS (rTMS) at 1Hz was found to decrease the motor evoked response (Chen et al., 1997). Conversely, rTMS at higher frequencies (5-20Hz) was found to increase the motor evoked response (Pascual-Leone, Valls-Solé, Wassermann, & Hallett, 1994). Later, the rhythmic application of triplets of pulses at 5Hz, so-called theta-burst stimulation, was shown to either facilitate or inhibit the motor response, depending on whether bursts were applied continuously or intermittently (Huang, Edwards, Rounis, Bhatia, & Rothwell, 2005).

Application of TMS has been used to study a wide range of cognitive functions. Using rTMS, neural activity in a certain cortical region is transiently disrupted. Applied in combination with a behavioural experiment, rTMS allows for conclusions about the involvement of a certain cortical region in a given task. An early application in the language domain was performed by Pascual-Leone and colleagues (1991), who induced speech arrest by applying 25Hz rTMS in epilepsy patients. rTMS can either be applied during the task, in so-called online fashion, or offline, making use of plasticity-like effects that are presumed to last for the duration of the experimental task. Alternatively, single-pulse TMS can be used in a chronometric way, by varying the onset of simulation across trials, thereby scrutinising the temporal aspect of a certain cognitive process (Devlin, Matthews, & Rushworth, 2003; Schuhmann, Schiller, Goebel, & Sack, 2012). Finally, TMS can be applied in combination with neuroimaging techniques to map local and remote effects on neural activity (Ruff et al., 2006), and multiple coils can be used to draw inferences concerning the interaction between different brain regions (Hartwigsen, Baumgaertner, et al., 2010a).

Given the high spatial resolution of TMS (around 1 cm^2), the method can be used to segregate adjacent cortical regions, enabling it to investigate processing in different parts of the IFG (Devlin et al., 2003; Gough, Nobre, & Devlin, 2005; Hartwigsen, Price, et al., 2010b; Klaus & Hartwigsen, 2019). Furthermore, because of its high temporal resolution (in order of milliseconds), it is a highly suitable method to investigate sentence-level processes. Finally, its capacity to transiently disrupt ongoing activity in a cortical region allows for investigation of the functional relevance of a given cortical region in a given cognitive process. These qualities combined motivated the use of rTMS in **Chapter 5** of this thesis. Drawing on results from both **Chapter 3** and **Chapter 4**, rTMS is used to investigate the functional relevance of the left IFG in sentence processing cued by prosody.

Chapter 3

Intonation guides sentence processing in the left inferior frontal gyrus

Based, with modifications, on *Van der Burght, C.L., Goucha, T., Friederici, A.D., Kreitewolf, J., Hartwigsen, G. (2019). Intonation guides sentence processing in the left inferior frontal gyrus. Cortex.*

Abstract

Prosody, the variation in sentence melody and rhythm, plays a crucial role in auditory sentence comprehension. Specifically, changes in intonational pitch along a sentence can affect our understanding of who did what to whom. To date, it remains unclear how the brain processes this particular use of intonation and which brain regions are involved. In particular, one central matter of debate concerns the lateralisation of intonation processing. To study the role of intonation in sentence comprehension, we designed a functional MRI experiment in which participants listened to spoken sentences. Critically, the interpretation of these sentences depended on either intonational or grammatical cues. Our results showed stronger functional activity in the left inferior frontal gyrus (IFG) when the intonational cue was crucial for sentence comprehension compared to when it was not. When instead a grammatical cue was crucial for sentence comprehension, we found involvement of an overlapping region in the left IFG, as well as in a posterior temporal region. A further analysis revealed that the lateralisation of intonation processing depends on its role in syntactic processing: activity in the IFG was lateralised to the left hemisphere when intonation was the only source of information to comprehend the sentence. In contrast, activity in the IFG was right-lateralised when intonation did not contribute to sentence comprehension. Together, these results emphasise the key role of the left IFG in sentence comprehension, showing the importance of this region when intonation establishes sentence structure. Furthermore, our results provide evidence for the theory that the lateralisation of prosodic processing is modulated by its linguistic role.

1. Introduction

In spoken conversation, listeners rely on various sources of information provided in the speech stream to understand what someone is saying. Besides the meaning of each individual word, it is crucial to understand the grammatical structure of the sentence, or *who did what to whom* (Everaert et al., 2015; Sportiche, Koopman, & Stabler, 2013). One way in which this information can be conveyed is through prosody: the changes in rhythm and melody of speech (Cutler et al., 1997). An important acoustic aspect of prosody is intonation, marked by the changes in pitch along a sentence. Intonation can dramatically change the interpretation of a sentence. In the example *"the teacher said the student is mistaken"*, the distinction between the two possible interpretations of this utterance is in fact determined exclusively by the particular intonation that is realised. One can either say *"the teacher said: the student is mistaken"* or *"the teacher, said the student, is mistaken"*. Specifically, the particular use of intonation determines whether the teacher or the student is alleged to be wrong, by creating boundaries between different parts of the sentence. By signalling syntactic boundaries between groups of words, prosody here determines the syntactic structure, and as a consequence, the interpretation of the sentence. The prosodic features marking these boundaries are a pause between the two sentence parts, preceded by a rise in pitch and a lengthening of the syllable before the pause. Together, these features acoustically separate the different parts of a sentence, and constitute a so-called *intonational phrase boundary* (IPB) (Selkirk, 1984).

Despite many years of neurocognitive research on prosody, it remains largely unknown how exactly intonation contributes to sentence comprehension, and what the neural implementation of this process is. Although pitch was shown to be preferably processed in the right hemisphere (Zatorre, 2001), early neurocognitive models on prosody postulated that the stronger the linguistic function of prosody the larger the lateralisation to the left hemisphere would be (Friederici & Alter, 2004). A recent study using intracranial cortical recordings showed that intonation is processed in specific neural populations in the temporal lobe—neural populations that can be dissociated from those involved in processing other speech components, such as the sounds of words (Tang, Hamilton, & Chang, 2017). Yet, intonation is rapidly integrated with other phonetic components (e.g., consonants and vowels) to interpret a sentence, as has been shown in early behavioural studies (Marslen-Wilson et al., 1992). Furthermore, electrophysiological studies have demonstrated that prosodic information and information about sentence structure are integrated online during sentence processing (Friederici et al., 2007; Männel & Friederici, 2009; Sammler et al., 2010; Steinhauer et al., 1999; see Bögels et al. (2011) for a review).

To date, neuroimaging studies have been inconclusive with regard to the brain regions involved in this use of intonation for sentence comprehension. Most functional neuroimaging research has focused on particular parts of prosody rather than its actual contribution to sentence comprehension. For instance, a network of superior temporal and fronto-opercular regions in the right hemisphere has been found to be involved in speech processing depending on the presence of pitch information (M. Meyer et al., 2002; 2004; Plante et al., 2002). A similar fronto-temporal network has been found in the perception of natural compared to hummed speech (Ischebeck et al., 2008). However, since these previous studies compared various types of filtered speech, they emphasised the acoustic processing of intonation rather than its use for sentence comprehension. Only few neuroimaging studies have investigated which brain regions are involved when prosodic information guides sentence comprehension. These studies either involved a rather quantitative analysis of the intonational cue (e.g., investigating the presence of two intonational phrase boundaries versus a single one (Ischebeck et al., 2008)) or compared conditions in which the stimuli were not lexically matched (Strelnikov et al., 2006). Consequently, several brain regions have been found to support the processing of intonational contours in speech, but it is unknown whether these regions also play a role in guiding sentence comprehension.

Aside from intonation, grammatical cues can guide sentence comprehension, by means of a particular word form (morphosyntax). For example, in the sentence *"The teachers said the student is mistaken"* the word form of *teachers* and *said* (both signal plural) and *student* and *is* (both singular) establishes that the teachers describe the student's behaviour, not the other way around. This example shows how sentence structure can be established by grammatical cues. Previous work has shown that these grammatical cues are processed in a left-hemispheric network of frontal and temporal regions (see Friederici (2011) and Hagoort (2014) for reviews). Specifically, when grammatical cues are the only informative elements available to interpret sentence, the posterior part of the left inferior frontal gyrus (IFG) has been shown to be engaged (Goucha & Friederici, 2015). Functional imaging and lesion studies have further shown that successful processing of grammatical cues relies on an intact left superior temporal cortex (Bornkessel et al., 2005; Regel, Kotz, Henseler, & Friederici, 2017; Rolheiser, Stamatakis, & Tyler, 2011). Since the regions supporting the processing of grammatical cues have been well-described, the approach of the current study was to compare the neural implementation of grammatical cues and prosodic cues: we investigated processing of prosodic cues and processing grammatical cues in the same sentence environment, when both cue types have similar roles in disambiguating the sentence structure.

The second goal of this study was to investigate the hemispheric lateralisation of intonation processing. Although a general consensus exists that processing of linguistic components such as grammatical cues is predominantly left-lateralised (Friederici, 2011; Vigneau et al., 2006), it has long been debated whether a similar lateralisation exists for the processing of intonation (Luks et al., 1998; van Lancker, 1980; Wildgruber et al., 2004). In general, the right hemisphere is seen as dominant in the processing of pitch information, including intonation (Poeppel, 2003). However, dichotic listening (Luks et al., 1998) and lesion studies (reviewed in Witteman et al. (2011)) have shown that lateralisation of pitch processing depends on the linguistic function of intonation. Specifically, early studies attributed different hemispheres to processing of intonational contours depending on whether these were used to convey linguistic or emotional information (conveying the emotional state of the speaker): discrimination of linguistic prosody (question/statement intonation) was shown to have a left-hemispheric preference, and discrimination of emotional prosody (angry/sad intonation) a right-hemispheric preference (Luks et al., 1998). In later work, these results were corroborated using functional magnetic resonance imaging (fMRI) (Wildgruber et al., 2004). Subsequent functional neuroimaging studies suggested that intonation processing in the IFG and temporal cortex is lateralised, but that the contribution of either hemisphere depends on the specific control task used. Studying word-level prosody, discrimination of intonational contours predominantly recruits the right hemisphere when contrasted to a linguistic control task (phoneme discrimination; Sammler et al., 2015; Kreitewolf et al., 2014), but involves the left hemisphere when a non-linguistic control task is used (speaker identity discrimination; Kreitewolf et al., 2014). In sum, it is likely that processing of prosody relies on fronto-temporal networks in both hemispheres (Belyk & Brown, 2014; Witteman et al., 2011), with a dominance of the left hemisphere when pitch information is used to signal linguistic aspects (Friederici & Alter, 2004; van Lancker, 1980). However, it remains elusive whether intonation processing is lateralised when it contributes to sentence comprehension, and to which hemisphere.

Taken together, grammatical as well as prosodic cues can guide sentence comprehension by resolving ambiguities and establishing the structure of a sentence. Whereas the cortical network supporting processing grammatical cues has been extensively studied, it remains poorly understood how exactly intonation contributes to sentence comprehension, and what the neural correlate of this contribution is. Furthermore, it remains to be shown if the contribution of prosody to sentence structure influences the hemispheric lateralisation of prosody processing. We aimed to fill these gaps by studying sentence processing in which either intonational cues or grammatical cues are fundamental to understand what is being said. To achieve this, we designed an fMRI paradigm in which participants had to comprehend specific sentence types (see Figures 1 and 2). Across conditions, the structure of each spoken sentence structure was established by different disambiguating cues. That is, sentences could be interpreted in two possible ways until a point at which the cue ensured only one possible interpretation (Marslen-Wilson et al., 1992). This cue was either intonational (an IPB) or grammatical. The grammatical cue was established by morphological marking of the grammatical case of a personal pronoun, such that it matched only one of the two verbs in the sentence. The paradigm centred around the following sentence, which is open to two interpretations:

Peter verspricht Nick dafür zu bezahlen
(i) *Peter **promises Nick** to pay for it*
(ii) *Peter promises **to pay Nick** for it*

In these sentences, intonational and/or grammatical cues are required to convey who did what to whom. Without them, listeners cannot identify whether *Nick* was promised something or paid for something instead. In our key conditions, the position of an IPB (marked with #) helped the listener to identify one of the two possible interpretations:

(A) Peter verspricht Nick # dafür zu bezahlen
*Peter **promises Nick** to pay for it*
(B) Peter verspricht # Nick dafür zu bezahlen
*Peter promises **to pay Nick** for it*

Alternatively, the presence of a grammatical cue established an unambiguous interpretation. Here, we made use of German case marking, which distinguishes between the different grammatical roles a word can have in a sentence. Depending on the word form and its corresponding case (dative or accusative), the personal pronoun can only be the object of the verb *to promise* or *to pay*.

(C) Peter verspricht sie dafür zu bezahlen
Peter promises^{+DAT} *to pay*$^{+ACC}$ *her*^{ACC} *for it*

Finally, the current paradigm allowed for an investigation of the possible hemispheric lateralisation of prosody, while keeping the experimental task constant across conditions: by manipulating the disambiguating role of the intonational cue in each sentence, keeping acoustical information identical, we aimed to investigate functional activity in function of the linguistic importance of prosody. To this end, we included a condition in which the IPB was present but not essential to establish the sentence structure (see Figure 1).

In sum, the current study was designed to address two outstanding questions in prosody research. First, we investigated how the presence of intonational and grammatical cues influences sentence processing. We hypothesised that processing depends on the availability of the specific cue type in the sentence, and whether this cue appeared in isolation or in combination with a second cue. Based on previous studies (Goucha & Friederici, 2015; Kreitewolf et al., 2014), we expected increased activity in the left IFG (and possibly additional bilateral superior temporal regions) in conditions in which intonation was the only cue establishing the structure. When sentence comprehension relied on a grammatical cue only, we also expected increased activity in the left IFG, possibly with additional recruitment of the left posterior temporal cortex (Bornkessel et al., 2005; Regel et al., 2017). Our second research question concerned the lateralisation of intonation processing. Specifically, we investigated whether the role of the intonational cue in establishing the sentence structure determined the lateralisation of brain areas involved in intonation processing. Based on previous work (e.g Kreitewolf et al., 2014), we hypothesised that lateralisation depends on the linguistic function of the intonational cue. For processing of intonational cues that establish sentence structure, we expected left-lateralised activity of core language regions (IFG and posterior superior temporal gyrus, pSTG). In contrast, we expected a shift towards the right IFG when prosodic content was present, but not used to establish the structure of the sentence.

2. **Methods**

2.1. *Participants*

Twenty-six native German speakers (15 female; mean age: 26.3 years; age range: 20-33 years) were included in the final analyses. All participants were right-handed (Oldfield, 1971) and had normal or corrected-to-normal vision. All reported normal hearing and none were professional musicians. None had a history of neurological or psychiatric illness, drug or alcohol abuse, chronic medical disease, or any other contraindication against participation in an MRI experiment. Twelve additional participants had to be excluded because they did not complete the experiment (n = 2) or because they performed below chance level in at least one of the six stimulus conditions (n = 10). The sample size was determined based on previous fMRI studies on sentence processing (e.g., Goucha & Friederici, 2015; Kristensen, Wang, Petersson, & Hagoort, 2013; Perrone-Bertolotti, Dohen, Lœvenbruck, Sato, Pichat & Baciu 2013). The exclusion criteria were established prior to data analysis. All participants gave written consent prior to participating in the experiment, which was approved by the ethics committee of the University of Leipzig.

2.2. *Experimental design*

To investigate the effect of intonational and grammatical cues on sentence comprehension, we used an event-related fMRI design that employed six different sentence types with varying amount of intonational and grammatical information (see Figure 1A). The stimulus set was built around the following sentence:
A verspricht B dafür zu bezahlen (literally: *A promises B for it to pay*)
which has two possible interpretations.

i. [A verspricht B [dafür zu bezahlen]]
[A promises B [to pay for it]]
ii. [A verspricht [B dafür zu bezahlen]]
[A promises [to pay B for it]

In German, the two structures (i) and (ii) can be realised by an identical string of words. This requires specific language cues to distinguish the two possible meanings and to clarify whether *B* is the object of the verb *to promise* or *to pay*. One such cue is the position of an IPB (indicated with "#"), which can create the distinction as follows:

Prosody Only 1 (1) [Peter verspricht Nick # [dafür zu bezahlen]]
(*ProsOnly1*) *[Peter promises Nick # [to pay for it]]*
Prosody Only 2 (2) [Peter verspricht # [Nick dafür zu bezahlen]]
(*ProsOnly2*) *[Peter promises # [to pay Nick for it]]*

The IPB acoustically divides the sentence and groups the proper noun *Nick* to either of the two verbs. Without the IPB, *ProsOnly1* and *ProsOnly2* are ambiguous. The IPB is defined by a pitch rise and syllable lengthening, followed by a pause (Selkirk, 1984) (see Figure 1B).

An additional cue can resolve the ambiguity, for example, when a personal pronoun is used (such as *she*) instead of a proper noun (*Nick*). In German, personal pronouns are inflected, meaning that their morphosyntactic form defines their role in the sentence (i.e., by case marking). Similarly, verbs require objects in a specific case. For example, “versprechen” *(to promise)* requires objects in the dative case, whereas “bezahlen” *(to pay*) requires an accusative. Making use of the German case marking system, we constructed sentences in which the structure is built by a grammatical cue only:

Grammatical Only (3) [Peter verspricht [sie dafür zu bezahlen]]
(*GramOnly*) *[Peter promises*$^{+DAT}$ *[to pay*$^{+ACC}$ *her*^{ACC} *for it]]*

Although the position of the word “sie” (*her*) does not yet clarify to what verb the word belongs, the case marking of the word ensures that “sie” is necessarily an object of *to pay* and cannot belong to the verb *to promise.* The sentence can only be interpreted in one way because of the morphosyntactic form of *her*^{ACC} (“sie”).

To investigate sentence processing guided by these cues, we designed control conditions with additional cues, for example:

Baseline Prosody Only (4) [Peter verspricht Nick # [sie zu bezahlen]]
(*BL ProsOnly*) *[Peter promises*$^{+DAT}$ *Nick # [to pay*$^{+ACC}$ *her*^{ACC} *for it]]*

In this sentence, identification of the syntactic structure is facilitated by the additional grammatical cue “sie”, as compared to (*ProsOnly1*). Thus, it is not necessary to disambiguate the verb-argument structure because two objects (*Nick* and *her*) are present in this sentence.

Similarly, as a control condition for the experimental condition *GramOnly*, we created sentences that contained an intonational cue in addition to the grammatical cue, for example:

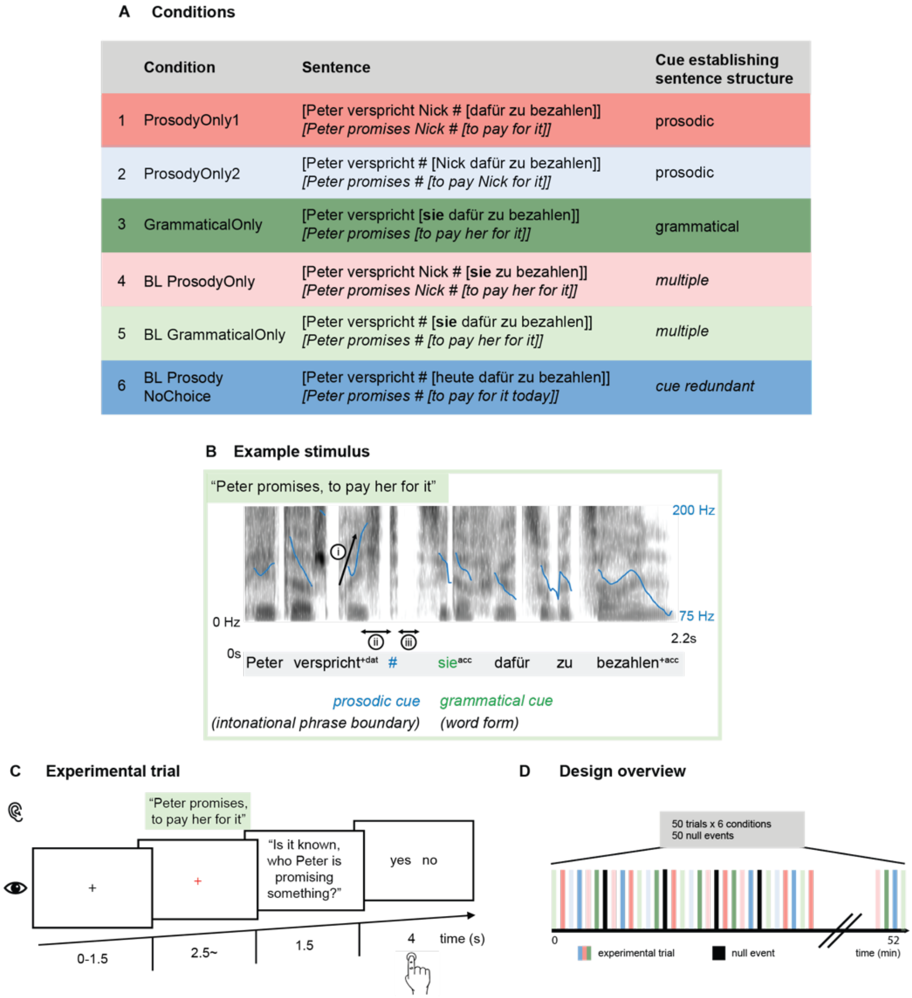
Baseline Grammatical Only (5) [Peter verspricht # [sie dafür zu bezahlen]]
(*BL GramOnly*) *[Peter promises*$^{+DAT}$ *# [to pay*$^{+ACC}$ *her*^{ACC} *for it]]*

A final baseline condition was created, in which intonation was not required to understand who did what to whom the in the sentence. This sentence type had an IPB, as in *ProsOnly1* and *ProsOnly2,* but the verb-argument structure did not have to be resolved.

Baseline Prosody No Choice (6) [Peter verspricht # [heute dafür zu bezahlen]]
(*BL ProsNoChoice*) *[Peter promises*$^{+DAT}$ *# [to pay*$^{+ACC}$ *for it today]]*

Each condition consisted of 50 unique verb combinations matched to a variety of German first names (yielding a total of 300 sentences). In each sentence, the verb in the main clause required an object in the dative form and the verb in the subordinate clause required an object in the accusative form, or vice versa. This ensured that the grammatical cue (the personal pronoun), in either the dative or accusative form, could be unambiguously assigned to either verb. The matching of dative and accusative verbs to main clause or subordinate clause was pseudo-randomised across trials.

To confirm that participants were equally likely to attribute the object in the sentence to the first or the second verb*,* we calculated if participants had a response bias for either condition *ProsOnly1* or *ProsOnly2*. Using methods of signal detection theory (Macmillan & Creelman, 1991) this response bias turned out not to be significant from 0, suggesting that participants had no intrinsic bias for either syntactic structure (see Meyer et al., 2016, for a similar approach).



	Condition	Sentence	Cue establishing sentence structure
1	ProsodyOnly1	[Peter verspricht Nick # [dafür zu bezahlen]] *[Peter promises Nick # [to pay for it]]*	prosodic
2	ProsodyOnly2	[Peter verspricht # [Nick dafür zu bezahlen]] *[Peter promises # [to pay Nick for it]]*	prosodic
3	GrammaticalOnly	[Peter verspricht [**sie** dafür zu bezahlen]] *[Peter promises [to pay her for it]]*	grammatical
4	BL ProsodyOnly	[Peter verspricht Nick # [**sie** zu bezahlen]] *[Peter promises Nick # [to pay her for it]]*	*multiple*
5	BL GrammaticalOnly	[Peter verspricht # [**sie** dafür zu bezahlen]] *[Peter promises # [to pay her for it]]*	*multiple*
6	BL Prosody NoChoice	[Peter verspricht # [heute dafür zu bezahlen]] *[Peter promises # [to pay for it today]]*	*cue redundant*

Figure 1. Experimental design. (A) Experimental conditions. Across conditions, a different combination of language cues established the verb-argument structure; that is, whether the object in the sentence ("Nick" or "she") belongs to the first or second verb. Prosodic cue (indicated by "#"): an acoustic break marking a transition in a sentence (i.e., intonational phrase boundary; IPB). Grammatical cue (in bold typeface): morphosyntactic case marking of the personal pronoun "sie" (*she*), matched to either the verb in the main clause ("verspricht" (*promises*)) or sub clause ("zu bezahlen" (*to pay*)). 'Prosody': presence of a prosodic cue. 'Grammatical': presence of a grammatical cue. 'Only' indicates that that cue was the only cue present in that sentence. 'BL': baseline condition matched to the specific cue. 'NoChoice': the prosodic cue did not influence the response choice in the task. (B) Spectrogram of an example stimulus with intonational and grammatical cues. Here, the syntactic structure is established by

figure caption continues on next page

both the grammatical cue "sie" (*she*) and an intonational cue in shape of an IPB. The IPB is composed of three acoustic events, indicated with arrows: (i) a pitch rise and (ii) lengthening of the syllable, followed by (iii) a pause. (C) Overview of an experimental trial. (D) Overview of the fMRI session.

2.3. Experimental procedure

Each experimental trial (see Figure 1C) started with a white fixation cross, which turned red 200 ms prior to auditory stimulation to alert the participant. Subsequently, the spoken sentence was presented. After each sentence, a visual comprehension question was shown for 1500 ms, to which participants were asked to respond with a right-handed button press. Participants had to respond within 4 s. The subsequent trial started after the response phase and an additional delay of 0, 750 or 1500 ms (uniformly jittered).

To ensure active listening, the comprehension question was visually presented after the sentence. The question probed sentence comprehension by asking whether an object was present in either the main or subordinate clause: participants were asked *Do you know who Peter promises something?* ("Weiß man, wem Peter etwas verspricht?") or *Do you know, who is paid?* ("Weiß man, wer bezahlt wird?"). The question types were presented pseudo-randomly, with each of the two question types occurring evenly across sentence conditions.

During the experimental session (Figure 1D), the six experimental conditions were presented in a pseudo-random order: two stimuli of the same condition were always separated by at least two trials so that the conditions were distributed evenly throughout the experiment. 50 null trials with an average-trial duration of 8.5 s were pseudo-randomly interspersed with the other conditions throughout the experiment. The experiment was performed within one session with a total duration of 52 minutes. Each participant performed a short practice session immediately before the fMRI experiment, which mirrored the main experiment but consisted of different stimuli.

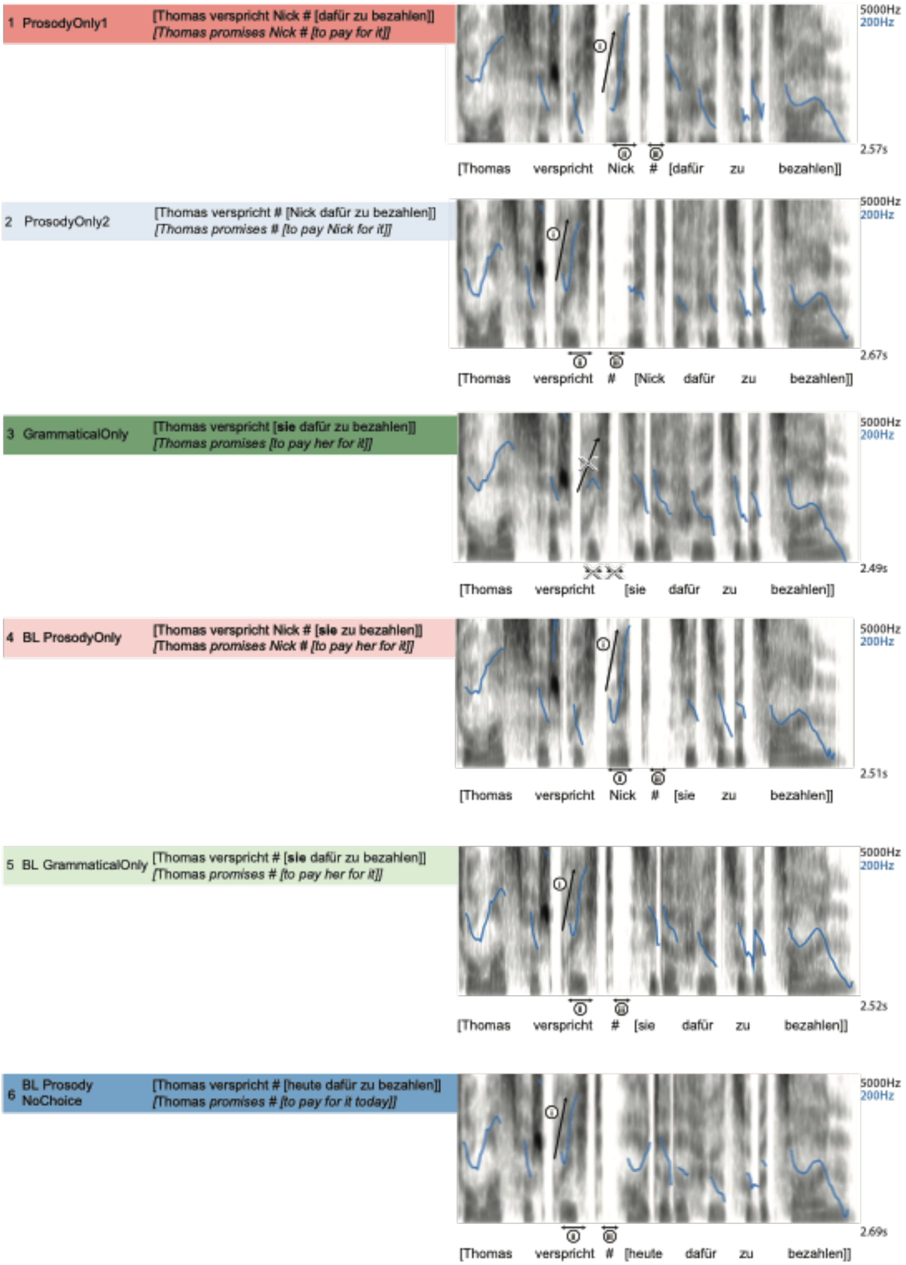


Figure 2. Spectrograms with pitch contours for each of the experimental conditions. In the five conditions with intonational phrase boundary (IPB), three acoustic events can be observed: (i) a pitch rise and (ii) syllable lengthening, followed by (iii) a pause. Note that in the Grammatical Only condition the IPB is absent, marked by an absence of pitch rise, syllable lengthening and pause (indicated with an X).

Auditory stimuli were presented through MR-compatible headphones (MR confon OPTIME 1; MR confon GmbH, Magdeburg, Germany). Participants additionally wore earplugs to attenuate scanner noise. Stimulus presentation and response collection were controlled via Presentation (Neurobehavioural Systems, Inc., Albany, CA, USA), with visual stimuli presented on an LCD projector (PLC-XP50L, SANYO, Tokyo, Japan). Participants could see the projection via a mirror that was attached to the head coil.

2.4. Stimulus properties

Sentences were spoken by a male, professional native German speaker and recorded in a sound-attenuating chamber (IAC – I200 series, Winchester, United Kingdom). The digitised speech signals (sampling rate 44.1kHz; resolution 16 bits) were adjusted to the same root mean square value using MATLAB (Mathworks, Inc., Sherborn, MA, USA). To ensure consistent comparisons between stimuli with matching main or subordinate clauses, all stimuli were cross-spliced: the clauses before and after the pause were cut in Adobe Audition CS5.5 and concatenated to form the stimulus sentences. This procedure ensured that identical sentence parts across conditions originated from the same recording.

Importantly, in this way we guaranteed that in contrasts between two sentences with IPBs, those IPBs were acoustically identical. That is, for *ProsOnly1* & *BL_ProsOnly*, and for *ProsOnly2*, *BL_GramOnly* & *BL_ProsNoChoice*, the onsets of the stimuli up to and including the IPB originated from the same recordings. To further improve acoustic consistency across the stimulus set, in those sentences that contained an IPB (all except *GramOnly*) we introduced a pause of constant duration (100 ms): all first parts of the stimuli were cut *until* the pause, to which a pause of constant duration was added, followed finally by the second part of the stimuli (which had been cut *after* the pause). We chose 100 ms based on pilot study results, showing that such a pause could be clearly perceived and sounded natural.

The *GramOnly* condition, containing no IPB, was also constructed by cross-splicing two elements. To prevent the realisation of an IPB in the first element, we had the speaker produce a sentence without a syntactic boundary after the verb (where an IPB would be illegal). Subsequently, we spliced the recording after the verb and concatenated it to the same sentence ending as in *BL_GramOnly*. This yielded a sentence with natural prosody but without any of the three acoustic cues characterising the IPB (pitch rise, syllable lengthening and a pause). Furthermore, this ensured that the sentence endings of *GramOnly* and its baseline equivalent were matched. Spectrograms of all 6 sentence conditions are provided in Figure 2.

Participant debriefings and a pilot study on a separate sample of participants (n = 18) confirmed that all stimuli were perceived as natural, grammatical, and non-ambiguous.

2.5. fMRI acquisition

Functional imaging was performed on a 3 Tesla Siemens Skyra scanner (Siemens Healthcare, Erlangen, Germany) using a 20-channel head coil. A gradient-echo echo-planar-imaging (EPI) sequence was run (acquisition time [TA] = 2s; continuous scanning; echo delay time [TE] = 30ms; flip angle 78°; matrix size 64 × 64; field of view [FOV] = 192 × 192mm; 30 slices of 3mm thickness; in-plane resolution = 3mm x 3mm; gap = 1mm). For anatomical registration, T1-weighted images were either acquired during the scanning session or obtained from the in-house database when available.

2.6. Data analysis

2.6.1. Behavioural data

Response times and accuracy data were analysed using SPSS (IBM Corp., Armonk, NY, USA). Since behavioural measures were not normally distributed (Kolmogorov-Smirnov tests; all $p < 0.05$), Friedman tests were used as a non-parametric alternative to repeated-measures analyses of variance. Follow-up Wilcoxon signed-rank tests were performed as post-hoc tests. Initial *p*-values lower than $\alpha = 0.05$ (two-tailed) were considered significant for all comparisons. To correct for multiple comparisons (a total number of 15), Bonferroni corrections were applied, yielding a corrected α-level of 0.0033 (0.05/15).

2.6.2. *fMRI data*

fMRI data were pre-processed and statistically analysed using SPM12 (www.fil.ion.ucl.ac.uk/spm, Wellcome Trust Centre for Neuroimaging). All functional images were realigned to the first image in the time series to correct head motion and unwarped to correct distortions caused by inhomogeneity in the magnetic field. After the T1-weighted image was co-registered to the mean EPI image, it was normalised to the Montreal Neurological Institute (MNI) template image. The deformation parameters resulting from this step were used to normalise all EPI images to MNI space. Finally, the data were smoothed using an isotropic Gaussian kernel of 8mm full-width at half-maximum.

Statistical analysis of the fMRI data was performed using a general linear model in SPM12. The onset and duration of each sentence were modelled per condition and convolved with the canonical hemodynamic response function. To account for domain-general effects of task performance on brain activation, we took into consideration between-condition differences in reaction times in our model. To this end, we built a regressor with response onsets and response times for each trial. This regressor was orthogonalised to the condition regressors and included in the general linear model (following Grinband, Wager, Lindquist, Ferrera, & Hirsch, 2008). Incorrect trials were modelled as a separate noise condition. A high-pass filter with 128s cut-off was applied. Contrast images of each condition of interest and participant were combined in a group random effects analysis with a factorial design: the six experimental conditions entered as levels of the factor CONDITION. Results were thresholded at an FWE-corrected cluster level of $p < 0.05$, using an initial uncorrected voxel-wise threshold of $p < 0.001$ (Friston, Worsley, Frackowiak, Mazziotta, & Evans, 1994b). All activation peak coordinates are reported in MNI space and the SPM anatomy toolbox (version 2.2c) (Eickhoff et al., 2005) was used for anatomical localisation. Results were visualised using the BrainNet Viewer (Xia, Wang, & He, 2013).

Additionally, we performed a lateralisation analysis. This analysis was conducted by normalizing the raw EPI images to a symmetrical MNI template. The first-level analysis was run as described above, and the resulting contrast images were left-right flipped (Bozic, Tyler, Ives, Randall, & Marslen-Wilson, 2010; Josse, Kherif, Flandin, Seghier, & Price, 2009; Liégeois et al., 2002). On the second level, paired t-tests were run to compare the image of a particular contrast of interest to its left-right flipped equivalent. We applied the same statistical thresholds that were used in the activation analysis.

2.7. *Availability of study materials*

Data from this study have not been publicly archived since the conditions of our ethics approval do not permit to do so. Analysis code and stimulus materials are available at https://github.com/CLvanderBurght/prossyn/. The study procedures or analyses were not pre-registered prior to the research being conducted.

3. Results

3.1. *Behaviour*

Both reaction times (RTs; Figure 3A) and accuracy rates (Figure 3B) differed across conditions, as shown by Friedman tests (RTs: $\chi^2(5) = 75.87$, $p < 0.001$; accuracy: $\chi^2(5) = 50.41$, $p < 0.001$). Pair-wise comparisons between conditions showed differences in the difficulty of sentence comprehension reflected in accuracy and reaction times. In general, participants showed lower accuracies and higher reaction times in conditions where only one cue was available compared to the matched baseline conditions. Accuracy decreased and reaction times increased in *ProsOnly1* (1) as compared to *BL_ProsOnly* (4), indicating that sentence comprehension was more difficult when only one language cue was present (RTs: $Z = -4.457$, $p < 0.001$; accuracy: $Z = -3.523$, $p < 0.001$). Similarly, sentence comprehension was more difficult in *GramOnly* (3), which contained only a grammatical cue, compared to *BL_GramOnly* (5), which contained both a grammatical and an intonational cue (RTs: $Z = -4.026$, $p < 0.001$; accuracy: $Z = -3.760$, $p < 0.001$). Other comparisons between matched sentences were significant (e.g., conditions 2 vs 6: RTs: $Z = -4.178$, $p < 0.001$; accuracy: $Z = -3.816$, $p < 0.001$; see supplementary tables S1 and S2 for complete pair-wise comparisons). Comparisons between matched conditions of interest (1 versus 2) or control conditions (4 versus 6) were not significant.

3.2. fMRI – activity analysis

We investigated how the presence of specific language cues shapes sentence comprehension in the brain. To this end, we contrasted sentences in which only one specific language cue established the sentence structure to matched control conditions (i.e., 1 vs 4 and 3 vs 5, cf. Figure 1A). In the control sentences, processing of the sentence structure was facilitated in comparison to the conditions of interest, because multiple cues instead of a single cue marked the sentence structure. For an overview of significant activation clusters, see Table 1.

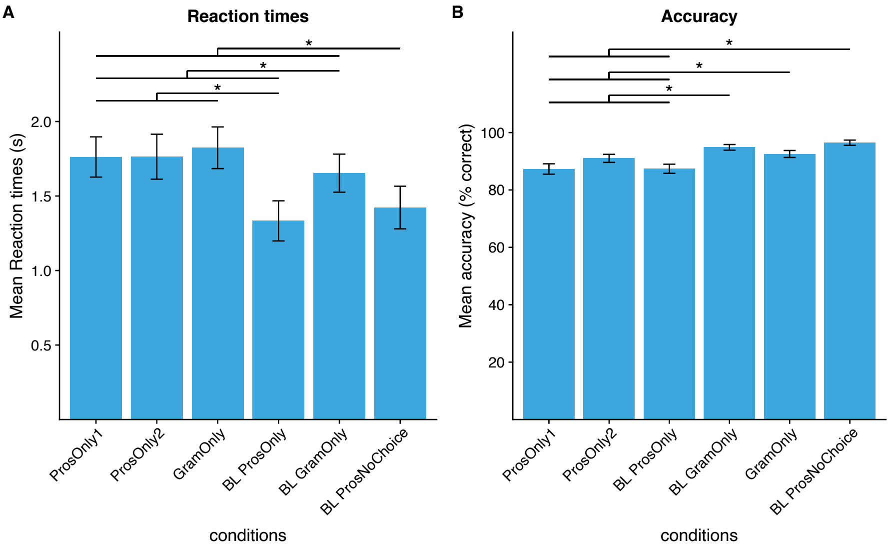


Figure 3. Behavioural results: reaction times (A) and accuracy rates (B) per condition. Error bars indicate ± 1 SEM. Lines between conditions and asterisks indicate pair-wise comparisons with p-values smaller than 0.0033 (Bonferroni-corrected). BL stands for baseline.

Syntactic structure established by a prosodic cue

To investigate processing of sentence structure established by prosodic information, the following experimental conditions were contrasted: *ProsOnly1* (1), in which a prosodic cue is the only factor establishing the sentence structure, versus *BL_ProsOnly* (4), in which additional cues determined the sentence structure (a grammatical cue). This contrast, reflecting sentence processing guided by a prosodic cue, yielded increased task-related activity in the left inferior frontal gyrus (IFG, peak activity at pars triangularis, x, y, z = -45, 29, -4; T = 4.93; Figure 4A and Table 1).

Syntactic structure established by a grammatical cue

To investigate processing of sentence structure marked by a grammatical cue, we contrasted *GramOnly* (3), in which only a grammatical cue marks the sentence structure, to a matched control condition in which an additional intonational cue establishes the sentence structure. Since in *BL_GramOnly* (5) the sentence structure was already established by the intonational cue, the grammatical cue was less important for resolving the structure. This contrast resulted in functional activation clusters in the pars opercularis of the left IFG (x, y, z = -51, 11, 8; T = 4.43) and the left superior temporal gyrus and sulcus (x, y, z = -57, -16, 2; T = 5.23; Figure 4B).

The reverse of the above described contrasts (3 > 1 and 4 > 5) did not yield significant activation clusters. Additionally, other contrasts between matched sentences (ProsOnly2 > BL_GramOnly and ProsOnly2 > BL_ProsNoChoice) did not show significant results at $p < 0.05$, FWE-corrected (cluster-level).

3.3. fMRI – lateralisation analysis

A right-hemispheric dominance for intonation processing is often found in prosody research (M. Meyer et al., 2002; Sammler et al., 2015). However, meta-analyses on prosody studies point towards a bilateral network for prosody processing (Belyk & Brown, 2014; Witteman et al., 2011). It has previously been suggested that intonation processing is left-lateralised specifically when pitch information is linguistically relevant (Friederici & Alter, 2004; Kreitewolf et al., 2014; van Lancker, 1980). However, this has not yet been shown with well-matched sentence stimuli. We therefore investigated sentence conditions in which the intonation was matched acoustically but differed in terms of linguistic importance. Specifically, we compared

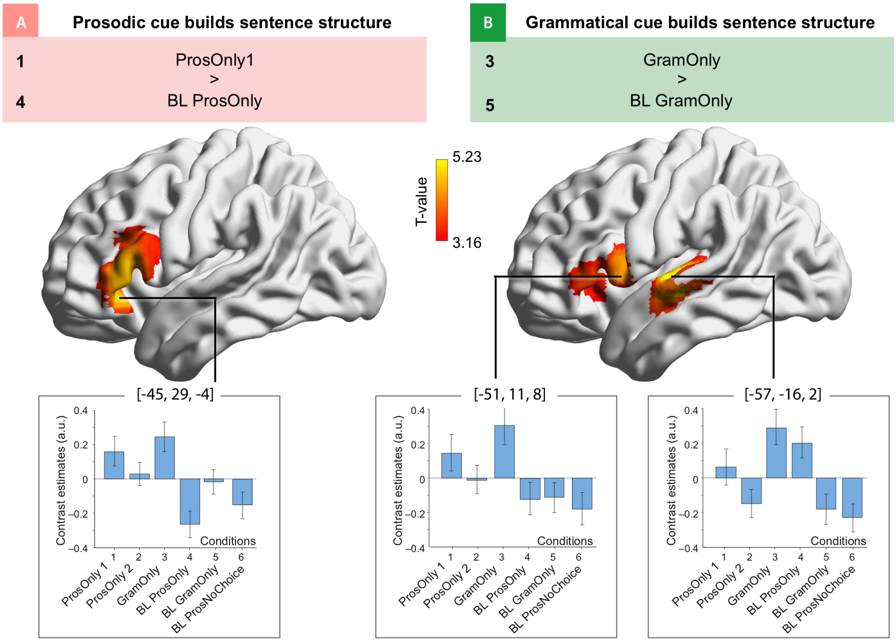


Figure 4. Functional MRI results showing significant activation clusters for the different contrasts of interest. (A) Syntactic structure processing guided by a prosodic cue. (B) Syntactic structure processing guided by a grammatical cue. Bar plots show contrast estimates for each condition at activation peaks, indicated by the pointer, in arbitrary units (a.u.). All comparisons are thresholded on the cluster level at $p < 0.05$, FWE-corrected. Peak activity coordinates are in MNI space. BL stands for baseline.

conditions in which intonation guided sentence comprehension with matched conditions in which intonation was superfluous for sentence comprehension. The resulting contrast images were compared to their equivalent images in right-left flipped orientation. Results are summarised in Table 2.

First, we investigated lateralisation of intonation processing when the prosodic cue was crucial for sentence comprehension, assessed by the contrast *ProsOnly1* vs *BL_ProsOnly* (same contrast as in the activity analysis in Figure 4A). The results showed that the functional activation in the IFG was left-lateralised (x, y, z = -54, 29, 5, pars triangularis; T = 6.08; Figure 5A). Other areas that showed left-lateralised activity were the supplementary motor area (x, y, z = -6, 23, 50; T = 4.87) and the superior temporal gyrus (x, y, z = -51, -34, 2; T = 4.20). Additionally, functional activation was right-lateralised in the pre- and post-central gyrus (x, y, z = 30, -19, 56; T = 5.53) and in the superior temporal gyrus (x, y, z = 54, -4, 8; T= 5.20).

Table 1 Task-related activity for the comparisons of interest thresholded on the cluster level at $p < 0.05$, FWE-corrected.

Region	**hemisphere**	**MNI coordinates (x y z; in mm)**			**T**	**cluster size**
Prosodic cue establishes sentence structure (ProsOnly1 (1) > BL_ProsOnly (4))						
Inferior frontal gyrus	L	-45	29	-4	4.93	301
Grammatical cue establishes sentence structure (GramOnly (3) > BL_GramOnly (5))						
Superior temporal sulcus	L	-57	-16	2	5.23	190
Inferior frontal gyrus	L	-51	11	8	4.43	123

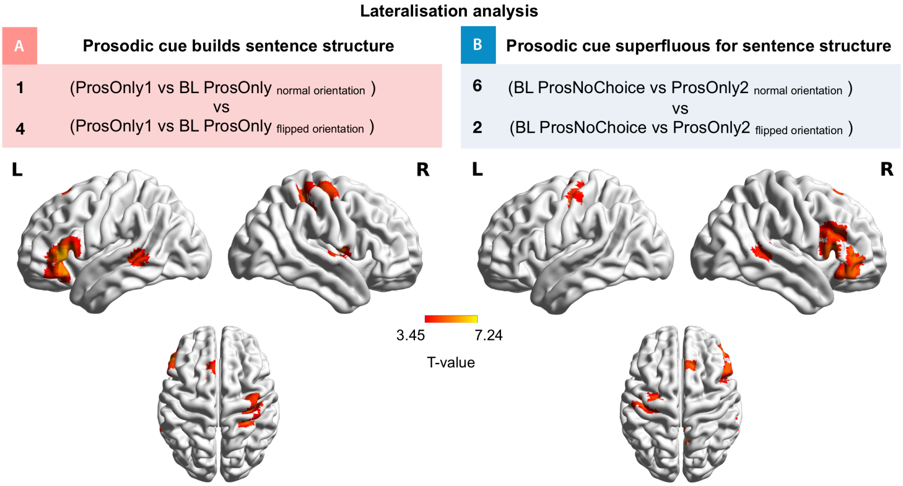


Figure 5. Lateralisation analysis showing functional contrasts of interest compared to their left-right flipped equivalent. (A) Lateralised functional activity evoked by processing of sentence structure guided by a prosodic cue. (B) Lateralised functional activity evoked by processing a sentence structure in which the prosodic cue is superfluous. All comparisons are thresholded on the cluster level at $p < 0.05$, FWE-corrected. BL stands for baseline.

Table 2 Task-related activity for the comparisons of interest in the lateralisation analysis. All results were thresholded on the cluster level at $p < 0.05$, FWE-corrected.

Region	hemisphere	MNI coordinates (x y z; in mm)			T	cluster size
Prosodic cue establishes sentence structure (ProsOnly1 (1) vs BL_ProsOnly (4))						
Inferior frontal gyrus	L	-54	29	5	6.08	262
Precentral gyrus	R	30	-19	56	5.53	169
Superior temporal gyrus	R	54	-4	8	5.20	32
Supplementary motor area	L	-6	23	50	4.87	44
Superior temporal gyrus	L	-51	-34	2	4.20	35
Prosodic cue superfluous for sentence structure (BL_ProsNoChoice (6) vs ProsOnly2 (2))						
Supplementary motor area	R	9	23	50	7.24	43
Precuneus	R	6	-55	41	6.01	61
Inferior frontal gyrus, pars triangularis	R	48	44	8	5.45	96
Inferior frontal gyrus, pars opercularis	R	51	20	8	5.19	92
Precentral gyrus	L	-39	-16	50	4.94	147
Superior temporal gyrus	R	57	-37	8	4.34	38

In a second contrast, we isolated prosodic processing when the prosodic cue was superfluous for the sentence structure (*BL_ProsNoChoice* vs *ProsOnly2).* In the condition *BL_ProsNoChoice*, the task did not require processing of the intonational cue to disambiguate the sentence structure, whereas condition *ProsOnly2* was a matching sentence in which the IPB was necessary for building the sentence structure. The processing of a superfluous intonational cue showed an overall pattern of right-lateralised activity. Functional activation of the inferior frontal gyrus was right-lateralised, with peak activations in the pars opercularis (x, y, z = 51, 20, 8; T =

5.19) and pars triangularis (x, y, z = 48, 44, 8; T = 5.45) (Figure 5B). Additional right-lateralised activations were found in the superior temporal sulcus and gyrus (x, y, z = 57, -37, 8; T = 4.34), the supplementary motor area (x, y, z = 9, 23, 50; T = 7.24), and the precuneus (x, y, z = 6, -55, 41; T = 6.01). Activity in the pre/post-central gyrus (x, y, z = -39, -16, 50; T = 4.94) was stronger in the left than right hemisphere.

4. Discussion

This study showed that the left inferior frontal gyrus plays a key role in processing prosodic information that is used to guide sentence comprehension. More specifically, results suggest that this region is involved when prosodic cues establish the grammatical structure of a sentence. By comparing the disambiguating function of prosodic and grammatical cues in sentence processing, we provide novel evidence that prosodic information carrying a syntactic function is processed in the left hemisphere. Our first aim was to investigate whether different types of language cues that help to understand the structure of a sentence recruit different brain areas. The study shows that the left IFG is involved in sentence processing both when intonational and grammatical cues establish the sentence structure. A second aim was to address the lateralisation debate on prosody processing, which is unresolved concerning the conditions under which pitch information may be processed in a lateralised manner. We show that lateralisation of activity depends on whether or not intonation is decisive for the interpretation of the sentence structure. When prosody was the only cue disambiguating the syntactic structure, activity in the IFG was left-lateralised. Conversely, activity in the IFG was lateralised to the right hemisphere when the prosodic cue was superfluous for sentence comprehension, even though the cues were acoustically identical.

These results extend previous neuroimaging work that emphasised the importance of the left IFG for sentence comprehension (Bornkessel-Schlesewsky & Schlesewsky, 2013; Friederici, 2011; Hagoort, 2014). We show that the left IFG plays a major role when an intonational cue is used to build sentence structure. Previous neuroimaging studies on prosody processing reported the left IFG as part of a wider network of bilateral fronto-temporal regions (reviewed in Belyk & Brown (2014)). In contrast, in this study we find the left IFG in isolation. This difference from previous work is likely due to two aspects of prosody which were tackled in the present study but have been largely ignored in the literature to date. First, many previous neuroimaging studies have focused on the acoustic aspect of prosody processing rather than its role in guiding sentence comprehension. A predominantly right-hemispheric temporal network has often been identified in prosody experiments drawing comparisons between normal speech and acoustically manipulated speech, such as speech with flattened pitch (M. Meyer et al., 2004) or filtered speech in which only the pitch contour remained (Hesling et al., 2005; M. Meyer et al., 2002; 2004). The temporal areas found in these studies are likely to reflect processing of acoustic properties of linguistic prosody, and in particular of pitch. In contrast to these previous studies, we presented an intonational cue that was acoustically identical in our condition of interest (in which the cue was used for sentence comprehension; *ProsOnly1*) and in its matched control condition. Our finding of activity in the left IFG without additional activity in auditory regions can be explained by the acoustic similarity of these two conditions.

As another novel aspect, our study investigated how intonation is used to guide the interpretation of the sentence. Notably, linguistic prosody can come in various forms (Cutler et al., 1997), of which marking of a syntactic boundary by an intonational phrase boundary (IPB) is arguably the most important for sentence structure. The importance of prosodic information in syntactic phrasing has been demonstrated in electrophysiological studies (Friederici et al., 2007; Steinhauer et al., 1999). Previous fMRI studies, however, have not studied this use of prosody. Rather, fMRI research has focused on types of linguistic prosody which are not as crucial for the syntactic structure of a sentence, such as marking a question or statement (Kreitewolf et al., 2014; Sammler et al., 2015) or placing stress (Kristensen et al., 2013; Perrone-Bertolotti et al., 2013). Moreover, studies often used a low-level or non-linguistic baseline condition rather than a comparable linguistic control task (M. Meyer et al., 2002; 2004; Plante et al., 2002). Right fronto-temporal areas have been found in question/statement versus phoneme discrimination tasks (Kreitewolf et al., 2014; Sammler et al., 2015), with functional activity switching to the left hemisphere when contrasted against a non-linguistic task of speaker identification (Kreitewolf et al., 2014). In turn, processing of pitch focus was shown to involve bilateral frontal and superior temporal regions (Kristensen et al., 2013; Perrone-Bertolotti et al., 2013), rather than the isolated recruitment of the left IFG found here. Critically, in the aforementioned studies, analysis of pitch differences was required to deduce linguistic meaning from the speech signal (i.e., by distinguishing question/statements or establishing constituent focus), but it was not used for the interpretation of the syntactic structure. In sum, we argue that the type of linguistic prosody in the current study (i.e., the use of the IPB) forms a more direct link to sentence structure processing than the previous studies, thus isolating functional activation in the left IFG.

Our results show that the left IFG was also involved when a grammatical cue (i.e., word form) guided sentence comprehension. In the *grammatical cue* condition *(GramOnly)*, the sentence structure could only be resolved by matching the case of the personal pronoun (morphosyntactic information) to either one of the verbs in the sentence. Although different from the intonational cue, both cues had the syntactic function of unambiguously attributing the object in the sentence to one of two verbs. Case marking ensured that the personal pronoun could only match one of two verbs, similar to how the position of the IPB established a single possible interpretation of the sentence. We found that the left IFG was engaged in the processing of both cue types, which indicates that this area responds to different kinds of cues resolving ambiguity in sentence structure. This finding points to a more general involvement of the left IFG in the processing of sentence structure. Activity in the left STG/STS, on the other hand, was only present when sentence structure was built by a grammatical cue. This is not surprising given that superior temporal regions have been associated with morphosyntactic processing in lesions studies (Dronkers, Wilkins, Van Valin, Redfern, & Jaeger, 2004) and fMRI studies on assigning subject and object to a verb (Bornkessel et al., 2005). Additionally, the posterior STG has been shown to play a critical role in the production of the correct morphosyntactic form (D. K. Lee et al., 2018).

To isolate the processing of each type of linguistic cue, we compared an experimental condition in which only one cue (either intonational or grammatical) was available to resolve sentence structure ambiguity, to a control condition in which both cues were available. These comparisons did not only reveal differences in the neural activity but also on the behavioural level: participants responded faster and more accurately in the control conditions compared to the experimental conditions. Consequently, one could argue that the increased activity in the left IFG reflects differences in task difficulty rather than differences in linguistic processing per se. However, our general linear model included a regressor which modelled all trial-by-trial responses as a boxcar function with trial-by-trial reaction times as duration (Grinband et al., 2008). Since one regressor was built modelling reaction times across all conditions, this regressor should account for variance introduced by between-condition differences in reaction times and should therefore regress out domain general effects. Moreover, increased cognitive demand usually relies on a domain-general network that in the frontal lobe excludes most of the IFG (Fedorenko, Duncan, & Kanwisher, 2013) and rather includes premotor regions, the anterior cingulate cortex, and the middle frontal gyrus (Duncan, 2010). Taken together, we did not find support for the alternative explanation that the observed activity in left IFG was due to differences in task difficulty.

With respect to the lateralisation of intonation processing, we set out to advance a debate that has been held for decades. Although early studies indicated a right-hemispheric advantage for emotional prosody and left-hemispheric dominance for linguistic prosody (Heilman, Bowers, Speedie, & Coslett, 1984; Luks et al., 1998), recent meta-analyses suggest involvement of a more bilateral network (Belyk & Brown, 2014; Witteman et al., 2011). Our paradigm allowed us to assess the lateralisation of prosody processing in function of its linguistic importance since we varied the linguistic role of the intonational cue across conditions while keeping acoustical information identical across conditions. We found that processing intonation was left-lateralised in the IFG when it guided sentence comprehension. In contrast, when intonation was superfluous for disambiguation of the sentence structure, activation in the IFG was shifted to the right hemisphere. The latter finding can be explained by our manipulation in which the IPB was not relevant for disambiguating the sentence structure. This resulted in a relative dominance of the right IFG when prosody was processed without being used to establish the sentence structure. This interpretation is consistent with previous studies (Kreitewolf et al., 2014; Sammler et al., 2015), demonstrating right IFG involvement when intonational contours were processed without requiring integration into a sentence structure. The observed right-hemispheric lateralisation of the pSTS in our study further converges with previous work (M. Meyer et al., 2002; 2004; Sammler et al., 2015) and with models describing a right-hemispheric dominance of auditory regions in processing pitch information in speech, such as intonational contours (Poeppel, 2003). Together, the previous and present results suggest that the right pSTS is preferentially involved in processing of intonational contours as such, but not in the subsequent integration of this information during sentence comprehension.

4.1. Conclusion

In summary, this study provides evidence for the left IFG playing a key role in sentence processing when only intonation conveys the grammatical structure of the sentence. Activity in this region overlapped with the region that was active when the sentence structure was established by a grammatical cue (the particular word form providing case information). This finding extends previous work on the contribution of the left IFG in sentence comprehension, highlighting the role of this region in the integration of prosodic as well as grammatical cues into the sentence structure. Since overlapping regions were recruited when either a prosodic or a morphosyntactic cue established the sentence structure, the results underline the similar function that prosodic and morphosyntactic cues have in influencing the grammatical interpretation of a sentence.

Furthermore, we found that lateralisation of intonation processing depends on whether or not intonation is critical for understanding a sentence structure. This supports the notion that processing of prosodic information is lateralised in function of its linguistic role (Friederici & Alter, 2004; Kreitewolf et al., 2014; Luks et al., 1998;

van Lancker, 1980), showing this distinction for the first time in an fMRI study using sentence-level intonation in natural speech.

In conclusion, the left IFG, a core region for grammatical processing (Bornkessel-Schlesewsky & Schlesewsky, 2013; Friederici, 2011; Hagoort, 2014), was shown to be involved when prosodic cues established the sentence structure. Yet, the prosodic cue used in this study—the IPB—is a prosodic phenomenon that generally coincides with syntactic boundaries, and is therefore necessarily closely intertwined with grammatical processing. The next chapter of this thesis will therefore investigate how a different type of prosodic cue—the pitch accent—is involved in sentence comprehension: by influencing the syntactic as well as semantic processing domains.

Chapter 4

Pitch accents create dissociable syntactic and semantic expectations during sentence processing

Based, with modifications, on *Van der Burght, C.L., Friederici, A.D., Goucha, T., Hartwigsen, G. (In revision). Pitch accents create dissociable syntactic and semantic expectations during sentence processing.*

Abstract

The language system uses syntactic, semantic, as well as prosodic cues to efficiently guide auditory sentence comprehension. Prosodic cues, such as pitch accents, can build expectations about upcoming sentence elements. This study investigates to what extent syntactic and semantic expectations generated by pitch accents can be dissociated and if so, which cues take precedence when contradictory information is present. We used sentences in which one out of two nominal constituents was placed in contrastive focus with a third one. All noun phrases carried overt syntactic information (case-marking of the determiner) and semantic information (typicality of the thematic role of the noun). Two experiments (a sentence comprehension and a sentence completion task) show that focus, marked by pitch accents, established expectations in both syntactic and semantic domains. However, only the syntactic expectations, when violated, were strong enough to interfere with sentence comprehension. Furthermore, when contradictory cues occurred in the same sentence, the local syntactic cue (case-marking) took precedence over the semantic cue (thematic role), and overwrote previous information cued by prosody. The findings indicate that during auditory sentence comprehension the processing system integrates different sources of information for argument role assignment, yet, primarily relying on syntactic information.

1. Introduction

Language comprehension is guided by various types of linguistic information. Previous work shows that auditory sentence processing is facilitated by expectations established by syntactic, semantic, as well as prosodic cues. One type of prosodic cue is the pitch accent, which gives prominence to a particular part of the sentence through an increase in pitch and intensity (Grabe, 1998). In written form, the sentence “John kissed Mary, not Peter” is ambiguous concerning the role of Peter: either he did not kiss Mary, or he was not kissed by John. In such cases, pitch accents can be crucial for sentence comprehension. Realising a pitch accent on either “John” or “Mary” places one of the words in so-called focus. This determines which arguments in the sentence are contrasted with each other (Rooth, 1992): either John and Peter, or Mary and Peter. Thereby the pitch accent clarifies the role “Peter” occupies in the otherwise syntactically ambiguous sentence (i.e., the pitch accent establishes *who did what to whom*). It has been suggested that the two elements that are in contrastive focus are interpreted to have parallel syntactic roles (Carlson, Dickey, Frazier, & Clifton, 2009); (Carlson, 2015). In turn, these parallels influence the interpretation of the noun phrase “Peter”, which occurs in that part of the sentence where important information is omitted, a so-called ellipsis structure (see Winkler (2019) for a review). In sum, pitch accents, by marking contrastive focus, can draw parallels between constituents that occupy the same syntactic role. This implies that after perceiving the first focused constituent in a sentence, a certain expectation about the upcoming constituent may be established. How different types of linguistic information interact to form these expectations is unclear. The current study investigates this interaction by exploring which expectations are formed when pitch accents highlight constituents that contain overt syntactic and semantic cues. Specifically, we asked if syntactic and semantic expectations can be dissociated, and furthermore, which type of information listeners rely on when competing cues from multiple domains are present.

There are several ways in which pitch accents can cue syntactic structure. First, they can resolve attachment ambiguities, as has been shown by several early studies on the interaction between pitch accents and syntactic structure (Schafer et al., 1996; Schafer, Carlson, Clifton, & Frazier, 2000). For example, in "the propeller of the plane that the mechanic was so carefully examining…", a pitch accent on either "propeller" or "plane" helps to clarify what the mechanic was examining, something that is ambiguous without focus-marking. It is therefore supposed that ambiguous sentence parts are likely to be attached to the sentence element that bears focus (but see Lee & Watson (2010) for an alternative explanation). Second, as discussed above, by assigning contrastive focus, pitch accents can mark parallels between constituents and influence the interpretation of their syntactic role (Carlson, 2001). Importantly, it has been argued that the disambiguating effects of prosody are in part predictive. Several eye-tracking studies have shown that listeners anticipate a certain syntactic structure as a result of a prosodic cue (Nakamura et al., 2012; Weber et al., 2006b). For example, in German – a language with relatively free word order, where the object can precede the subject – the sentence "The cat possibly hunts the dog" contains a temporary ambiguity: "the cat" can be both subject and object of a sentence until the determiner of "the dog" is perceived. This is because "the cat" carries the syntactic gender feminine, which is not case-marked with an unambiguous form (nominative case: *die/the*; accusative case: *die/the*). The role of the noun phrase can only be disambiguated by clear case-marking of a second determiner, as in the masculine noun phrase "the dog" (nominative: *der/the*; accusative: *den/the*), causing *der/the dog* to be the subject and *den/the dog* to be the object of the sentence. However, a pitch accent on either "cat" or "hunts" can mark the correct interpretation of the sentence as well, since the pitch contour of sentences in which the object precedes the subject differs from those in which the subject comes first. Indeed, depending on the prosodic structure of a given sentence, listeners showed increased anticipatory eye movements to the correct interpretation in a visual scene (Weber et al., 2006b). This shows that pitch accents can influence the analysis of syntactic structure *before* additional disambiguating input has been observed (see Snedeker & Trueswell (2003) for a similar experiment using prosodic boundaries).

Aside from cueing syntax, pitch accents play an important role in the semantic domain. By marking focus, prosody forms a direct link with the information structure of a sentence. The information structure guides the listener to what is new or important in a sentence. Focus, which can be marked by pitch accents, gives prominence to sentence elements, highlighting the difference between new and given information (Jackendoff, 1972). Focus-marking is also thought to trigger semantic alternatives (reviewed in Gotzner & Spalek (2019)). For instance, in a sentence such as “Anna bought [BANANAS]”, the listener automatically considers what else Anna could have bought or did not buy (capital letters indicate focus-marking by a pitch accent). The set of alternatives that becomes activated must share semantic features with the focused constituent - although the scope and time course of this pre-activation are debated (Braun & Tagliapietra, 2010; Husband & Ferreira, 2016). What is undisputed, however, is that this activation of semantic alternatives occurs in a predictive manner. Several eye-tracking studies have shown that after perceiving focus, participants fixate at semantically appropriate items more than at control items, showing a predictive capacity of focus in the semantic domain (Ito & Speer, 2008; Karimi et al., 2019; Watson et al., 2008; Weber, Braun, & Crocker, 2006a).

Taken together, it has been shown that prosody can have a predictive function in sentence processing, both syntactically and semantically. Furthermore, in a sentence such as “JOHN kissed Mary, not PETER”, the two contrastively focused arguments occupy parallel roles. This implies that after encountering the first of these constituents, there may be a certain expectation about the second, parallel one. However, the nature of these expectations is unclear, and it remains to be shown whether the contributions of syntactic and semantic information can be dissociated. Furthermore, it is unclear which type of cue takes precedence when several contradictory indicators of sentence structure are present. To address these questions, we used focus-marking to create sentences of the type “Yesterday, the policeman arrested the thief, not the murderer” (translated from German). Realising a pitch accent on either the first (Fig 1A) or second noun (Fig 1B) resulted in the variants A and B of that sentence. Note that the noun phrases in the German sentences are marked by case (nominative [NOM] and accusative [ACC]), and that focused noun phrases are indicated with CF (contrastive focus).

A. Yesterday, [the$^{\text{NOM}}$ POLICEMAN]$_{\text{CF}}$ arrested the$^{\text{ACC}}$ thief, not [the$^{\text{NOM}}$ INSPECTOR]$_{\text{CF}}$

Gestern hat [der POLIZIST] den Dieb verhaftet, nicht [der KOMMISSAR]

B. Yesterday, the$^{\text{NOM}}$ policeman arrested [the$^{\text{ACC}}$ THIEF]$_{\text{CF}}$, not [the$^{\text{ACC}}$ MURDERER]$_{\text{CF}}$

Gestern hat der Polizist [den DIEB] verhaftet, nicht [den MÖRDER]

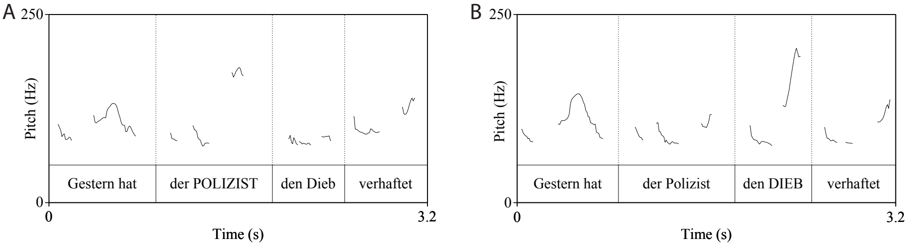


Figure 1. Pitch contours illustrating the difference between subject-focus and object-focus in the example sentence *Yesterday, the policeman arrested the thief* ("Gestern hat der Polizist den Dieb verhaftet"). The noun phrase that is placed in contrastive focus bears a pitch accent (indicated by capital letters), whereas it is deaccented in the other condition.

To dissociate syntactic and semantic processes, we included explicit cues in both domains. Syntactically, grammatical case of the determiner in the noun phrase marked the subject [NOM] vs object role [ACC]. As semantic cue, we made use of thematic role typicality: the notion that a verb is associated with a set of thematic roles, corresponding to the participants in an event (Jackendoff, 1972). For example, the verb "to arrest" has typical agents (doers, e.g., a policeman) and patients (undergoers, e.g., a thief) that participate in the action. We hypothesised that focus-marking either the subject or object noun phrase of the main clause should establish expectations concerning the syntactic and semantic content of the ellipsis structure.

We examined the nature of these expectations in two experiments. In Experiment 1, we tested if these expectations can be probed *implicitly*. We should then be able to find evidence of inhibited processing in case these expectations are violated. To tease apart the syntactic and semantic components of these expectations, we manipulated the syntactic and semantic congruency between the upcoming constituent in the ellipsis part and the expectations formed in the main clause. In this experiment, listeners were then asked whether they interpreted the different noun phrases of the sentence as subject or object. If mismatching cues between two focused constituents resulted in delayed responses, we can argue that the noun phrase in the ellipsis part violated a syntactic or semantic expectation established by the pitch accent. Experiment 2 investigated if listeners form an *explicit* expectation, in which case we should find evidence of prosodic focus-marking when directly probing the listener's preferred continuation of a sentence. To test whether participants formulated an explicit prediction, participants in this experiment completed an auditory sentence, which was cut before the second focused constituent was produced ("Yesterday, the POLICEMAN arrested the thief, not…"), by selecting the case of the determiner and the role of noun. Together, these two experiments enabled us to investigate the expectations that pitch accents establish, and to what extent they can manipulate the interpretation of an ellipsis structure. By highlighting constituents that contain a syntactic as well as semantic cue, we could assess if syntactic and semantic processes can be dissociated within these expectations. Finally, considering that syntactic cues and thematic roles interact (Trueswell et al., 1994), we asked to what extent listeners rely on syntactic and semantic components when multiple indicators of sentence structure are available.

2. Experiment 1

2.1. Methods

The design and analysis plan of this experiment were preregistered at the Open Science Framework (Experiment 1: https://osf.io/94bp5). Experiment 1 involved a sentence comprehension task with a 3x2x2 factorial within-subject design with the factors violation type (baseline; syntactic; semantic), focus position (subject; object) and target of comprehension question (main clause; ellipsis). Raw data and analysis scripts can be found at https://osf.io/v5xga/.

2.1.1. Participants

36 healthy native German speakers (20 female; age *M* = 23.8 years, *SD* = 4.0, range 18-34) were included in the analysis. Right-handed participants (Oldfield, 1971) were recruited from the database of the Max Planck Institute for Human Cognitive and Brain sciences. All participants had normal or corrected-to normal vision. Exclusion criteria were hearing loss or professional musical training. One participant was excluded from the analysis because of incorrect handedness information. The experiment was approved by the ethics committee of the University of Leipzig, and all participants gave written consent prior to participation.

To determine our sample size, we ran a power analysis using the powerSim function of the simR package in R on data from an independent sample tested in a pilot version of the experiment (n=7). We tested for the interaction term *violation type* x *comprehension question target* from our original hypothesis, running 25 simulations in 36 participants. We determined this initial sample size of 36 to have a minimum of 1600 observations per cell (Brysbaert & Stevens, 2018). Our stimulus set consisted of 48 items, leading to an estimated sample size required of at least 34 (1600/48=33,33), to which we added 2 to achieve a full balancing-out of our design. These simulations yielded an estimated power of above 99%. This suggests that a smaller sample size would achieve sufficient power, however, to avoid going below the minimum number of observations recommendation by Brysbaert & Stevens (2018), we determined our required sample size at 36.

2.1.2. Stimulus design

In our stimulus sentences (in German), one out of two constituents in a first clause was placed in contrastive focus with a third constituent in a second, elliptical clause (as exemplified previously in sentences A and B; analogous to Stolterfoht, Friederici, Alter, & Steube (2007). A pitch accent (indicated with capital letters in the examples below) marked whether focus was on the subject (1) or the object noun phrase (2). To tease apart the syntactic and semantic components of the expectations created by focus, the noun phrases contained specific syntactic information (case marking of the determiner) and semantic information (thematic role of the noun). In the ellipsis structure that followed, a third noun phrase occurred that corresponded grammatically and thematically to the focused noun phrase in the main clause (baseline condition).

(1) Yesterday, [the$^{\text{NOM}}$ POLICEMAN]$_{\text{CF}}$ arrested the$^{\text{ACC}}$ thief, not [the$^{\text{NOM}}$ INSPECTOR]$_{\text{CF}}$
Gestern hat [der POLIZIST] den Dieb verhaftet, nicht [der KOMMISSAR]

(2) Yesterday, the$^{\text{NOM}}$ policeman arrested [the$^{\text{ACC}}$ THIEF]$_{\text{CF}}$, not [the$^{\text{ACC}}$ MURDERER]$_{\text{CF}}$
Gestern hat der Polizist [den DIEB] verhaftet, nicht [den MÖRDER]

In (1) the determiners of the two contrasted noun phrases are in nominative case, and both nouns are typical agents of the verb "to arrest". In (2) the contrastive constituents are case-marked accusative and typical patient nouns.

To form syntactic and semantic mismatches between the two focused constituents, we created combinations with mismatching grammatical case and thematic roles. In the condition with a syntactic violation (3 and 4), the grammatical case of the determiner in the ellipsis structure mismatches the focused constituent in the main clause (nominative vs. accusative).

(3) Yesterday, [the$^{\text{NOM}}$ POLICEMAN]$_{\text{CF}}$ arrested the$^{\text{ACC}}$ thief, not [the$^{\text{ACC}}$ INSPECTOR]$_{\text{CF}}$
Gestern hat [der POLIZIST] den Dieb verhaftet, nicht [den KOMMISSAR]

(4) Yesterday, the$^{\text{NOM}}$ policeman arrested [the$^{\text{ACC}}$ THIEF]$_{\text{CF}}$, not [the$^{\text{NOM}}$ MURDERER]$_{\text{CF}}$
Gestern hat der Polizist [den DIEB] verhaftet, nicht [der MÖRDER]

In the condition with a semantic violation (5 and 6), the thematic role in the ellipsis structure mismatches the focused noun in the main clause (typical agent vs. patient).

(5) Yesterday, [the$^{\mathrm{NOM}}$ POLICEMAN]$_{\mathrm{CF}}$ arrested the$^{\mathrm{ACC}}$ thief, not [the$^{\mathrm{NOM}}$ MURDERER]$_{\mathrm{CF}}$
Gestern hat [der POLIZIST] den Dieb verhaftet, nicht [der MÖRDER]

(6) Yesterday, the$^{\mathrm{NOM}}$ policeman arrested [the$^{\mathrm{ACC}}$ THIEF]$_{\mathrm{CF}}$, not [the$^{\mathrm{ACC}}$ INSPECTOR]$_{\mathrm{CF}}$
Gestern hat der Polizist [den DIEB] verhaftet, nicht [den KOMMISSAR]

The experimental items consisted of verb-argument combinations with clear agent-patient relationships. All nouns were required to be masculine to enable the overt morphosyntactic marking of grammatical case of the determiners (in German, the nominative and accusative case of feminine and neuter determiners share surface form). Furthermore, we excluded nouns of which the shape in accusative differs from the nominative, to ensure that case was marked solely by the determiner. The number of syllables of the nouns that belonged to the same verb was matched as closely as possible.

The semantic properties of the materials were evaluated in a normative study on a separate sample (n=40) based on Ferreira (2003). To assess the semantic-thematic relationships between the verbs and their noun phrase arguments, all verbs were presented with an agent and patient in plausible and implausible order. The items were divided over four lists, such that each participant rated each verb twice: with one agent-patient pair in a plausible sentence (e.g., *The policeman arrested the murderer*) and a different pair in an implausible sentence (e.g., *The thief arrested the detective*). Participants were instructed to carefully read the sentences and rate them on a scale from 1 (“extremely implausible”) to 6 (“extremely plausible”), with examples provided. From an initial set of 73 items the 48 items with the largest difference plausible-implausible were selected. These 48 verb-argument combinations had a clear thematic role assignment, with the implausible versions rated less plausible than their plausible counterparts (plausible: $M = 5.33$, $SD = 0.40$; implausible: $M = 1.57$, $SD = 0.55$).

2.1.3. Stimulus construction

A professional native German speaker was recorded producing two variants of 48 critical items (listed in Supplementary Table 7). The speaker was instructed to realise a pitch accent on either the subject (Fig. 1A) or object (Fig. 1B) of the main clause. At the sentence-final position, a filler noun phrase was produced that was later removed. The sentence-final noun phrases were taken from separate recordings: a typical agent (a and c) or typical patient (b and d) of the verb (in this case "to arrest"), combined with a determiner in either nominative (a and b) or accusative case (c and d). These sentence-final nouns all carried a contrastive pitch accent.

a) … the^{NOM} INSPECTOR
b) … the^{NOM} MURDERER
c) … the^{ACC} INSPECTOR
d) … the^{ACC} MURDERER

The items in a)-d) enabled us to create combinations in which the two focused constituents either had corresponding grammatical case (determiners) and thematic role typicality (nouns) or carried mismatching syntactic or semantic information. The cross-splicing procedure ensured that the comparisons between conditions of interest involved materials that were acoustically identical, and the speaker never had to produce sentences containing violations. Figure 2 provides an overview of the experimental conditions.

Recordings were made in a sound-attenuating chamber (IAC – I200 series, Winchester, United Kingdom) and the digitised speech signals (sampling rate 44.1kHz; resolution 16 bits) were adjusted to the same root mean square amplitude using Praat (Boersma & Weenink, 2018). In the same programme, sound files were manually cut and subsequently concatenated using a custom-made script.

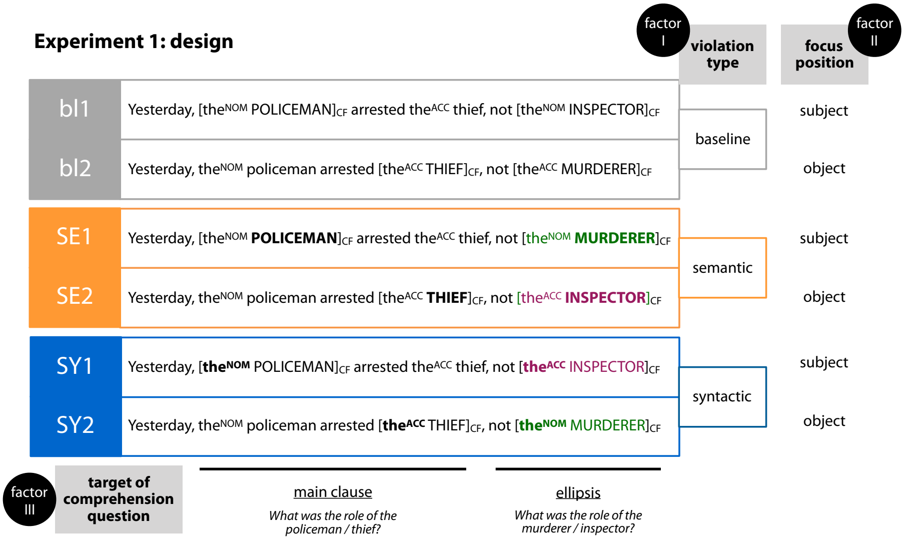


Figure 2. Design overview of Experiment 1. The two factors violation type and focus position resulted in six sentences. Each sentence could be probed by a comprehension question related to the noun phrase at the main clause or ellipsis (experimental factor 3). Violating sentence elements in bold typeface. Sentence-final determiner-noun pairs are colour-coded separately (see Results). Pitch accents are indicated by capital letters. bl = baseline; se = semantic; sy = syntactic; CF = contrastive focus.

2.1.4. *Procedure*

Participants performed a sentence comprehension task (Fig 2 & 3). At trial onset, a white fixation cross was presented which turned red 200 ms prior to auditory onset to alert the participant. The auditory stimulus was followed by the comprehension question and two visually presented answer options. Participants responded via button press with the right index or middle finger. Subsequently, a fixation cross was presented for approximately 2 s until the next trial started.

A comprehension question probed how listeners interpreted the sentence. They were asked what role a certain participant played in the action described in the sentence: *“What was the role of the policeman?”* (in subject-focus trials) or *“What was the role of the thief?”* (in object-focus trials). They indicated whether the policeman/thief was doer or undergoer of the action *(“has arrested”* or *“was* *arrested”*). The comprehension question could target one of the two noun phrases in contrastive focus. If the noun phrase in the ellipsis structure was probed (*“What was the role of the inspector/murderer?”*) the response options were *“has not arrested”* or *“was not arrested”*. Comprehension questions probing main clause and ellipsis occurred equally often and were presented counter-balanced across conditions. The assignment of the active/passive answer options to the response buttons was counter-balanced between subjects.

The trial sequences were pseudo-randomised with the following constraints: each item (verb) was presented once in each block of 48 trials; the same violation conditions, focus position, and the target of the comprehension questions (probing either main clause or ellipsis part of the sentence) were not repeated more than twice. To draw the participants’ attention to the semantic-thematic content of the verb-argument structure rather than merely to the three noun phrases, catch trials were included (amounting to 20% of the total number of trials) which probed the verb of the auditory stimulus (e.g., *Did someone… arrest / instruct?*). The experiment lasted for approximately 52 minutes including 5 breaks, the duration of which was self-timed. A short practice session preceded the experiment, mirroring the main experiment but consisting of different stimuli.

Participants sat in a sound-attenuated chamber and listened to the auditory stimuli over headphones. Visual stimuli were presented on a screen (Sony Trinitron Multiscan 300GS, Sony Corporation) and responses were given on a response-box placed on their lap. Stimulus presentation and response collection was controlled via Presentation (Neurobehavioural Systems, Inc., Albany, CA, USA).

2.1.5. *Data analysis*

Response times were analysed using a Linear Mixed Model (Baayen et al., 2008). Upon visual inspection, response times were log-transformed to approach a normal distribution. Response counts were analysed using a logistic Generalized Linear Mixed Model (Baayen et al., 2008). In both models, we included the factors *violation type, focus position, comprehension question target*, and their interaction as fixed effects. The three-level violation type factor was dummy coded with the semantic

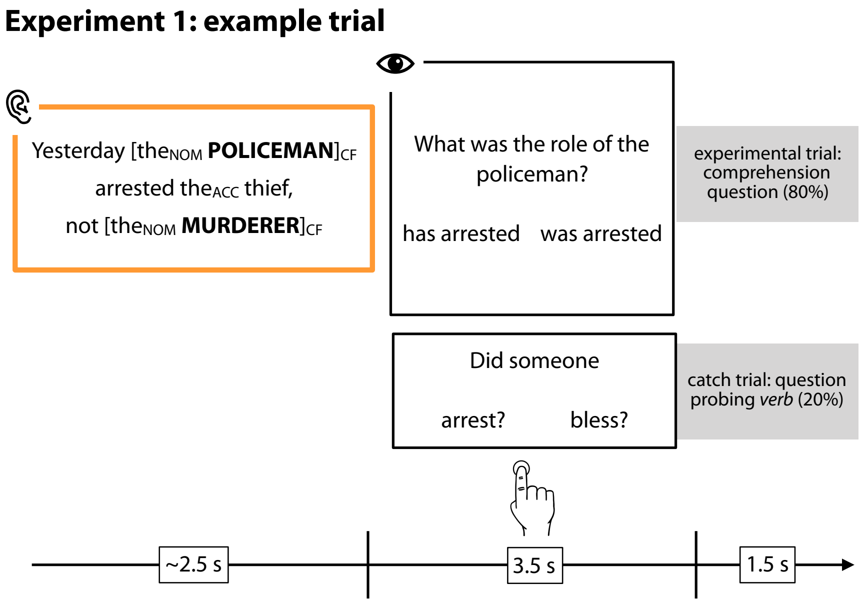


Figure 3. Example trial of Experiment 1 – sentence comprehension paradigm. Experimental trials contained comprehension questions probing one of the two contrastively focused noun phrases. Catch trials probed the verb.

condition being the reference category. Contrary to our a-prior hypothesis that only the factors *violation type* and *comprehension question target* would interact, visual inspection of the response times (see Fig 4 & 5) motivated us to consider a three-way interaction as the most appropriate way to model the data. We aimed to include a maximal random effects structure (Barr et al., 2013). However, due to convergence issues, we simplified the random effects structure until the models converged, by removing the interaction terms and finally the main effects, first for item and then for participant (for the main effects, we prioritised inclusion of the factor *violation type*). This led to the use of an intercept-only model in the Linear Mixed Model (reaction times) and inclusion of by-participant random slopes for the factor *violation type* in the Generalized Linear Mixed Model (response counts).

We tested the effect of the three-way interaction using a likelihood ratio test comparing the full model with a reduced model lacking the interaction term (Barr et al., 2013); Dobson & Barnett, 2008). Pair-wise follow-up comparisons were done by calculating estimated marginal means (Searle, Speed, & Milliken, 1980) using the package emmeans (Lenth, Singmann, Love, Buerkner, & Herve, 2019). The models were fitted in R (version 3.6.0; R Core Team (2019)) using the functions lmer and glmer of the package lme4 (version 1.1-21; Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). We used raincloud plots (Allen, Poggiali, Whitaker, Marshall, & Kievit, 2018) for visualisation of the response times, to show both summary statistics and the response distributions per condition.

2.2. **Results**

In the response times, we found a significant interaction between violation type, focus position, and comprehension question target ($\chi^2(2)=30.63$, $p<.0001$). The same three-way interaction was significant in the analysis of the response counts ($\chi^2(2)=29.71$, $p<.0001$). Response behaviour to comprehension questions targeting the main clause of the stimuli is shown in Figure 4. Behavioural results when targeting the ellipsis with the comprehension question are shown in Figure 5. The estimated fixed and random effects are shown in Supplementary Tables 1 (reaction times) and 2 (accuracy).

2.2.1. Comprehension question probing the main clause

In the interpretations of the main clause, planned pair-wise comparisons showed significant increase in response times of the syntactic condition as compared to the semantic and baseline conditions (Fig 4A and Supplementary table 3). This was the case after subject focus – syntactic vs semantic: $t(10225)=-3.820$, $p=.001$; syntactic vs baseline: $t(10225)=-4.847$, $p<.001$) – and after object focus – syntactic vs semantic: $t(10225)=-2.689$, $p=.036$; syntactic vs baseline: $t(10225)=-3.318$, $p=.006$ – (note that the high number of degrees of freedom is due to single-trial information on which the estimated marginal means are based).

Importantly, the sentence material that participants were asked to interpret in the main clause was identical in all conditions: *the*^{NOM} *policeman* in case of a subject-focus stimulus, and *the*^{ACC} *murderer* after an object-focus stimulus. The sole difference between the conditions was the type of violation (semantic or syntactic) that followed in the ellipsis part of the sentence. These violations are reflected in the response times, with the syntactic violation leading to an additional processing cost. The proportions of subject/object judgements (Fig 4B) were not affected by these violations: analysing the proportion of responses that correctly interpreted the syntactic and semantic cues of the main clause, there were no significant differences in the pair-wise comparisons between the accuracies of each condition (see Supplementary Table 3: Accuracy).

2.2.2. Comprehension question probing the ellipsis

In the responses at the ellipsis site (Fig 5), we did not find evidence violations of the prosodically cued syntactic and semantic expectations generated in the main clause (Fig 5A; Supplementary table 3). Rather, the response times differences of the semantics and syntax conditions depended on whether focus in the main clause was on the subject or object noun phrase: responses were faster in the syntax condition as compared to the semantics condition after subject focus (*t*(10225)=5.564, *p*<.001), whereas after object focus responses were slower in syntax than in semantics (*t*(10225)=-4.103, *p*<.001).

Here, we need to take into account that, at the ellipsis site, participants were asked to make a judgement on the role of a noun phrase, which in itself held conflicting semantic and syntactic information except in the baseline condition: in *the*^{NOM} *MURDERER,* a typical patient of *to arrest* was preceded by a determiner in the nominative case (cueing a subject role); in contrast, *the*^{ACC} *INSPECTOR* is a typical agent preceded by a determiner in the accusative (cueing an object role). When considering the congruency of grammatical case and role typicality at the ellipsis, the pattern of response times shows a striking correspondence: response times were shorter when a role judgement was required on *the*^{ACC} *INSPECTOR,* but longer when judging *the*^{NOM} *MURDERER*. In sum, the pattern of reaction times at the ellipsis does not reflect the type of violation present in the sentence as a whole, but rather the

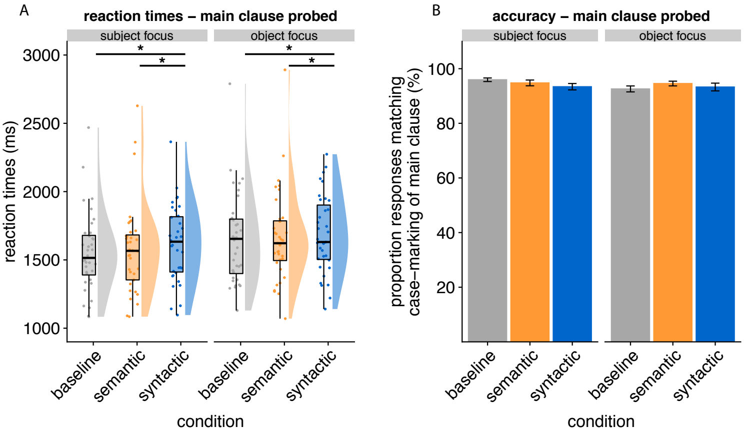


Figure 4. Reaction time (A) and accuracy (B) plots for the comprehension questions that probed the main clause (Experiment 1). Error bars indicate ±1 SEM. Asterisks mark planned pair-wise comparisons with *p*-values smaller than .05 (Bonferroni-Holm-corrected).

local grammatical-thematic congruency of the determiner-noun pairs at the ellipsis site itself.

This interpretation is supported by the analysis of the accuracy rates at the ellipsis part of the sentence (Fig 5B). Firstly, participants responded according to the grammatical case of the determiner presented at the ellipsis site: *the*^{ACC} *INSPECTOR* was interpreted as object of the sentence and *the*^{NOM} *MURDERER* as subject, despite the conflicting semantic information. However, in the case of *the*^{NOM} *MURDERER*, we observed a lower accuracy as compared to the other sentence endings, with a significant decrease in the number of “subject” responses (a “subject” response is in line with the nominative case of the determiner). This pattern driven by sentence endings was present both after subject focus (semantics vs baseline: z=5.065, p=<.001; semantic vs syntactic: z=-5.005, p<.001) and after object focus (syntactic vs baseline: z=6.643, p<.001; syntactic vs semantic: z=5.524, p<.001).

Importantly, the role judgements made at the ellipsis site corresponded to the syntactic cue presented at the ellipsis site, regardless of whether conflicting syntactic or semantic information was focused in the main clause. This implies that, even though pitch accents can establish an expectation concerning upcoming

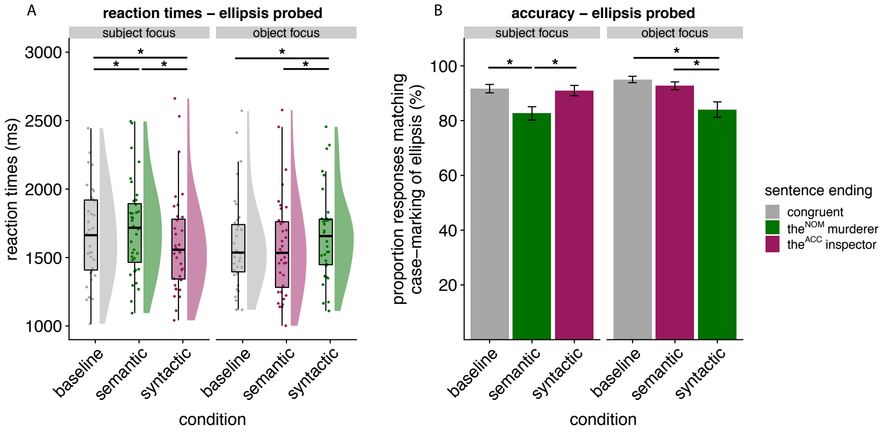


Figure 5. Reaction time (A) and accuracy (B) plots for the comprehension questions that probed the ellipsis clause (Experiment 1). Error bars indicate ±1 SEM. Asterisks mark planned pair-wise comparisons with *p*-values smaller than .05 (Bonferroni-Holm-corrected).

syntactic information (as can be seen in the response times of the main clause), it is the incoming local syntactic cue that is decisive for the role judgement at the ellipsis site.

3. Experiment 2

From Experiment 1, it remained unclear whether prosodically-marked semantic information establishes expectations about upcoming sentence constituents since pair-wise comparisons between semantics and baseline were not significantly different. We therefore conducted a follow-up experiment, in which the stimuli from Experiment 1 had the final constituent removed and in which participants had to explicitly continue the sentence in a forced-choice task (see Figure 6). The removal of the sentence final constituent resulted in (I) and (II).

(I) Yesterday, [the^{NOM} POLICEMAN]$_{CF}$ arrested the^{ACC} thief, not …

- *Gestern hat [der POLIZIST] den Dieb verhaftet, nicht …*

(II) Yesterday, the^{NOM} policeman arrested [the^{ACC} THIEF]$_{CF}$, not …

- *Gestern hat der Polizist [den DIEB] verhaftet, nicht …*

Participants were then asked to listen to the beginning of the sentence and to complete the sentence. Crucially, the appropriate determiner and noun of the missing noun phrase had to be chosen sequentially: participants first selected a case-marked determiner (syntactic completion) and then a noun (semantic completion). We created separate syntactic and semantic experimental conditions as follows, to prevent the syntactic decision from influencing the subsequent semantic decision.

In the syntactic condition, participants had to choose between two determiners marked in nominative or accusative case (*der/the*^{NOM} or *den/the*^{ACC}). By presenting the decision on the determiner first, participants made a purely syntactic decision, without possible semantic influence from a co-occurring noun. In the semantic condition, the agent and patients were presented in their feminine versions. In German, nominative and accusative case marking of the feminine determiner *die/the* is ambiguous (representing both cases). In this way, the decision on the determiner on sentences with feminine noun phrases was meaningless. Consequently, the subsequent decision on the noun (*police officer*^{FEM} or *thief*^{FEM}) was a purely semantic one, without possible influence from a preceding syntactic judgement.

3.1. Methods

Experiment 2 involved a sentence completion task, using a 2x2 factorial within-subject design with the factors *decision typ*e (syntactic; semantic) and *focus position* (subject; object). Raw data and analysis scripts can be found at https://osf.io/v5xga/.

3.1.1. Participants

36 native German speakers (19 female; age *M* = 24.6 years, *SD* = 4.9, range 18-35) who had not taken part in Experiment 1 were included in the analysis. The inclusion and exclusion criteria were the same as those for Experiment 1. Eight additional data sets had to be excluded (incorrect handedness information, n=1; native language other than German, n=1; incorrect button-response pairing, n=6). We determined our sample size at 36 to remain analogous to Experiment 1, despite the difference in complexity of the design. The experiment was approved by the ethics committee of

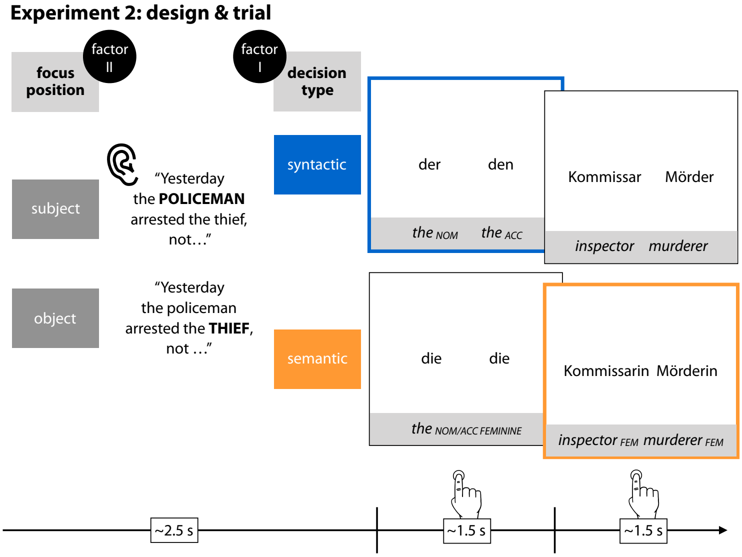


Figure 6. Experimental design of Experiment 2 – completion paradigm. Pitch accents are indicated by capital letters. NOM = nominative; ACC = accusative; FEM = feminine.

the University of Leipzig, and all participants gave written consent prior to participation.

3.1.2. Stimulus description

The auditory stimuli were the same sentence beginnings as used in Experiment 1 (resulting in sentences (I) and (II)). In this sentence completion task, participants were asked to make a syntactic judgement by choosing an appropriate continuation of the sentence (a determiner in either the nominative or accusative case, presented visually). The two nouns that were presented subsequently (a pair of a typical agent and patient of the verb in the preceding spoken stimulus) were taken from the sentence endings of Experiment 1 (the nouns from (a)-(d), see Supplementary table 7). We used feminine versions of these nouns for the semantic condition (see below).

3.1.3. Procedure

In this experiment participants performed a sentence completion task: the stimuli from Experiment 1 were cut before the noun phrase in the ellipsis part (sentences (I) and (II), modified from sentences (1) and (2)) and participants completed them by button-press in a two-alternative forced choice task. As described in the introduction to Experiment 2, participants made two consecutive decisions: they first selected a determiner and then a noun. In the syntactic condition, participants chose between two determiners marked in nominative or accusative case (*der/the*^{NOM} or *den/the*^{ACC}). By presenting the determiners first rather than simultaneously with the noun, participants made a purely syntactic decision, void of a possible semantic influence (see Figure 6). In the semantic condition, the agent and patients were presented in their feminine versions. As nominative and accusative case-marking of the determiner *the* is ambiguous in German, the decision on the determiner was meaningless. The subsequent decision on the noun (“*policewoman*” or “*thief*^{FEM}*”)* was therefore a purely semantic one, without possible influence from the preceding syntactic judgement. Participants were instructed to select the determiner and noun that would complete the sentence in the way they deemed most sensible. They were asked to give their response as quickly and accurately as possible.

Trial sequences were pseudo-randomised with the following constraints: stimuli with the same focus position were not repeated more than twice, and syntactic and semantic response conditions not more than three times. The assignment of the nominative/accusative and agent/patient answer options to the response buttons was counter-balanced within subjects.

As in Experiment 1, each trial started with a white fixation cross which turned red 200 ms prior to the onset of the auditory stimulus. After the interrupted sentence, the two determiner options were presented visually. The two nouns were presented as soon as the response to the determiner was made (or after 1500 ms in case of a missing response). The experiment lasted for approximately 25 minutes, including 3 self-timed breaks.

3.1.4. Data analysis

Reaction time and response count data were analysed in the same way as for Experiment 1. As fixed effects, the factors *decision type* and *focus position* and their interaction were included. We aimed to include a maximal random effects structure

(Barr et al., 2013), however, due to convergence issues, we simplified the random effects structure until the models converged (see Experiment 1). This led to the inclusion of by-participant random slopes for the factors *decision type* and *focus position* and by-item random intercepts in the Linear Mixed Model (reaction times), and an intercept-only structure in the Generalized Linear Mixed Model (response counts). To investigate possible interaction effects, likelihood-ratio tests were performed comparing the full model to the reduced model lacking the interaction term. (Barr et al., 2013); (Singmann & Kellen, 2019). To confirm that the pitch accent manipulation was perceived and determined response patterns in the syntactic and semantic decision types, it was required that participants performed above chance in all conditions. For this we used the intercept estimate in the binomial model: an intercept deviating from 0 indicates that response counts are not divided equally over the reference levels of the factors (suggesting a deviation from chance performance). We re-leveled our fixed effects *decision type* and *focus position* to obtain the intercepts for all four cells (subject focus, syntactic decision; subject focus, semantic decision; object focus, syntactic decision; object focus, semantic decision).

Furthermore, we performed an exploratory follow-up analysis investigating the inherent bias of individual participants to choose nominative/accusative determiners or agent/patient-like nouns. We employed methods from signal detection theory (Macmillan & Creelman, 1991) to dissociate sensitivity to the prosodic manipulation (d-prime) and response bias. To this end, we treated the subject-focus trials as ‘signal’ and object-focus trials as ‘noise’. Responses congruent with subject and object roles were coded as ‘hits’ and ‘correct rejections’, respectively. Incongruent responses were coded as ‘misses’ (subject focus) and ‘false alarms’ (object focus) (see L. Meyer et al. (2016) for a similar approach).

3.2. Results

We found a significant interaction between the factors decision type and focus position in the response times ($\chi^2(1)=21.19$, $p<.001$) as well as the response counts ($\chi^2(1)=40.08$, $p<.001$). More importantly, participants performed above chance in all conditions, indicating that their syntactic and semantic judgements depended on the focused constituent in the main clause: after subject focus (sentence I), participants preferred to continue the sentence with a determiner in the nominative case (*M*=71.0%, *SE*=4.1%, *z*=5.77, *p*<.001) and an agent-like noun (*M*=76.2%, *SE*=3.2%, *z*=7.25, *p*<.001). After object focus (sentence II), we saw the opposite pattern: accusative-marked determiners were preferred (*M*=76.0%, *SE*=3.5%, *z*=7.20, *p*<.001) as well as patient-like nouns (*M*=68.7%, *SE*=3.7%, *z*=5.13, *p*<.001). This shows that focus established an expectation about syntactic structure as well as semantic content of the upcoming clause (Fig 7B). The estimated fixed and random effects of this experiment are shown in Supplementary tables 4 (reaction times) and 5 (accuracy).

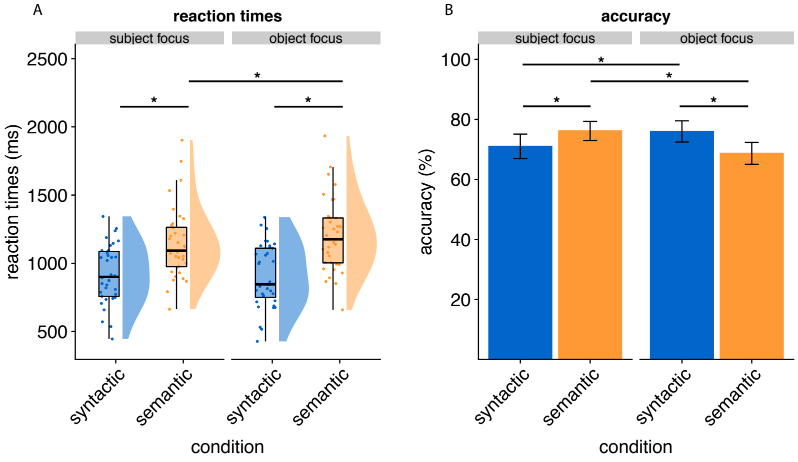


Figure 7. Reaction time (A) and accuracy (B) for Experiment 2. Error bars indicate ±1 SEM. Asterisks mark planned pair-wise comparisons with *p*-values smaller than .05 (corrected using the Bonferroni-Holm method).

Experiment 2 shows that participants formed a syntactic expectation that could be probed *explicitly*, since their preferred sentence continuation was syntactically congruent with the focused constituent they had perceived. This evidence goes in line with our result of Experiment 1, in which a mismatch between syntactic information in the main clause and in the ellipsis led to an inhibited interpretation of the role of the focused noun phrase in the main clause. In addition, Experiment 2 shows that focus can indeed establish an expectation about the semantic content of an upcoming clause, at least when explicitly probed: participants based their agent/patient preference on whether they had perceived a focused subject or object in the main clause. Specifically, there was a preference for typical agent nouns after subject focus sentences and typical patients after object focus. Since these semantic predictions did not cause an increase in response times in the main clause of Experiment 1, this indicates that although pitch accents can establish semantic expectations, they are not sufficiently strong to lead to additional processing cost in case they are violated.

The decreased accuracy both in syntactic decisions after subject-focus as compared to object-focus (z=-3.607, p<.001) and in semantic decisions after object-focus as compared to subject-focus (z=5.351, p<.001) may reflect that participants had an overall preference for accusative determiners and agent-like nouns, respectively (see Supplementary table 6 for all planned pair-wise comparisons). This possibility, in combination with the between-subject variability in the response patterns, led us to conduct an exploratory analysis using signal detection theory methods (Figure 8). This analysis enabled us to distinguish between sensitivity to the prosodic manipulation and a possible response bias. From the plots, two sources of individual differences can be recognised. First, a difference in sensitivity to the prosodic manipulation (variability along the solid line). Second, a difference in response bias (variability along the dashed line). In the syntactic decisions (Fig 8A) direction of this bias differed strongly between participants, showing some participants with an overall bias towards nominative-determiner responses (above the solid line), and others towards accusative-determiner responses (below the solid line), regardless of the focus position (see Fig 8A). In the semantic decisions, a bias for agent-like nouns was visible (most participants above the solid line), and the range in bias was less wide than in the syntactic decisions (Fig 8B).

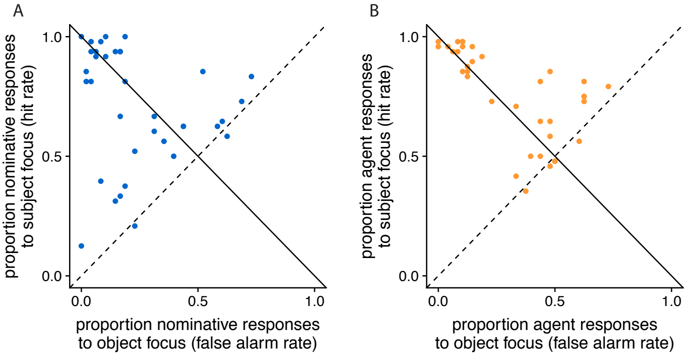


Figure 8. Signal detection theory analysis for the syntactic (A) and semantic decisions (B) in Experiment 2. Dots represent individual subjects. Positions distanced further above the dashed line indicate a higher sensitivity. Positions on either side of the solid line indicate a response bias towards a subject-focus (right side) or an object-focus interpretation (left side).

4. Discussion

This study shows that in online sentence comprehension pitch accents establish dissociable linguistic expectations about upcoming sentence elements. Since pitch accents can influence the interpretation of a sentence by marking contrasts and parallels between constituents of a sentence (Carlson, 2001; 2015; Carlson et al., 2009), we hypothesised that pitch accents establish expectations about syntactic and semantic aspects of the upcoming constituents. To test the existence of these expectations and whether they can be probed implicitly or explicitly, we used sentences with contrastive focus and an ellipsis structure in two experiments, using a sentence comprehension and a sentence completion paradigm. The results show that pitch accents, by highlighting constituents that contain syntactic and semantic cues, establish expectations concerning both the syntactic and semantic properties of an upcoming noun phrase. Results of the sentence comprehension task (Experiment 1) revealed that participants built syntactic expectations implicitly: when pitch accents marked syntactic information that was met with mismatching syntactic information later in the sentence, responses were slower. This effect was not found for mismatching semantic information. In turn, the sentence completion task (Experiment 2) provided evidence for both syntactic and semantic expectations, when explicitly probed. Participants were able to complete the sentence with a determiner and noun in agreement with the respective syntactic and semantic properties of the pitch-accented noun phrase in the preceding clause. Finally, our results demonstrate that, when contradictory cues occur in the same sentence, the syntactic cue (case-marking) takes precedence over the semantic cue (thematic role), and previous prosodically-cued information is overwritten. These data reveal that during auditory sentence comprehension prosodic, semantic and syntactic information types are processed to create expectations about the upcoming linguistic elements in the sentence. All information types are used online, but there is a clear precedence for local, unambiguous syntactic information when assigning a constituent's role in the sentence.

The first experiment showed that pitch accents form a syntactic expectation about the upcoming sentence structure. This expectation could be probed *implicitly* by measuring the effects that contradictory syntactic cues in noun phrases receiving contrastive pitch accents have on sentence comprehension. Contradictory syntactic cues in the two focused constituents led to lengthened reaction times when the participants where asked about the role of the first constituent (i.e. *What was the role of the policeman/thief?*). Importantly, in these trials, where only the first part of the sentence was tested, the violation was irrelevant for the task: the probed noun phrase in the main clause always held congruent syntactic-semantic information and its interpretation was independent of the cues provided in the ellipsis, where the violation occurred. This finding supports the notion that the parallel roles of the two constituents in contrastive focus occupy syntactically identical functions (Carlson, 2001; Stolterfoht et al., 2007; Winkler, 2019). Furthermore, it suggests that after having heard the pitch accent on the first contrasted noun phrase, a specific expectation about the syntactic properties of the second contrasted noun phrase is formed. A violation of this assumption (by mismatching grammatical case) results in additional processing costs. This finding provides further insight into the role of pitch accents in the prosody-syntax interface. In addition to disambiguating case (Weber et al., 2006b) and resolving structural (Nakamura et al., 2012) and attachment ambiguities (Carlson & Tyler, 2017), pitch accents can also establish expectations about the syntactic role of upcoming sentence elements early on in the sentence. We suggest that, in case of an ellipsis site without any structural information (such as in remnants with a proper name ("…, not Peter"), this syntactic expectation influences the interpretation of the ellipsis structure. While we hypothesised that contradictory semantic cues could have analogous effects on sentence processing (e.g., longer reaction times), the results of Experiment 1 did not show evidence that focus had established semantic expectations. We will discuss these differences between the processing of syntactic and semantic cues below, but will first address the response behaviour at the ellipsis site.

The response behaviour at the ellipsis site (Experiment 1) allows for several conclusions concerning the relative dominance of the prosodic, syntactic, and semantic cues when contradictory information is present. First, the syntactic expectation established by focus-marking in the main clause was not strong enough to interfere with the interpretation of the ellipsis noun phrase. Rather, when this noun phrase was probed (*What was the role of the inspector/murderer?*), participants based their response on the local syntactic cue (their subject/object interpretation followed the case of the determiner). This suggests that the local syntactic cue had overwritten the syntactic expectation established by focus-marking in the main clause. The second observation is that the local semantic cue did influence the response at the ellipsis site. We found slower responses to *the*^{NOM} *MURDERER* as compared to *the*^{ACC} *INSPECTOR* as well as a significant decrease in the number of "subject" responses. In accordance with a large body of research showing that thematic role typicality can influence syntactic parsing (Trueswell et al., 1994), this suggests that the thematic content of the object-typical noun MURDERER cued a syntactic role that was incompatible with the preceding syntactic cue of the determiner (*the*^{NOM} assigning subject role), yielding an interpretation that was difficult to process. The finding that the subject-interpretation of *the*^{NOM} *MURDERER* led to processing difficulties whereas the object-interpretation of *the*^{ACC} *INSPECTOR* (with *the*^{ACC} assigning object role) did not, may be due to the type of verb-argument items used in our stimulus set. In most items, it was less plausible for the noun phrases in patient-role to reverse their typical role (i.e. to adopt an agent-role) than vice versa. Yet, regardless of this semantic effect, we can conclude that, in the type of construction investigated in our study, the syntactic cue was decisive for the interpretation of the ellipsis. This may also explain why in the responses to the constituents in the main clause, effects of the syntactic violation were stronger than those of the semantic violation, since a more decisive cue may lead to more disruptive processing once violated.

The stronger effect observed in the syntactic violations as compared to the semantic violations in responses to the main clause can be explained in several other ways. A first, straightforward explanation may be given by the different nature of the two cues: grammatical case is invariably mapped to subject and object roles of a sentence, whereas the thematic role of a noun is dependent on the semantic features of the verb and accompanying arguments. It is plausible to assume that in the sentence construction under investigation, the syntactic cue of the noun phrase highlighted by focus is more decisive in establishing the sentence structure, because its binary nature (nominative/accusative) makes it more categorical than the semantic cue. Alternatively, a general lack of reliability of the semantic expectation during the whole experiment may have diminished the relative effect of these cues, since our sentences contained a semantic incongruency in approximately half of the trials: the semantic mismatch between the two focused constituents in the semantic violation condition, in addition to the local syntactic-semantic mismatches at the ellipsis site (*the*^{NOM} *MURDERER* and *the*^{ACC} *INSPECTOR)*. Indeed, if predictions are disconfirmed frequently enough in an experiment, their predictive strength is diminished (Brothers, Swaab, & Traxler, 2017). Similarly, intonational cues have recently been suggested to lose their predictive value when the listener deems them unreliable (Roettger & Franke, 2019), which, in combination with the semantic expectations possibly being weaker than the syntactic expectations, may have contributed to the lack of semantic effect. Finally, it has to be considered that semantic expectations might not have been formed at all. From Experiment 1, we could not conclude if the expectations formed by pitch accents were too weak to lead to lengthened response times when violated, or if they had not been established in the first place.

Since Experiment 1 did not yield conclusive evidence concerning expectations established in the semantic domain, we aimed to probe these expectations directly using the same material in an alternative paradigm in Experiment 2. Our stimulus design enabled us to assess if focus-marking establishes *explicit* expectations, by employing a sentence completion task that teased apart syntactic and semantic decisions. Here, we found evidence for prosodically-formed expectations in both the syntactic and semantic domains. The results of Experiment 2 showed that participants preferred to complete the sentence with syntactic and semantic elements that corresponded to the focused constituent in the main clause. After subject focus, participants preferred to continue the sentence with a determiner in the nominative case and an agent-like noun. The opposite pattern was found after object-focused sentences. This evidence of syntactic expectations is in line with our result of Experiment 1. In addition, Experiment 2 showed that focus can in fact establish a semantic expectation: participants showed a preference for typical-agent nouns after subject focus sentences and typical patient-nouns after object focus. Since focus activates a set of alternatives to the focused noun (Gotzner & Spalek, 2019), it is likely that listeners activated nouns associated with thematic roles to the verb. Our results show that depending on the focus location, they subsequently selected a noun associated with either the subject- or object-role of the pitch-accented constituent. However, it remains to be explained why semantic expectations were revealed when explicitly probed, yet did not cause an increase in response times in the main clause of Experiment 1. This discrepancy between the two experiments supports the idea that, in contrast to the syntactic cues, the semantic cues were not decisive enough to lead to processing costs when violated. Indeed, the effects of semantic cues in establishing parallels between constituents have been shown to be relatively small (Carlson, 2015; Carlson et al., 2009). Furthermore, discrepancies between results from offline tasks such as sentence completion and online tasks (EEG or eye-tracking) have been reported previously (Chow, Smith, Lau, & Phillips, 2015; Karimi et al., 2019). Considering these task-dependent differences, our results may suggest that, even though semantic expectations could be established by pitch accents and subsequently accessed during offline processing, their role in online processing is not decisive enough to yield measurable effects.

Notably, while focus-marking influenced syntactic and semantic responses in Experiment 2, some listeners responded more according to their inherent biases in both domains. Previous studies in both German (Stolterfoht et al., 2007) and English (Carlson et al., 2009) have provided evidence for the existence of a default interpretation concerning the information structure of a sentence such as "Yesterday the policeman arrested the thief". Listeners tend to show a bias to assign prominence late in the sentence, to the object noun phrase (*the thief*). These studies showed that prosodic (Carlson, 2015) and semantic factors (Carlson, 2001) have limited effects in shifting this interpretation, and the inherent bias usually persists. However, most of the previous studies used grammaticality judgements, questionnaires, or (self-paced) reading. By explicitly probing the preferred syntactic or semantic structure of the upcoming phrase, we were able to obtain a direct measure of the perceived focus position and a possible bias. Participants indeed showed a bias in their syntactic responses. A majority of participants had a preference for accusative determiners, confirming a bias for an object-focus interpretation. The bias in the semantic responses went in the opposite direction, showing a response for agent-like nouns, that is, significantly fewer focus-congruent responses after object vs subject focus trials. Again, this is in accordance with the results from Experiment 1, which showed that a subject-role of typical-patient nouns was more difficult to process than an object-role of typical-agent nouns. This could explain an overall shift towards agent-responses.

We observed considerable inter-individual variability within the syntactic and semantic biases in Experiment 2. Inter-individual variability in syntactic attachment is a well-known phenomenon and has previously been linked to differences in working-memory constraints (Swets, Desmet, Hambrick, & Ferreira, 2007). Such variability has also been reported in prosody processing, both in the perception (Roy, Cole, & Mahrt, 2017) and production of prosodic cues (Ferreira & Karimi, 2015), as well as in implicit prosody perception (Jun & Bishop, 2015). An important observation stemming from the present results is that some listeners appear to rely on their biases, whereas others rely more strongly on the prosodic signal. This result is in line with a recent study showing inter-individual variability in the acoustic and linguistic variables used by listeners to determine prominence (Baumann & Winter, 2018). A worthwhile avenue for future research would be to further investigate the factors that determine whether a listener is rather led by acoustic cues or inherent bias in perceiving prosodic events. Finally, for the listeners that responded according to an inherent bias in our study, the results do not allow us to determine whether the source of that bias was at the perceptive or at the response level. One possibility is that listeners had a *perceptive* bias for either subject or object focus constructions. Alternatively, the participants could possess a *response* bias for a specific syntactic or semantic structure at the ellipsis site, yielding however the same results. Further research is required to tease these two explanations apart.

4.1. *Conclusion*

In conclusion, this study sheds new light on the interfaces of prosody with syntactic structure and with information structure. We show that pitch accents can establish expectations on upcoming sentence elements. Here, separate syntactic and semantic processes can be distinguished and only the expectations in the syntactic domain were decisive enough to increase processing costs when violated. Furthermore, our design enabled us to draw conclusions concerning the relative dominance of syntactic, semantic, and prosodic cues in guiding sentence comprehension. In case of multiple contradictory cues, we show that the effects of prosodically cued expectations are limited and readily overwritten by local syntactic cues. This is in line with the notion that the role of prosody in sentence comprehension is influential, but not decisive (e.g., (Frazier, Carlson, & Clifton, 2006; Carlson, 2009). Finally, we could observe individual differences within the use of pitch accents in establishing sentence structure, and we put forward that future studies should further investigate the factors that make a listener rely on bottom-up acoustic information or rather be driven by top-down internal biases.

Following the first chapter in this thesis, which attributed a key role to the left inferior frontal gyrus (IFG) for processing prosodic cues that guide the syntactic analysis of a sentence, the current study showed how pitch accents guide both syntactic and semantic processing during sentence comprehension. The next chapter of this thesis aims to bring these two studies together, investigating the possible causal involvement of the IFG in the syntactic and semantic processes that are cued by pitch accents.

Chapter 5

Disruption of the left posterior inferior frontal gyrus impairs grammatical processing guided by prosodic cues

Abstract

Auditory sentence processing involves semantic, syntactic and prosodic information. Prosodically guided sentence processing has been shown to involve the left inferior frontal gyrus (IFG). Prosodic cues are known to interact closely with both syntax and semantics, and these processing domains in turn have been attributed to two different subregions within the left IFG: based on neuroimaging studies, the anterior part is associated with semantic processing and syntactic processing is ascribed to the posterior part. Yet, the causal role of this regional specialisation remains unclear. The current study used focal perturbations induced by repetitive transcranial magnetic stimulation (rTMS) to probe the causal role of the posterior IFG for syntactic processing and the anterior part for semantic processing in prosodically varied sentences. Since the interpretation of a pitch accent in the sentence was essential for successful task performance, we additionally were able to assess the involvement of left IFG in sentence processing when crucial information was conveyed by prosody. Healthy participants performed a sentence completion task with a syntactic and a semantic decision. The pitch accent in the truncated spoken utterance cued which determiner and noun (presented visually) would form the most suitable sentence ending, which were selected by button-press. Healthy participants underwent three sessions with 10 Hz rTMS bursts being applied over either anterior or posterior left IFG, or vertex (control region). Although we found no significant interaction between rTMS site and decision type, a main effect of rTMS site indicated decreased task accuracy in both decision types after posterior IFG stimulation versus vertex. As both decision types required processing of the grammatical roles in the sentence, these results provide evidence for the functional relevance of left posterior IFG in grammatical processing guided by prosodic cues. We suggest the use of participant-specific functional localisers in future TMS studies to further elucidate the specific contribution of different IFG subregions in sentence comprehension.

1. Introduction

Understanding spoken language is principally a rapid and efficient process. To achieve this, listeners make use of various sources of information available in a sentence, such as grammatical or semantic cues. Additionally, listeners rely on the way in which a sentence is acoustically produced. Variations in speech melody, rhythm, and intensity, together called *prosody*, can play a decisive role in the interpretation of a sentence (Cutler et al., 1997; Wagner & Watson, 2010). For example, at the end of a sentence a rise or fall in pitch distinguishes questions from statements. Additionally, by increasing pitch and intensity of a word, the speaker can emphasise specific parts of a sentence. Prosody processing is supported by a bilateral network in the human brain, including several cortical areas in the frontal and temporal lobes (Belyk & Brown, 2014; Friederici, 2011). In particular, the involvement of the left inferior frontal gyrus (IFG) is thought to depend on whether prosody is conveying linguistic information or not (Chien et al., 2020; Friederici & Alter, 2004; Van der Burght, Goucha, Friederici, Kreitewolf, & Hartwigsen, 2019; van Lancker, 1980). Prosody can convey linguistic information in several ways. For example, the difference between "*the reviewer said: the author is mistaken"* and "*the reviewer, said the author, is mistaken*" is marked by punctuation in written form, but in spoken language it is established exclusively by prosody. This clearly shows how the different use of pauses and pitch variations in the sentence dramatically changes its syntactic (grammatical) structure: by defining how words are grouped together, prosody directly affects the syntactic analysis of the sentence, and, as a consequence, our interpretation. In the semantic domain, the role of prosody is apparent in a sentence such as "Anna bought APPLES at the market", where prosody indicates prominent or important information in the sentence. Here, a rise in pitch and intensity (marked by capital letters) conveys that it was apples that Anna bought, rather than a different type of fruit. Taken together, prosody interacts closely with both the syntax and semantics of a sentence (Dahan et al., 2002; Kjelgaard & Speer, 1999; Marslen-Wilson et al., 1992; Speer et al., 1996; Steinhauer et al., 1999). As a further manifestation of this interaction, we recently demonstrated that a single prosodic cue can establish expectations about both the syntactic and semantic properties of upcoming sentence material (Chapter 4, this thesis).

Within the language network, the left IFG is known to be an important region for sentence comprehension, and in particular for the processing of syntactic and semantic cues. An example of syntactic information is the word order of a sentence: If we consider the sentence "the police officer arrested the thief", we know *who did what to whom* in part because "the policeman" occurred before the verb and "the thief" after. Simultaneously, the sentence structure in the example above is established by semantic cues. If the word order cue had been absent, the semantics of the words in this example sentence would have sufficed to infer the message. When presented with a word list containing "arrest", "thief", and "police officer", we are still able to infer what the most probable version of the event was. Specifically, the typical thematic roles of these nouns in relation to this specific verb provide a plausible explanation of *who did what to whom* (Trueswell et al., 1994). This linguistic subdivision between syntactic and semantic processing is thought to have neuroanatomical correlates. Indeed, models based on many years of neuroimaging research posit that a functional dissociation can be made in relation to anterior and posterior parts of the left IFG. These models, based on literature reviews (Friederici, Chomsky, Berwick, Moro, & Bolhuis, 2017) and meta-analyses (Hagoort & Indefrey, 2014), attribute syntactic processing to the posterior part of the IFG (pars opercularis), whereas semantics is predominantly processed in the more anterior part of the IFG (pars triangularis). These anatomically defined subregions in turn correspond to a subdivision of the IFG into cytoarchitectonic areas, that is Brodmann area (BA) 44 (pIFG) and BA45 (aIFG) (Amunts et al., 1999). Although established by a rich body of neuroimaging studies, evidence for this double dissociation should be substantiated by using neurostimulation to show the functional relevance of different IFG subregions for syntax and semantics. A suitable method is transcranial magnetic stimulation (TMS), which can focally and transiently perturb neural processing in selective parts of the cortex. Combined with behavioural tasks, TMS can be used to demonstrate the functional relevance of a cortical area for a given cognitive process (Hallett, 2007; Hartwigsen, 2015). TMS has previously been employed to probe the functional specialisation of two IFG subregions, providing evidence for a key role of left pIFG for phonological processing and left aIFG for semantic processing (Devlin et al., 2003; Gough et al., 2005; Hartwigsen, Price, et al., 2010b; Klaus & Hartwigsen, 2019; Romero, Walsh, & Papagno, 2006). However, although the syntax-semantics dissociation within the left IFG is well-established in the neuroimaging literature, the functional relevance of either subregions for both functions has not been demonstrated.

As a core region in the language network, the IFG has been associated not only with processing of syntax and semantics, but also of prosody. Traditionally, the right hemisphere has been assumed to be dominant in processing prosodic information, in line with right-lateralised processing of pitch information in speech (McGettigan & Scott, 2012; Poeppel, 2003). However, pitch information carried in prosodic cues often serves a linguistic purpose, and this linguistic purpose affects lateralisation of activity in the IFG: specifically, the left IFG was found to be involved when the syntactic structure of a sentence is established by the location of an intonational phrase boundary, a type of prosodic cue (Van der Burght et al., 2019). Similarly, the left IFG has been associated with processing of pitch accents, the prosodic phenomenon that stresses certain words in a sentence (as in the example "Anna bought APPLES"). Pitch accents can place a word in so-called focus, highlighting novel or particularly relevant information in a sentence (Rooth, 1992). When pitch accents matter for the linguistic interpretation of a stimulus, involvement of the left IFG has frequently been shown: posterior IFG is involved when pitch accented and neutral sentences are compared (Perrone-Bertolotti et al., 2013), and most areas within the left IFG are involved when the position of a pitch accent in the sentence is incongruent with what was semantically and pragmatically expected (Kristensen et al., 2013; van Leeuwen et al., 2014). Furthermore, pitch accent processing as compared to an emotional prosody task recruits the left IFG (Wildgruber et al., 2004). Together, this supports early theoretical models stating that prosody processing is lateralised to the left hemisphere when the linguistic function of prosodic cues is emphasised (Friederici & Alter, 2004; van Lancker, 1980).

However, it remains to be addressed if the left IFG is functionally relevant for processing of prosodic cues during sentence comprehension.

In sum, the left IFG is known to have a fundamental role in supporting syntactic and semantic processing. Additionally, this region has been shown to be important for processing of linguistically relevant prosodic cues. However, although this has been established by neuroimaging work, the causal role of the IFG in these different processes remains unclear. We therefore set out to investigate the functional relevance of the left IFG in sentence processing guided by prosodic cues. More specifically, we used TMS to probe the functional specialisation of IFG subregions for semantic and syntactic processing during sentence comprehension in prosodically varied sentences. To be able to address this within one paradigm, we employed a sentence completion task that required integration of syntactic and semantic as well as prosodic information (Chapter 4, this thesis). Healthy participants listened to spoken sentences in which either the subject or object received so-called focus by means of a prosodic cue (a pitch accent). Participants then selected their preferred continuation of the sentence based on the focus position in the sentence. This sentence completion task required isolated syntactic and semantic decisions to be made across trials. During the task, short bursts of repetitive rTMS were applied simultaneously with the onset of the visual presentation of the response options. We used a within-subject design, in which participants received rTMS over either aIFG or pIFG, or a control site (vertex), divided over three pseudorandomised sessions. We hypothesised that rTMS of pIFG would selectively affect syntactic decisions, which would be reflected in a delay in response times, a decrease in accuracy, or both. In contrast, rTMS of pIFG should not affect semantic decisions. Conversely, we expected that rTMS of aIFG would selectively impair behaviour during semantic, but not syntactic decisions.

2. Methods

The hypotheses and analysis plan of this experiment were preregistered at the Open

Science Framework (https://osf.io/7bx2k). Raw data and analysis scripts can be found at https://osf.io/5k8ze/.

2.1. *Participants*

30 healthy native German speakers were included in the final analysis (18 females, age: *M*=27.1 years, *SD*=3.9, range=19-37). All were right-handed (handedness score: *M*=91.0, *SD*=-9.6 (Oldfield, 1971)), none had a history of neurological or psychiatric disorders or other contraindications to TMS, and all gave informed consent prior to participation. Sampling continued until 30 complete datasets (i.e. including three experimental TMS sessions) had been acquired, because full balancing of TMS sites (aIFG, pIFG, vertex) required a multiple of six. Participants were recruited from the database of the Max Planck Institute for Human Cognitive and Brain Sciences. Two volunteers dropped out because of excessive discomfort during stimulation of the IFG and were replaced with two new participants to complete the sample. The study was approved by the local ethics committee at the Medical Faculty of the University of Leipzig.

2.2. *Experimental design and procedure*

We used a 3x2x2 factorial, within-subject design with the factors *stimulation site* (pIFG; aIFG; vertex), *decision type* (syntactic; semantic) and *focus position* (subject; object), as illustrated in Figure 1. Experimental trials were divided over four blocks separated by a self-timed break (minimum pause duration: 20s). During each block, 48 trials were presented pseudo-randomly, with a maximum of two consecutive repetitions of the same decision type and focus position. Each unique verb-noun combination occurred once per block. The order of TMS sites across experimental sessions was assigned pseudo-randomly and counter-balanced across participants. Stimulus presentation, collection of the responses, and timing of the TMS trains was controlled using the software Presentation (Neurobehavioral Systems, Inc., Berkeley, CA; www.neurobs.com).

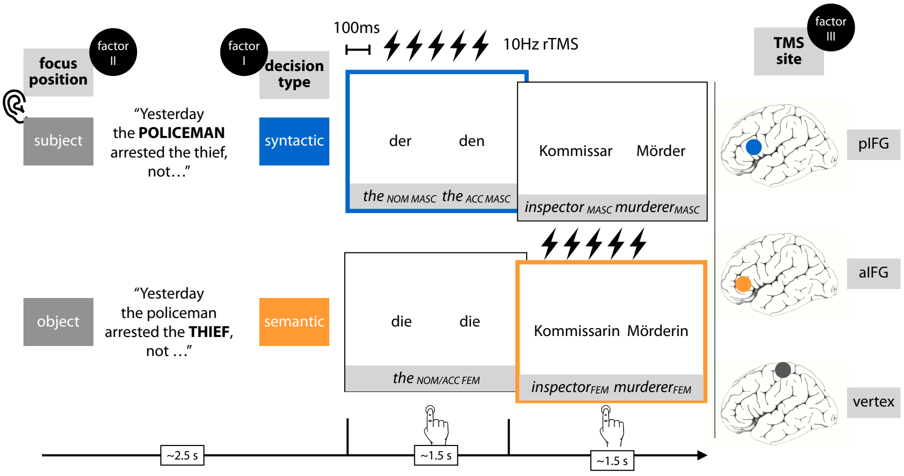


Figure 1. Overview of the experimental design with within-subject factors decision type, focus position, and TMS site. Trials of each decision type and focus position were presented pseudo-randomly within each session. During each session, participants received short TMS bursts (5 pulses at 10 Hz, starting 100 ms after the visual onset of the determiner or noun response options) over one of the three TMS sites, the order of which was counter-balanced across participants. Circles illustrate the three stimulation sites. aIFG: anterior inferior frontal gyrus. pIFG: posterior inferior frontal gyrus. NOM: nominative. ACC: accusative. FEM: feminine. MASC: masculine.

2.3. Task

Participants performed a sentence completion task in which they were presented with spoken sentences of the type (I) or (II), according to subject or object focus. In these sentences, case marking of the determiners is indicated with NOM (nominative) or ACC (accusative). Focus, as assigned by a pitch accent, is indicated with F.

(I) Yesterday, [the$^{\text{NOM}}$ POLICEMAN]$_{\text{F}}$ arrested the$^{\text{ACC}}$ thief, not …

- *Gestern hat [der POLIZIST]$_{\text{F}}$ den Dieb verhaftet, nicht …*

(II) Yesterday, the$^{\text{NOM}}$ policeman arrested [the$^{\text{ACC}}$ THIEF]$_{\text{F}}$, not …

- *Gestern hat der Polizist [den DIEB]$_{\text{F}}$ verhaftet, nicht …*

They were asked to complete these spoken sentences with visually presented words by button-press in a two-alternative forced choice task. Participants made two consecutive decisions: they first selected a determiner and then a noun. In the syntactic condition, participants chose between two case-marked masculine determiners signalling either subject (*der/the^{NOM}*) or object (*den/the^{ACC}*). By presenting the determiners first rather than simultaneously with the noun, the decision on the determiner was purely syntactic without a possible semantic influence. In the semantic condition, the nouns were presented in their feminine versions. As German does not distinguish between nominative and accusative case of the determiner *the* in feminine noun phrases (both are indicated with *die*), the decision on the determiner was meaningless. The subsequent decision on the noun (*"police officer^{FEM}"* or *"thief^{FEM}")* was arguably a purely semantic one, since no meaningful syntactic judgment had taken place previously. Participants were instructed to select the determiner and noun that would complete the sentence in the way they deemed most sensible and to give their response as quickly and accurately as possible.

Although the task was identical to our previous behavioural study (Chapter 4, this thesis), new experimental items were created and selected after a norming study (based on Ferreira (2003); see Chapter 4 of this thesis, for full details). The final list of experimental items can be found in Supplementary Table 1.

2.4. *Repetitive transcranial magnetic stimulation*

Mean coordinates for the two IFG sites were taken from a meta-analysis of neuroimaging studies on syntactic and semantic processing (Hagoort & Indefrey, 2014). This study reported local maxima plus standard deviations for syntactic processing (pIFG, corresponding to BA44) and semantic processing (aIFG, corresponding to BA45). To prevent overlap of the stimulation area at the two sites, we chose coordinates that were at least 20mm apart, but still fell within the standard deviation of each region. These coordinates were transformed from Talairach to Montreal Neurological Institute (MNI) space (BA44: x, y, z = -51, 11, 14; BA45: x, y, z = -51, 33, 2). Finally, these coordinates were transformed into individual subject space by using the inverse of the normalisation matrix obtained in SPM 12 (www.fil.ion.ucl.ac.uk/spm, Wellcome Trust Centre for Neuroimaging, London, UK). T1-weighed images had been previously acquired on a 3T MRI scanner (Siemens Healthcare, Erlangen, Germany) using a magnetisation-prepared rapid gradient echo (MPRAGE) sequence in sagittal orientation (inversion time = 650 ms, repetition time = 300 ms, flip angle = 10, field of view = 256 mm × 240 mm,voxel-size = 1mm × 1mm × 1.5mm). Individual coordinates were visually inspected based on microanatomical landmarks to ensure that their localisation in the subregions of the IFG was correct and manually adjusted if necessary. The vertex (control) site was determined manually in each individual as the intersection between two lines: the shortest distances between the tragi of the left and right ear and nasion and inion.

A neuronavigation system (TMS Navigator, Localite, Sankt Augustin, Germany) was used to navigate the TMS coil and maintain its location and orientation throughout the experimental sessions. The coil was placed over the IFG with an angle of 45° to the sagittal plane whereas vertex stimulation was achieved holding the coil with the handle oriented posteriorly (parallel to the midline). Simulation intensity was set at 90% of the individual resting motor threshold, following similar studies from our research group that targeted the IFG (Hartwigsen et al. 2010b; Kuhnke, Meyer, Friederici, & Hartwigsen, 2017), which resulted in a mean stimulation intensity of 45 ± 3 % (1SD) of maximum stimulator output. The participant's resting motor threshold was determined at the beginning of the first experimental session, using an electromyogram measured at the right first dorsal interosseous muscle. The motor hotspot was located by systematically searching the scalp contralaterally to the right hand at a low stimulation intensity. As a starting point, a mean coordinate of M1 was used (x, y, z = −37, −21, 58 mm, taken from Mayka et al. (2006)), transformed to individual subject space (see above). The motor hotspot was then defined as the location which yielded the largest and most consistent motor evoked potential. Subsequently, resting motor threshold was determined as the lowest stimulator output intensity to evoke a motor evoked potential in the relaxed muscle with a peak-to-peak amplitude larger than 50 µV in 5 out of 10 consecutive stimuli (Rossi, Hallett, Rossini, & Pascual-Leone, 2009).

During each experimental trial, a 5-pulse train of 10Hz TMS was applied over left aIFG, pIFG, or vertex (see Figure 1). The pulse train started 100ms after onset of the visual imperative stimulus, lasting until 600ms into the decision-making process on syntactic or semantic continuation on the sentence. This stimulation window was chosen to avoid interference with either early visual processing (see Devlin et al., (2003) for a similar rationale) or with the motor execution of the response. This allowed stimulation to cover similar processing stages in both syntactic and semantic conditions. rTMS was applied using a figure-of-eight coil (type C-B60; outer diameter = 7.5 cm) connected to a MagPro X100 stimulator (MagVenture, Farum, Denmark). The overall application of TMS pulses was well within safety limits (Rossi et al., 2009; Rossini et al., 2015).

2.5. Data analysis

Response times for correct trials were analysed with a Linear Mixed Model. Accuracy rates were analysed using a Generalised Linear Mixed Model with a binomial distribution (Baayen et al., 2008). Both models included the fixed effects *TMS site*, *decision type*, and *focus position* as well as two two-way interaction terms. The interaction between *TMS* site x *decision type* was specified, since we expected the TMS effect to be both task-specific (i.e., disrupting either syntactic or semantic decisions) and location-specific (i.e., selectively interfering with aIFG or pIFG, relative to the vertex). The interaction between *decision type* and *focus position* was modelled as well, because we found a significant interaction between both factors in our previous behavioural study (Chapter 4, this thesis). We did not expect *TMS site* to interact with *focus position* (i.e. the effect of TMS site should not depend on whether the subject or object noun phrase was accented) and consequently no three-way interaction was included. For inclusion in the fixed effects analysis, factors were dummy coded: the factors with two levels were sum-coded and the fixed effect with three levels (*TMS*) was treatment-coded with the vertex condition as reference level. We aimed to include a maximal random effects structure (Barr et al., 2013). In case of convergence issues, we simplified the random effects structure by first removing the correlations between intercepts and slopes, then the random slopes for the interaction terms (*decision type* x *focus position, TMS* x *decision type*, in that order), and the simple effects of each factor within participant and within item. Statistical inference was performed using likelihood-ratio test comparing the full model to a reduced model lacking the term of interest (Singmann & Kellen, 2019). We used the package emmeans for pair-wise follow-up comparisons to further explore significant interactions (Lenth et al., 2019). *P*-values below an alpha-level of .05 were considered significant.

3. **Results**

We did not find a significant interaction between TMS site and decision type in the response times (χ^2(2)=4.77, *p*=.090; Figure 2A). That is, TMS over aIFG, pIFG, or vertex did not differentially affect response speed in the syntactic and semantic decisions in our study. However, replicating the results from our behavioural study (Chapter 4, this thesis), the interaction between decision type and focus position was significant (χ^2(1)= 10.69, *p*=.001). Post-hoc comparisons revealed that responses were faster after

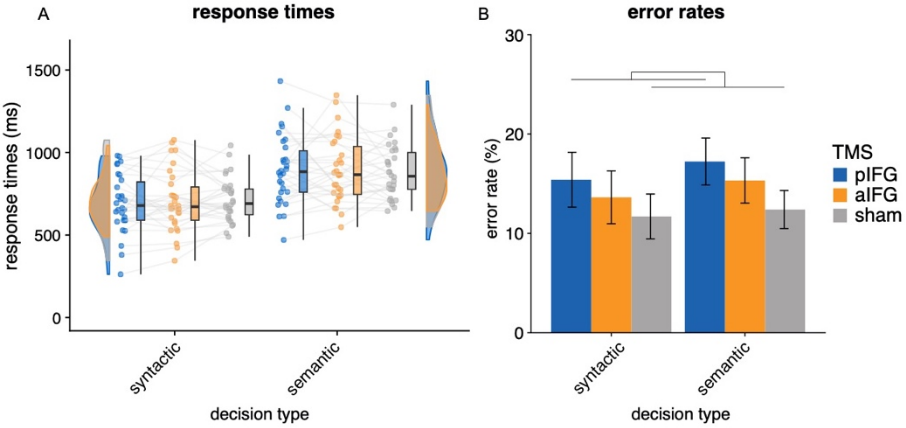


Figure 2. Response times (A) and error rates (B) for each decision type and TMS-site. In (B), lines indicate main effect of TMS site (pIFG contrasted to vertex). Error bars reflect ±1 SEM.

object focus as compared to subject focus sentences in the syntactic decisions (*z*=1.98, *p*=.045), whereas the semantic decisions showed the opposite pattern (*z*=-2.64, *p*=.016). Responses were slower in semantic as compared to syntactic decisions after both subject focus (*z*=-7.38, *p*<.001) and object focus sentences (*z*=-7.86, *p*<.001).

Table 1 Intercept estimates from separate generalised linear mixed models on the accuracy data. The significant intercept estimates reflect above-chance performance, by setting reference levels and dummy-coding according to each individual combination of decision type and TMS site.

Decision type	**TMS site**		**Estimate**	**SE**	***z***	***p***
syntactic	vertex	intercept	2.368	0.189	12.560	<.001
	pIFG		1.977	0.184	10.731	<.001
	aIFG		2.212	0.207	10.697	<.001
semantic	vertex		2.368	0.189	12.561	<.001
	pIFG		1.977	0.184	10.731	<.001
	aIFG		2.212	0.207	10.698	<.001

Participants performed above chance in all conditions, which shows that overall, responses were made according to the pitch accent and focus position perceived (all *z*-values >12.56; all *p*-values <.001; see Table 1). In the accuracy rates (Figure 2B), there was no significant interaction between TMS site and decision type (χ^2(2)=0.15, *p*=.929), meaning that we did not find evidence for location-specific effects of stimulation over aIFG, pIFG, or vertex on the syntactic and semantic decisions. However, there was a significant main effect of TMS site (*z*=-2.53, *p*=.011), indicating an overall increase in error rates for pIFG TMS as compared to vertex TMS in both syntactic and semantic decisions. There were no significant main effects when comparing pIFG TMS to aIFG TMS (*z*=1.61, *p*=.107) or aIFG TMS to vertex TMS (*z*=-1.07, *p*=.285). The interaction of decision type x focus position was also significant (χ^2(2)=10.31, *p*=.001), in agreement with our previous behavioural study (Chapter 4, this thesis). Post-hoc pairwise comparisons revealed lower accuracy for semantic decisions after object focus sentences when compared to subject focus sentences (z=5.73, p<.001), as well as when compared to syntactic decisions after object focus (z=3.89, p<.001).

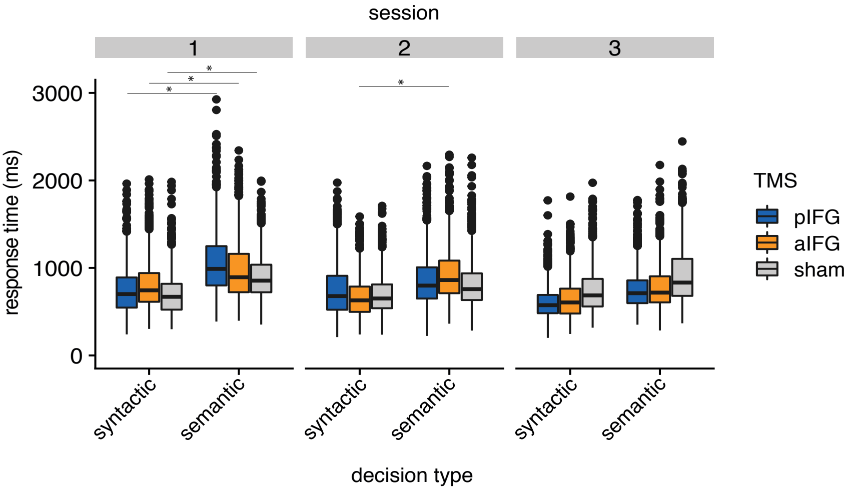


Figure 3. Response times for both tasks and all TMS conditions separately for each experimental session. Asterisks mark pair-wise comparisons with p-values smaller than .05 (Bonferroni-Holm-corrected).

Because in this within-subject design participants performed the task three times, learning effects may develop across the experimental sessions. This, in turn, may have an effect on the TMS-induced modulations. To explore an effect of session on the TMS induced modulation, we performed an additional analysis on the response times that included session as a fixed effect. This effectively resulted in treating TMS site as a between-subject factor, with 30 participants included in each session (10 per stimulation site). The three-way interaction decision type x TMS site x session (Figure 3, pooled across focus position), was marginally significant ($\chi^2(4)$= 9.16, p=.057). The distribution of response times per session (Figure 3) confirmed this trend. Given the high order of this interaction term and the between-subject nature of this analysis, this test is certainly underpowered using our current sample size. We therefore carried out exploratory tests on each session individually. These showed a significant interaction between decision type and TMS site in session 1 ($\chi^2(2)=6.29$, $p=.043$) and session 2 ($\chi^2(2)=6.35$, $p=.042$), but not in session 3 ($\chi^2(2)= 0.71$, $p=.701$). Post-hoc t-tests in session 1 showed significantly slower responses in semantic as compared to syntactic decisions after stimulation of either site (pIFG ($t(33.3)=-4.05$, $p<.001$), aIFG ($t(33.3)=-3.04$, $p<.001$), vertex ($t(33.3)=-3.10$, p<0.001). In session 2, the only significant comparison was between decision types after aIFG stimulation, with slower responses after semantic as compared to syntactic decisions ($t(33.3)=5.70$, $p<0.001$). There were no significant differences between TMS sites within each decision type.

4. **Discussion**

This study aimed to establish the functional relevance of the left IFG in sentence processing guided by a prosodic cue. In our paradigm, successive syntactic and semantics processing steps were performed in isolation from one another: this allowed us to use focal perturbation induced by rTMS to test the hypothesis that anterior and posterior parts of the IFG are specialised for semantic and syntactic processing, respectively. As a main finding, disruption of pIFG as compared to vertex (control site) induced an increase in error rates in both syntactic and semantic decisions. This finding is in line with our hypothesis that pIFG is involved in syntactic decisions guided by a prosodic cue. Yet, the result deviates from our initial hypotheses in two ways. Firstly, we hypothesised that pIFG stimulation would have a selective effect on syntactic decisions only, rather than on both decision types. Secondly, our hypothesis that aIFG stimulation would interfere with semantic decisions was not supported by the data. There was no significant difference between both active stimulation sites.

To explain why the effect of pIFG stimulation was similar in both syntactic and semantic decisions, we must consider the processing steps shared by both decision types. Performing both conditions required the perception of the pitch accent in the auditory stimulus and as a consequence an interpretation as to which

of the noun phrases was focused (subject or object). This template of the subject or object role had to be kept in working memory until the presentation of the visually presented response options. At this point, the two conditions started to diverge: depending on the response options that were presented, participants either made a syntactic decision (*der/the*^{NOM} vs *den/the*^{ACC}) or a semantic decision (*agent / patient*).
rTMS was applied at the point that required matching of two subject/object role templates: one cued by prosody in the preceding auditory stimulus and one from the incoming visual stimulus. Since rTMS over pIFG affected not only error rates in the syntactic decisions, but also in the semantic decisions, it is plausible to assume that rTMS disrupted the subject/object role templates required to take these decisions. Alternatively, it was the evaluation of those templates (the one from the auditory sentence and those from the visual stimulus) that rTMS interfered with. Indeed, without being able to evaluate the hierarchy between nouns and verb (i.e., the subject or object role), both subsequent syntactic and semantic processing should be impaired. Such mechanistic explanation is suggested by the observed main effect of TMS, showing increased error rates for both decision types.

In previous work, we showed that the pitch accents established an expectation concerning upcoming sentence elements (Chapter 4, this thesis). Involvement of pIFG has repeatedly been found in predictive processing of syntactic structure, for example in predicting word category information (noun or verb) (Bonhage, Mueller, Friederici, & Fiebach, 2015). Notably, syntactic pre-activation of left pIFG has been shown in response to a prosodic cue. In Swedish, the pitch height at the beginning of a sentence can be informative about upcoming sentence structure: more constraining syntactic predictions activated pIFG as well as the adjacent anterior insula (Söderström, Horne, Mannfolk, van Westen, & Roll, 2018). Another recent study found involvement of the left pIFG in syntactic surprisal (Henderson, Choi, Lowder, & Ferreira, 2016). Although our paradigm did not evaluate linguistic predictions in the strictest use of the word (i.e., as automatic and subconscious process (Huettig, 2015; Pickering & Gambi, 2018)), it did require intact expectations concerning upcoming syntactic positions to perform an explicit judgment. Therefore, it is plausible to assume that stimulation of pIFG, an area associated with processing of syntactic predictions, interfered with processing of the assignment of subject/object roles in our experiment.

Our study aimed to use TMS to probe the specialisation of two subregions within the IFG for syntactic and semantic processing – a regional specialisation that is well-established in the neuroimaging literature (Friederici, 2011; Hagoort & Indefrey, 2014). Yet, neither response times nor accuracy rates showed evidence of a functional dissociation. One could question if the paradigm was sensitive to dissociate both processes. However, since we were able to largely replicate the results from our previous behavioural study, the paradigm used seems validated in its ability to dissociate syntactic and semantic processing, guided by a prosodic cue (Chapter 4, this thesis). Alternatively, one could question if the spatial resolution of TMS was sufficiently high to dissociate our target regions within the IFG. However, anterior and posterior areas within IFG have been successfully dissociated in previous studies (Gough et al., 2005; Klaus & Hartwigsen, 2019) and the coordinates in those studies were separated at a distance similar to the coordinates in the current study. A way to address the question of focality of our TMS approach would be the inclusion of electrical field simulations to identify the effectively stimulated subregion within the IFG at the individual subject level (Weise, Numssen, Thielscher, Hartwigsen, & Knösche, 2020). Correlating the individual electrical field strength with the observed behavioural modulation in both tasks would further allow characterising the relationship between the behavioural effects and the effectively stimulated area.

A potential explanation for the overall weak TMS effects in our study may be found in the learning effect across sessions. Considering that the response to TMS is known to be highly variable between participants (Hamada, Murase, Hasan, Balaratnam, & Rothwell, 2013; Hordacre et al., 2016; Nettekoven et al., 2015), a within-subject approach is preferable when mapping function to brain structure. As a consequence, however, participants performed the experimental task three times, resulting in the observed learning effect across the three sessions. This may have masked any potential effect of TMS: as participants became faster over time, other cognitive processes (e.g., cognitive control or memory-related processing) may have become involved, which may have been affected differently in later as compared to earlier sessions. As an example of how a change in processing may influence TMS effects, a study using a cyclical picture naming paradigm found different rTMS effects in the earlier as compared to the later cycles of the experiment (Krieger-Redwood & Jefferies, 2014). These authors argued that, as lexical retrieval demands changed over time, TMS had different effects on processing. A similar mechanism could have been at play in the current study.

A final explanation for the lack of dissociation between anterior and posterior IFG is the well-known interindividual variability in the neuroanatomy of this region. The IFG is known to show large interindividual variability, both in terms of the organisation of gyri and sulci and in the way cytoarchitectonic regions relate to them (Amunts et al., 1999). To circumvent this issue, a functional localiser may have been required to target the exact areas supporting syntactic and semantic processing in each individual. Indeed, it has been argued that functional localisers are essential for dissociating functional areas within the IFG, for example to distinguish language-specific from domain-general regions (Fedorenko & Blank, 2020). Future TMS studies on syntactic and semantic processing with left IFG will certainly benefit from a functional localiser. Since individual localisers are time consuming and may be tricky to design if repetition of the same task and stimuli needs to be avoided, we relied on transferring mean group coordinates from previous fMRI studies to the individual subject level in our study. This approach has been successfully employed to demonstrate functional specialisation of different subregions for various language tasks in our previous studies (e.g., Hartwigsen et al., 2016; Klaus & Hartwigsen, 2019; Hartwigsen et al. 2010b; Kuhnke et al., 2017). Yet, a higher spatial precision of TMS can be achieved when relying on individual localisers (Sack et al., 2009; Sparing, Buelte, Meister, Paus, & Fink, 2008), which may be especially relevant for investigating higher cognitive such as the ones in the current study.

Concerning the semantic decisions, there are a number of possible explanations why stimulation over aIFG did not produce the hypothesised effect. Firstly, the current paradigm required lexical retrieval and semantic judgements on multiple words that required complex processing, as opposed to relatively simple semantic decisions on single words used in previous TMS studies (Devlin et al., 2003; Klaus & Hartwigsen, 2019). In a comparably more complex task, it is plausible that the semantic system was able to recover from the disruption during the prolonged response time. Indeed, in most studies in the visual domain, lexical retrieval and semantic processing of a single word was required (Devlin et al., 2003; Klaus & Hartwigsen, 2019), leaving the semantic system shorter time after the stimulation window to recover. Speaking against this argument are TMS effects in several studies presenting multiple words simultaneously, yielding response times longer than those in the current experiment (Gough et al., 2005; Whitney, Kirk, O'Sullivan, Lambon Ralph, & Jefferies, 2011; 2012). Instead of a temporal buffer, a more likely explanation concerns the broad cortical distribution of the semantic network (Binder & Desai, 2011; Ralph et al., 2017), enabling compensatory activity from other regions beyond the IFG. In addition, there is a high degree of flexibility with which cortical areas within the same network can redistribute after disruption of a specific node (Hartwigsen, 2018). Other areas within the semantic system could therefore have compensated for (semantic) processing that was disrupted by rTMS over aIFG, as previously demonstrated during semantic word judgements (Hartwigsen et al., 2016). Finally, previous studies have shown that TMS effects can be found in multiple regions, including IFG, middle temporal gyrus, and angular gyrus. However, the exact regions in which effects are found seemed to depend on the type and strength of the semantic associations involved per experimental condition (Davey et al., 2015; Whitney et al., 2011; 2012). This suggests that in some paradigms, probing several different areas is required to find effects at different levels of semantic processing.

To conclude, our study provides evidence for the functional relevance of pIFG in processing syntactic roles in a sentence. In particular, our data suggest that the pIFG is an important area for syntactic computations that are cued by prosody. Disruption of these computations affected both syntactic and semantic decisions on upcoming sentence elements. The present data are inconclusive concerning a possible functional-anatomical double dissociation between the aIFG for semantic processing and the pIFG for syntactic processing when assigning grammatical roles during sentence comprehension. The use of a functional localiser to circumvent the high interindividual variability of the inferior frontal cortex may form a worthwhile avenue for future research. Nevertheless, our study underlines the importance of the pIFG in grammatical processing for which prosody is decisive.

Chapter 6

General discussion

In this thesis, I investigated the effects of prosody on sentence processing and explored the neural implementation of these effects. To approach this, I presented neuroimaging and behavioural studies that were built around three novel paradigms involving two prosodic cues: the intonational phrase boundary (IPB) and the pitch accent. Together, they probed the effect of prosody on syntactic structure and information structure processing. By combining these paradigms with neuroimaging techniques, these effects were further investigated on the neural level. The designs used were inspired by some of the most influential psycholinguistic and electrophysiological studies investigating the role of prosody in syntactic disambiguation (Marslen-Wilson et al., 1992; Steinhauer et al., 1999) and focus processing (Bader, 1998; Stolterfoht et al., 2007). The experimental work presented in this thesis can be summarised as follows.

The fMRI study in **Chapter 3** used sentences in which processing a prosodic boundary—the IPB—was required to understand *who did what to whom* in the sentence. This study emphasised the key role of the left IFG when prosody establishes sentence structure. Specifically, the left IFG was involved in processing sentence structure in which an IPB is the sole disambiguating cue. This region was also recruited when a morphosyntactic cue (case information) established the sentence structure, underlining a similar functional influence that prosodic and morphosyntactic cues have on establishing the grammatical structure of a sentence. Finally, a lateralisation analysis showed that activity in the IFG was left-lateralised specifically when the IPB built the syntactic structure of the sentence: when the IPB was superfluous for understanding the sentence, activity in the IFG was right-lateralised.

This fMRI study highlighted the crucial role prosodic cues can play in sentence comprehension. However, as a prosodic cue coinciding with syntactic boundaries, the IPB is necessarily strongly connected to syntactic structure. **Chapter 4** therefore explored how prosodic phenomena other than the IPB still exert strong effects on sentence comprehension. This study investigated how a different prosodic cue—the pitch accent—influences both syntactic and semantic processing. The effects of pitch accents on these processing domains so far had only been studied in isolation. The present study therefore set out to demonstrate which cue type takes precedence when competing information is present in a sentence. Two behavioural experiments showed that a pitch accent can establish expectations concerning upcoming syntactic as well as semantic information. However, the effects of pitch accents were not decisive: likely, the information cued by the pitch accent was overwritten when novel, contradicting syntactic information became available.

Considering that the left IFG is involved in sentence processing guided by a prosodic cue (**Chapter 3**) and that prosodic cues can establish expectations concerning syntactic and semantic properties of upcoming sentence elements (**Chapter 4**), **Chapter 5** then aimed to connect the results from the first two studies. To this end, I used TMS to probe the functional relevance of the IFG in sentence processing guided by prosodic cues. Specifically, the study tested the hypothesis that the syntactic and semantic processes prompted by pitch accents could be attributed to posterior and anterior parts of the IFG, respectively. Disruption of the posterior IFG was shown to affect both syntactic and semantic processing, while stimulation over anterior IFG did not yield conclusive results. Since both the syntactic and semantic processes required interpretation of the grammatical roles that the pitch accents indicated, results suggest that the posterior IFG is causally involved in processing grammatical roles that are cued by prosody.

Together, these findings underline the central role of prosody in auditory sentence processing, and accordingly, the involvement of a core area in the language network: the left IFG. The implications of this work are discussed in two parts. To start with, I single out a specific result of each experimental chapter that is worth emphasising and well-suited to design future research. First, the central role of the IPB in building sentence structure is discussed, and how this is reflected on the neural level. Second, I discuss how the sentence comprehension and sentence completion paradigms from the behavioural study could be combined with neuroimaging methods: future studies could differentiate between the contributions of prosodic and focus structure on expectations formed, or between their syntactic and semantic effects. Third, I further consider the applicability of TMS to probe the perceptual properties of prosody as well as to probe prosodic effects on sentence processing.

Finally, based on the studies presented here and the wider neuroimaging literature that motivated these experiments, I put forward a model that summarises the main neuroanatomical substrates supporting sentence-level prosody processing.

In the final part of the discussion, I explore an important remaining gap in this model that requires further experimental work to be resolved, as well as broader questions that could be addressed in future research.

Part I - A central role of prosody in sentence processing and in the language network

1.1. *Processing of IPBs that determine sentence structure involves a core brain region for syntax*

The study presented in **Chapter 3** revealed how the processing of the IPB is reflected in the brain. To study this, the experiment made use of the fact that IPBs can resolve local syntactic ambiguities (Marslen-Wilson et al., 1992; Steinhauer et al., 1999). Furthermore, we investigated the disambiguating function of a prosodic cue (the IPB) by comparing it to a non-prosodic disambiguating cue (Marslen-Wilson et al., 1992; Speer et al., 1996): a case-marked personal pronoun. To isolate the contribution of each individual cue, we compared sentences in which a single cue disambiguated the sentence structure (either prosodic or morphosyntactic) to sentences that had multiple disambiguating cues. When the IPB was the only cue disambiguating the sentence structure, this yielded increased functional activity in the left IFG. The IFG was also shown to be involved when morphosyntax was the sole disambiguating cue. This contrast additionally showed activation in the left posterior STG, an area that is consistently involved in morphosyntactic analysis, allowing sentence level grammatical processing through agreement information (Friederici, Kotz, Scott, & Obleser, 2009; Quiñones et al., 2018; L. K. Tyler et al., 2010). Finally, lateralisation of activity in the IFG depended on whether the IPB was required to process sentence structure (left hemisphere) or whether it was superfluous for building sentence structure (right hemisphere). These results support early models on the functional lateralisation of prosody (Friederici & Alter, 2004; van Lancker, 1980). Here, I will focus on the left IFG result and the shared function of the prosodic and morphosyntactic cue types in this sentence comprehension task.

In **Chapter 3**, the two cues were labelled as *prosodic* cues (the IPB) and *grammatical* cues (case-marking). However, perhaps a more accurate use of terminology would have been to label the case-marking cue as a *morphosyntactic* cue. In fact, both the IPB and the morphosyntactic cue are syntactic cues, as both serve to disambiguate syntactic structure. The *prosodic* cue is therefore a *syntactic* cue, as it signals a syntactic phrase boundary. This is also reflected in the brain imaging data from this study: functional contrasts in which either the prosodic or the morphosyntactic cue was the sole disambiguating factor showed involvement of the left IFG, a core region for syntactic processing (e.g., Carreiras, Quiñones, Mancini, Hernández-Cabrera, & Barber, 2015; Goucha & Friederici, 2015; Matchin, Hammerly, & Lau, 2017; Zaccarella, Meyer, Makuuchi, & Friederici, 2015). Involvement of the IFG both for sentences with a prosodic cue and for those with a morphosyntactic cue is in line the with the notion that, under ambiguous circumstances, prosody and morphosyntax can have similar disambiguating effects during sentence comprehension (Marslen-Wilson et al., 1992). Indeed, in our fMRI experiment, there was no response time difference between the critical conditions (those with a single disambiguating cue), suggesting that both morphosyntactic and prosodic cues involved comparable processing demands.

A limitation of this study is the lack of information on the relative importance of the prosodic and morphosyntactic cue: which of the two cues would be decisive when they signal contradicting sentence structures? The current study was not designed to answer this question: in the baseline conditions (containing two disambiguating cues), the IPB always preceded the morphosyntactic cue, and agreement between verb and case marking was always congruent. An answer to this question could therefore be provided by comparing sentences that include agreement violations, such *as *Peter verspricht sie # dafür zu bezahlen* (*Peter promises^{+DAT} her^{ACC} # to pay^{+ACC} for it). Such a condition was not included in the current study, because processing violations may prompt additional cognitive resources such as syntactic reanalysis or error monitoring. We therefore opted to use exclusively natural, congruent sentence material. Nevertheless, the use of sentences that include a violation could provide an approach for future work to further explore the relative importance of prosodic and morphosyntactic cues in sentence processing.

In conclusion, the fMRI study showed that when the IPB is the decisive cue establishing sentence structure, its processing recruits an area known to be important for syntax (e.g., Carreiras et al., 2015; Goucha & Friederici, 2015; Matchin et al., 2017; Zaccarella et al., 2015). The results emphasised that in an ambiguous sentence structure, the influence of prosodic boundaries in determining syntactic processing during sentence comprehension is comparable to that of morphosyntactic cues. The fact that prosody processing in this context recruited a core syntactic area such as the left IFG is therefore in line with prominent models on language processing (Friederici, 2011; Hagoort & Indefrey, 2014).

1.2. Further explorations of expectations established by pitch accents

The question of how influential prosody is relative to other sentence processing cues was central again in the second study (**Chapter 4**). We showed that listeners can use pitch accents during sentence comprehension to anticipate syntactic and semantic properties of upcoming elements. However, the expectations formed by pitch accents did not guide the interpretation of the sentence under all conditions: when multiple, contradicting cues were available in the sentence, the local syntactic cue was decisive in determining the subject/object interpretation of each noun phrase in the sentence, overwriting previous information cued by the pitch accent. This underlines the notion that prosody is foremostly an *influential* cue for sentence processing and that it can be *decisive* when no other disambiguating cues are available (Carlson, 2009; Frazier et al., 2006).

This behavioural study demonstrated that a sentence completion task is a suitable paradigm to probe pitch accent and focus interpretations. Previous studies on focus have relied on various types of measures probing the appropriateness of intonation to a certain focus context. These tasks typically involve acceptability judgements on the intonation of an utterance given a particular focus context (Birch & Clifton, 2016; Gussenhoven, 1983; Kuthy & Stolterfoht, 2019) or perceptual tasks in which the appropriate focus context must be selected after hearing a specific prosodic realisation of an utterance (Breen et al., 2010). However, these aforementioned methods can only inform about the offline interpretation of pitch accents and information structure. Here, for the first time, a sentence completion task probed the perceived pitch accent interpretation directly. Further research could use a combination of acceptability judgement and sentence completion tasks, to evaluate how a meta-linguistic judgement and directly probed behaviour relate to one another. This could reveal how sentences with a syntactic violation in the current study were perceived: although the syntactic mismatch between contrastively focused constituents led to delayed responses, it is still unknown to what extent participants perceived these violations as grammatically unacceptable.

Further open questions remain concerning the error response evoked by the violations between contrastive elements during sentence comprehension. Here, neuroimaging and electrophysiological techniques may provide additional insight. For example, EEG can be used to elucidate the nature of the additional processing caused by the syntactic violations: different ERP components could be used to distinguish syntactic reanalysis from focus structural reanalysis processing (Stolterfoht et al., 2007). Finally, the processing of syntactic and semantic violations can be further explored in fMRI experiments. Syntactic and semantic violations may yield increased functional activity in different subregions within the left IFG: this would be predicted based on previous imaging studies, showing a functional specialisation of subregions of the IFG for syntactic and semantic processing (Friederici, 2011; Hagoort & Indefrey, 2014).

1.3. The causal role of the inferior frontal gyrus in prosody-guided processing

Results of the first two studies directly motivated the third study (**Chapter 5**). Firstly, the left IFG was found to be activated when prosody established the sentence structure (**Chapter 3**). However, this did not yet show the causal role of the IFG for sentence processing guided by prosodic cues. Secondly, we demonstrated that pitch accents can establish dissociable expectations in the syntactic and semantic domains (**Chapter 4**). These domains, in turn, are widely assumed to be processed in two subregions of the IFG (Friederici, 2011; Hagoort & Indefrey, 2014). We therefore set out to establish the functional relevance of the IFG in prosody-guided sentence processing. Furthermore, we aimed to establish the possible functional relevance of two subregions of the IFG for the syntactic and semantic processes prompted by pitch accents. Although we did not find evidence for this regional specialisation, we showed that disruption of the posterior part of the IFG impairs both syntactic decisions (case-marked determiner of the upcoming phrase) and semantic decisions (noun of upcoming phrase) that had been cued by pitch accents.

One question that the current study left open, concerns the exact process that was disrupted by TMS over posterior IFG. We suggested that pIFG was either involved in processing the subject/object role template activated by prosody, or an evaluation of this template against the template provided by the incoming visual stimulus. To disambiguate these two options, a follow-up experiment could apply TMS *before* presentation of the visual response options (at the end of the spoken sentence, during "und nicht…"—*and not…*). This would only disrupt the subject/object role template activated by prosody, since this is the only template available at this stimulation time point. If in such a control experiment error rates are not affected, it could be argued that in the current study the process of evaluation of the two templates was disrupted, rather than the prosodic representation itself.

Despite the apparent effects of prosody on sentence processing, previous TMS studies in the language domain have mostly investigated these two aspects in isolation: previous work has either demonstrated effects on processing of pitch contours, or on syntactic processing as such. Investigating syntactic processing in general (unrelated to prosody), a number of TMS studies have shown the IFG to be functionally relevant. These include processing of dependencies in artificial grammars (Uddén et al., 2008; Uddén, Ingvar, Hagoort, & Petersson, 2017), argument reordering (Kuhnke et al., 2017), and attachment processing (L. Meyer, Elsner, Turker, Kuhnke, & Hartwigsen, 2018). Several other studies only allow for limited interpretations on the relationship between IFG and syntax because of low sample sizes (Carreiras, Pattamadilok, Meseguer, Barber, & Devlin, 2012; Z. Cattaneo, Devlin, Vecchi, & Silvanto, 2009; Sakai, Noguchi, Takeuchi, & Watanabe, 2002).

Finally, one study found a functional role for posterior parietal regions and thematic role processing (Finocchiaro, Capasso, Cattaneo, Zuanazzi, & Miceli, 2015). Taken together, the available literature on TMS effects in syntactic processing is limited. This makes the current experiment one of the few studies establishing the functional relevance for (the posterior part of) the left IFG in grammatical processing.

While few TMS studies have investigated syntactic processing, the number of TMS studies on prosody is even more limited[6]. Sammler et al. (2015) demonstrated the involvement of right premotor cortex in pitch contour discrimination. Importantly, in this study TMS was applied during perception of the actual cue, which led to inhibited question/statement judgements. In contrast, in the study presented in this thesis, a prosodic cue prompted subsequent (syntactic and semantic) processing, and these processes were in turn targeted by TMS. Disruption of the prosodic cue itself was not feasible in the current experiment, because focus structure depends on the distribution of accented and de-accented information throughout the sentence (Féry & Kügler, 2008). Stimulation on the nuclear pitch accent would therefore have left ample prosodic cues in the rest of the sentence unaffected: participants would still be able to interpret the focus structure because of prosodic cues outside of the TMS window. In another recent TMS experiment on linguistic prosody, L. Meyer and colleagues (2018) investigated attachment processing guided by an IPB. Stimulating on a noun that was either followed by an IPB or not, these authors found no effect of TMS on processing of the IPB, yet established an association between the pIFG and inherent attachment preference. In sum, the study in **Chapter 5** is one of the first to show TMS effects on the sentence-level when comprehension is guided by a prosodic cue.

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[6] A number of TMS studies have been done investigating emotional prosody (Alba-Ferrara, Ellison, & Mitchell, 2012; Hoekert, Vingerhoets, & Aleman, 2010; Van Rijn et al., 2005).

1.4. Processing pathways for prosodic cues

The three studies presented in this thesis investigated various effects of prosodic cues on sentence comprehension. Importantly, when prosodic cues made a crucial contribution to sentence processing, an important role of the left IFG was found. Based on the literature and the data from these three studies, and building on a recently presented model (Friederici, 2017), I suggest the following neuroanatomical framework supporting sentence-level prosody processing (illustrated in Figure 1). Processing of pitch information starts in the superior temporal cortex (Tang et al., 2017), possibly with a right-hemispheric preference, and involves the STG and STS (M. Meyer et al., 2004; Plante et al., 2002; Sammler et al., 2015). Superior temporal regions are also involved in processing rhythmical and stress cues (Honbolygó et al., 2020). If pitch information is required to be held in working memory, this likely involves the right premotor cortex and IFG (M. Meyer et al., 2004; Plante et al., 2002; Sammler et al., 2015). Furthermore, these areas are important for interaction with other right hemispheric structures to support processing of non-linguistic information, such as emotional prosody (Seydell-Greenwald, Chambers, Ferrara, & Newport, 2020), speaker identity (Kreitewolf et al., 2014), and music (Albouy, Benjamin, Morillon, & Zatorre, 2020).

If prosody serves a linguistic function, pitch information must be transferred to the left hemisphere, requiring hemispheric crossing via the posterior part of the corpus callosum (Friederici et al., 2007; Sammler et al., 2010; 2018). In the left hemisphere, intonational information is then transferred to the frontal lobe. This likely occurs via the dorsal fibre tracts connecting to the premotor cortex, which support phonological processing (Saur et al., 2008). In case prosody carries out a syntactic role, the arcuate fascicle, connecting to the pIFG, may be particularly important, as a fibre tract associated with complex syntactic processes (Friederici & Gierhan, 2013). In the left IFG, prosody can be integrated with other linguistic information to guide sentence processing, both by influencing syntactic processing (Van der Burght et al., 2019; **Chapter 5** of this thesis) and information structural processing (Kristensen et al., 2013; Perrone-Bertolotti et al., 2013; van Leeuwen et al., 2014). In sum, especially right temporal and left frontal areas, which do not have direct anatomical connections, have been consistently shown to be fundamental regions supporting sentence-level prosody processing. This is further supported by EEG and MEG studies highlighting the importance of synchronised activity between both hemispheres (David, Maess, Eckstein, & Friederici, 2011), sometimes attuned to specific frequency bandwidths in speech: synchronisation between right posterior temporal and left inferior frontal regions has been shown to be particularly important for processing information at prosodically relevant frequencies (i.e., at the rhythm of intonational phrasing, 0.5-1 Hz) (Bourguignon et al., 2013; Molinaro, Lizarazu, Lallier, Bourguignon, & Carreiras, 2016).

Although this model encompasses the acoustic processing aspect of prosodic cues as well as their implementation into the sentence, an important gap remains: it must be addressed how and where acoustic features map onto an abstract prosodic representation.

Part II: Outstanding questions in prosody research

2.1. Mapping acoustic features onto prosodic cues

Any model that attempts to describe the neuroanatomical pathways involved in processing of prosodic cues needs to account for the transition from acoustic features to a prosodic percept. Along the way, the processing system is posed with a number of problems: it has to combine information with dissimilar spectral and temporal properties, as well as to map acoustic features that vary between different speakers onto abstract prosodic representations.

Firstly, prosodic phenomena and non-prosodic speech content are comprised of acoustic features that are presumed to be processed in a lateralised way. The auditory cortices in each hemisphere differ in their sensitivity to time and pitch domains, with a relative dominance for processing temporal information in the left hemisphere, and for spectral information in the right hemisphere (Flinker, Doyle,

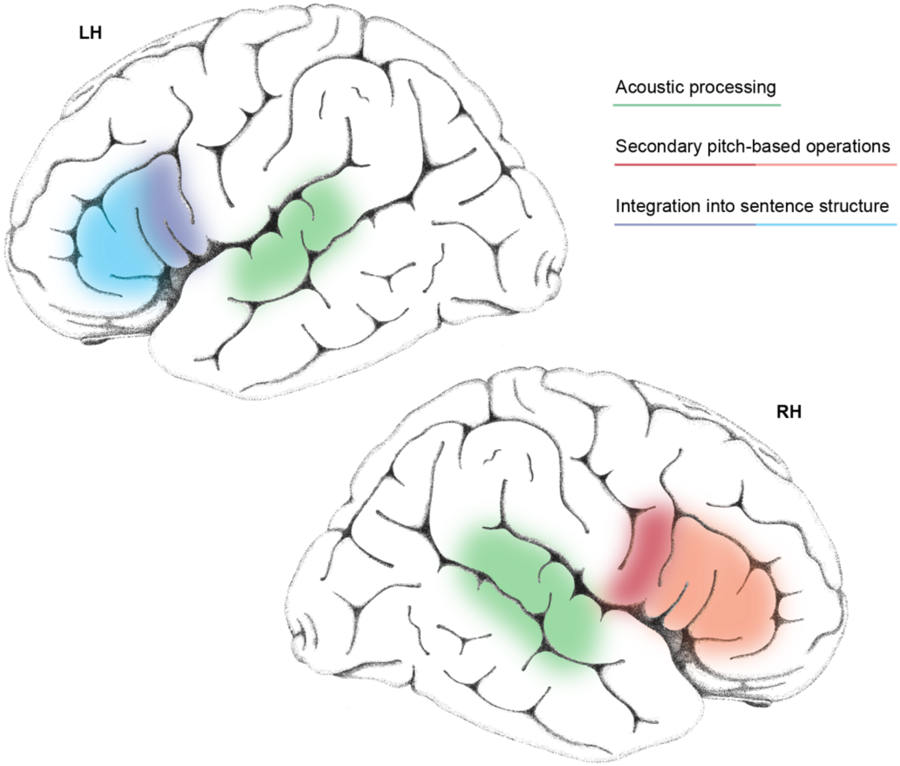

Figure 1. Illustration of the left and right hemispheres with the main neuroanatomical regions supporting sentence-level prosody processing (see text for details). LH: left hemisphere. RH: right hemisphere.

Mehta, Devinsky, & Poeppel, 2019). Consequently, there is a left-hemispheric advantage for the high temporal resolution that segmental units in speech rely on, and a right-hemispheric advantage for stimuli rich in spectral information, such as melody (Albouy et al., 2020). This relative sensitivity of each hemisphere poses an interesting question for prosody: segmental information, at a high temporal resolution, is predominantly processed in the left hemisphere, whereas the low-frequency modulations of pitch contours are predominantly right-lateralised. The question therefore remains how and where prosodic cues are integrated with segmental speech content.

Furthermore, the mechanisms with which acoustic cues map onto prosodic representations remain unresolved. For instance, there is great variability in the correspondence between acoustic features and prosodic representations between speakers. In fact, different speakers realise prosodic phenomena with a remarkable range: a pitch contour indicating a question in one speaker may be a statement-like intonational contour in another (Xie, Kurumada, & Buxó-Lugo, 2020). Listeners must therefore map acoustic features onto abstract prosodic representations, and be able to adapt to the particular prosodic realisations of different speakers (Kurumada, Brown, & Tanenhaus, 2017). How this is organised on the neural level is unknown. Furthermore, it remains unresolved if prosodic phenomena are processed in a continuous or perhaps in a categorical fashion (Ladd & Morton, 1997). In sum, the way in which acoustic features map onto prosodic representations remains an important gap in the model on prosodic processing presented in this discussion.

2.2. The reliance on prosodic cues during language processing in development and in the adult speaker

Another theme covered in this thesis that leaves ample questions for future research concerns the relative importance of prosody as compared to other cues in guiding sentence comprehension. Indeed, the fMRI study in **Chapter 3** suggested that processing prosodic and morphosyntactic cues that determine sentence structure takes place at least in part in the same neuroanatomical region (the left IFG). Yet, the results presented in **Chapter 4** suggest a divergence between the two cue types: ultimately, syntactic cues take precedence over prosodic cues in guiding sentence comprehension. This is in line with the notion that the role of prosody in sentence comprehension is influential, but not decisive (Frazier et al., 2006; Carlson, 2009). It is interesting to note that during development, the role of prosody in language processing has been shown to be much more significant. During language acquisition, perceptual analysis must necessarily precede syntactic or semantic analysis. The idea that infants may therefore use prosodic cues during language acquisition has formed the basis for the *prosodic bootstrapping hypothesis* (Gleitman & Wanner, 1982; Morgan & Demuth, 1996; Pinker, 1984). This framework is based on three assumptions: the fact that syntax and prosody reliably correlate, that infants are sensitive to prosodic cues, and that they use these cues during speech processing (Soderstrom, Seidl, Nelson, & Jusczyk, 2003). Indeed, infants are sensitive to prosodic cues already at the newborn stage and use them to organise acoustic input (Abboub, Nazzi, & Gervain, 2016) and to detect word boundaries (Christophe et al., 2001). Later during development, boundaries between phrases (Soderstrom et al., 2003) and between clauses are recognised (Holzgrefe-Lang, Wellmann, Höhle, & Wartenburger, 2018; Männel & Friederici, 2009). Besides aiding syntax acquisition, prosodic cues, together with knowledge of a limited set of function words, facilitate word learning (de Carvalho, He, Lidz, & Christophe, 2019).

In sum, during the early stages of language acquisition, prosodic structure enables children to parse input into syntactically relevant units, helping them to detect regularities in the speech stream (Jusczyk, 1997). Yet, although prosodic structure and syntactic structure correlate, they do not always show a strict correspondence. It is therefore assumed that prosodic cues facilitate syntax acquisition together with other cues available in speech. Ultimately, in adult language processing, a mere guiding role for prosody remains, with generally a primary reliance on syntactic cues. An outstanding question then remains how the different sensitivities to prosodic and non-prosodic cues develop during infancy, childhood and into adulthood, and how this may be reflected in brain structure and function.

2.3. Conclusion of future directions

In conclusion, neurocognitive research on prosody has many open questions to address. In what follows, I suggest three research directions that could further our understanding of prosody processing mechanisms in the brain. These directions concern the mapping of acoustic cues on prosodic representations, the interaction between left inferior and right temporal cortex in supporting prosody processing, and how developmental studies could inform the relative importance of prosodic and syntactic cues in guiding sentence comprehension.

First, to address the question of how acoustic features map onto prosodic representations, future fMRI studies could make use of multivariate analysis techniques. Although the standard univariate approach used in **Chapter 3** is an effective method, the advantage of multivariate methods is that they can provide information about distributed patterns of representations in the brain. Analysis techniques such as representational similarity analysis (Kriegeskorte, 2011; Kriegeskorte et al., 2008) could be an appropriate method to show how acoustic parameters map onto prosodic features. To this end, multiple acoustic realisations of the same prosodic cue could be studied, as well as a range of different cues that have partially overlapping acoustic parameters. Together, this could reveal brain regions that are sensitive to acoustic similarities or instead to similarities between abstract representations. In this way, this approach could help answer the question whether prosodic phenomena are neurally encoded in a continuous or categorical manner. This question could be further addressed by using resynthesised stimuli, in which two prosodic realisations of an utterance are morphed to create an acoustic continuum (Kurumada et al., 2017; Sammler et al., 2015). A final asset of multivariate pattern analyses is their sensitive to individual variability in activation patterns (Hartwigsen & Bzdok, 2018). This may provide a further advantage over univariate techniques in mapping between-subject differences in prosodic processing. These methods could be used in combination with a naturalistic approach to studying sentence processing, which has recently seen increased popularity. In these experiments, participants listen to a story or dialogue from which linguistic parameters are derived, which are later correlated to fMRI (Brennan, Stabler, Van Wagenen, Luh, & Hale, 2016), EEG (Brennan & Hale, 2019), or MEG (Bourguignon et al., 2013) measures. This could be an appropriate technique to further elucidate the temporal and neuroanatomical organisation of prosodic cue processing. For example, a pseudo-naturalistic story could be designed and recorded that contains prosodic cues that are acoustically similar, but where the linguistic environment in which they occur is manipulated. Together with electrophysiological measures, this could reveal activity profiles of listeners that are more sensitive to prosodic or syntactic and semantic cues in the sentence (Baumann & Winter, 2018).

Second, future research should investigate the nature of the interaction between left frontal, right temporal, and right frontal areas in prosody processing. Both regions are consistently found in prosodic research, and their synchronisation has been shown to be relevant for tracking the slow modulations in pitch that are characteristic of prosodic information. Considering the numerous top-down effects on prosodic processing that have been discussed, it is likely that activity in temporal regions is modulated by input from the IFG. Such interactions could be investigated by fMRI connectivity techniques (Friston, 2011; Friston, Harrison, & Penny, 2003; O'Reilly, Woolrich, Behrens, Smith, & Johansen-Berg, 2012). The method that is arguably most suited to address this question is that of cortical surface recordings, which have been used to demonstrate the time course of fronto-temporal interactions in word production (Flinker et al., 2015). As a non-invasive alternative, multifocal TMS could be used to further investigate the temporal dynamics of activity in these two regions, while simultaneously providing high spatial resolution. For example, a condition-and-perturb approach could be adopted, in which the combined effects of stimulation over STG and IFG in a sentence comprehension task could be explored (Hartwigsen et al., 2012; 2015).

Third, future developmental studies should investigate the developmental transition in linguistic cue processing, from a strong sensitivity to prosodic cues in infancy to a primary reliance on syntactic cues in adulthood. The fMRI study in this thesis suggests that in the adult brain, the processing of prosodic and syntactic cues shows convergence. Given that during development, prosodic cues play an important role in syntax acquisition, it is an intriguing outstanding question whether prosodic and syntactic processing show a similar convergence on the neural level during childhood. Previous work has successfully demonstrated in which stages of development children acquire sensitivity to various acoustic aspects of prosodic cues (Holzgrefe-Lang et al., 2018; Männel & Friederici, 2009). Other work has shown that across development, there are shifts in the cortical distribution of functional activity reflecting syntactic and semantic processing (Skeide, Brauer, & Friederici, 2014) and language comprehension in general (Enge, Friederici, & Skeide, 2020). It would therefore be worthwhile to further elucidate the developmental trajectories of the syntactic and prosodic processing systems on the neural level. For example, does the cortical distribution of the network supporting prosody processing manifest a shift similar to the syntactic and semantic networks? If so, it would be intriguing to be able to compare the time course of all three developing networks: syntactic, semantic, and prosodic.

Concluding remarks

The work in this thesis underlines the integral role of prosodic cues in the sentence processing system. For decades, this notion has been evident in linguistic, psycholinguistic, and electrophysiological research. Yet, in functional neuroimaging studies, it has often proven a challenge to investigate prosodic cues in what is arguably their most influential capacity during auditory language processing: as cues that steer grammatical processing. The work in this thesis therefore emphasises the necessity to study the effects that prosody exerts on sentence processing in parallel to studying the perceptual aspects of prosody. Clearly, it requires investigations of perceptual processing as well as of sentence-level effects to provide a complete account of the neuroanatomical network supporting prosody, and, ultimately, language.

The experiments presented here explored two instances in which prosodic cues play an integral role in sentence processing: by disambiguating syntactic structure and by establishing expectations concerning upcoming syntactic and semantic information. Results showed that prosody exerts these effects most strongly in an ambiguous sentence environment: when competing disambiguating cues are available, syntactic cues are the more decisive cue. Importantly, under circumstances where prosodic cues do play a decisive role in sentence processing, this both involves and requires a core brain region supporting syntax: the left IFG.

To conclude, this thesis provided novel insights into the effects of prosody during sentence comprehension. Crucially, in both of the paradigms presented here, sentence comprehension could not have occurred in absence of the prosodic cue without resorting to a default analysis of the syntactic or information structure. In both paradigms, results suggested a key role for the left inferior frontal gyrus, a core area for sentence processing. Consequently, it can be concluded that prosody makes a central contribution the sentence processing system, as is reflected both on the behavioural and neural level.

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Summary

Introduction

In spoken conversation, listeners rely on several language cues to understand what is being said. Besides syntax (grammar) and semantics (content), important information is conveyed by the way in which a sentence is spoken. Variations in speech melody, rhythm, and intensity, together called *prosody*, play a decisive role in the interpretation of a sentence. The effects of prosody on sentence comprehension are wide-ranging. One type of prosodic cue, the intonational phrase boundary (IPB, realised acoustically by a pitch rise and syllable lengthening, followed by a pause), can dramatically alter the syntactic structure of a sentence. For example, the difference between "*the reviewer said: the author is mistaken"* and "*the reviewer, said the author, is mistaken*", in spoken language is established exclusively by the different placement of prosodic boundaries. Another type of prosodic cue, the pitch accent, can influence syntactic, but also semantic processing. For example, in "Anna bought APPLES at the market", APPLES is marked by a pitch accent (an increase in pitch and intensity), highlighting the part of the sentence that carries prominent or important information. By assigning so-called focus, the pitch accent manipulates the information structure of the sentence (in this case, conveying that it was apples that Anna bought, rather than a different type of fruit).

Despite many years of psycholinguistic and neurocognitive research on prosody, important questions remain. On the neural level, it is unclear what brain regions are involved in processing prosodic information that determines the grammatical structure of a sentence. On the behavioural level, it has been shown that pitch accents play an important role in both syntactic and semantic processing. Yet, one question that remains outstanding is if pitch accents can establish expectations concerning both syntactic and semantic properties of a sentence. Furthermore, it is unclear which type of language cue (prosodic, syntactic, or semantic) takes precedence if multiple contradicting cues are present in the sentence. To address these questions, this thesis presented three novel experimental paradigms that probed the effects of prosody on syntactic structure and information structure processing. By combining these paradigms with neuroimaging techniques, these effects were further investigated on the neural level. The experimental work presented in this thesis can be summarised as follows.

Study 1: An fMRI study on intonational phrase boundary processing

Prosodic information is thought to be processed in a bilateral fronto-parietal network in the brain. However, the exact regions involved strongly depend on the stimulus type and experimental task used. In particular, the possible hemispheric lateralisation of prosody processing is a matter of debate. In this functional magnetic resonance imaging (fMRI) study we used sentences in which processing a prosodic cue—the IPB—was required to understand *who did what to whom* in the sentence. In a second condition, a grammatical cue (morphosyntactic case-marking) disambiguated the sentence structure instead. These critical conditions were compared to baseline sentences in which both a prosodic and a grammatical cue guided sentence comprehension. Participants listened to the spoken sentences and responded to comprehension questions by button press.

The results showed stronger functional activity in the left inferior frontal gyrus (IFG) when the prosodic cue was crucial for sentence comprehension as compared to a baseline sentence. When instead the grammatical cue was crucial for sentence comprehension, we found involvement of an overlapping region in the left IFG, as well as in a posterior temporal region. A further analysis revealed that the lateralisation of intonation processing depended on its role in syntactic processing: activity in the IFG was lateralised to the left hemisphere when the IPB was the only source of information to understand the grammatical structure of the sentence. In contrast, activity in the IFG was right-lateralised when the IPB did not contribute to sentence comprehension.

The results underline the similar influence that prosodic and morphosyntactic cues have on establishing the grammatical structure of a sentence. This is reflected on the neural level by the functional activity in the left IFG, demonstrating the importance of this region when either intonational or grammatical cues establish sentence structure. Finally, the results provide evidence for the theory that the lateralisation of prosodic processing is modulated by its linguistic role.

Study 2: Behavioural experiments on pitch accent processing

The fMRI study highlighted the crucial role prosodic cues can play in determining the syntactic structure of a sentence. However, as a prosodic cue coinciding with syntactic boundaries, the IPB is necessarily strongly connected to syntactic processing. This behavioural study therefore explored how a different prosodic phenomenon—the pitch accent—exerts effects on sentence comprehension. Pitch accents play an important role in syntactic as well as in semantic processing. One question that remains outstanding is if a single pitch accent can establish expectations simultaneously in both of these linguistic domains. Furthermore, it is unclear which type of linguistic cue takes precedence when multiple contradicting cues exist in the sentence.

To address these questions, we used sentences in which one out of two noun phrases was placed in contrastive focus with a third noun phrase. All noun phrases carried overt syntactic information (case-marking of the determiner) and semantic information (typicality of the thematic role of the noun). Two experiments (a sentence comprehension and a sentence completion task) showed that focus, marked by pitch accents, established expectations in both syntactic and semantic domains. However, only the violation of the syntactic expectations led to delayed responses in the sentence comprehension task. Furthermore, when contradictory cues occurred in the same sentence, the local syntactic cue (case-marking) took precedence over the semantic cue (thematic role), and overwrote previous information cued by prosody. In sum, results pointed to expectations established by pitch accents in both syntactic and semantic domains. However, only violated syntactic expectations were strong enough to interfere with sentence comprehension. The findings therefore indicate that during auditory sentence comprehension the language processing system integrates syntactic, semantic, as well as prosodic cues, yet, primarily relying on syntactic information.

Study 3: A TMS study on grammatical role processing cued by pitch accents

Considering that the left IFG is involved when sentence processing is guided by a prosodic cue (**Study 1**) and that prosodic cues can establish expectations concerning syntactic and semantic properties of upcoming sentence elements (**Study 2**), **Study 3** then aimed to connect the results from the first two studies. The first aim of this experiment was to explore the causal role of the left IFG for sentence processing guided by prosodic cues. A further objective was to investigate a possible causal role of subregions of the IFG in the syntactic and semantic processes prompted by prosody. This second aim was based on the functional specialisation of the anterior IFG for semantic processing and of the posterior IFG for syntactic processing, which is well-established in the functional imaging literature on language comprehension. To test this, we used focal perturbations induced by repetitive transcranial magnetic stimulation (rTMS) to probe the causal role of the posterior IFG for syntactic processing and the anterior part for semantic processing. The experimental paradigm used was the sentence completion task from **Study 2**, which required participants to take syntactic and semantic decisions across experimental trials. Since in this paradigm the interpretation of a pitch accent in the sentence was essential for successful task performance, we additionally were able to assess the causal role of left IFG in sentence processing when crucial information was conveyed by prosody.

Specifically, the paradigm presented truncated spoken utterances, in which a pitch accent cued which determiner and noun (presented visually) would form the most suitable sentence ending. Participants selected these by button press. In this within-subject design, participants underwent three sessions during which 10 Hz rTMS bursts were applied over either anterior or posterior left IFG, or vertex (control region). Results showed that disruption of the posterior IFG affected both syntactic and semantic processing, while stimulation over anterior IFG did not yield conclusive results. Since both the syntactic and semantic processes required interpretation of the grammatical roles that the pitch accents indicated, results suggest that the posterior IFG is causally involved in processing grammatical roles that are cued by prosody.

Discussion

Together, these studies underline the central role of prosody in auditory sentence processing, and accordingly, the involvement of a core area in the language network: the left IFG. The experiments presented here explored two instances in which prosodic cues play an integral role in sentence processing: by disambiguating syntactic structure and by establishing expectations concerning upcoming syntactic and semantic information. Results showed that prosody exerts these effects most strongly in an ambiguous sentence environment: when competing disambiguating cues are available, syntactic cues are the more decisive cue. Importantly, under circumstances where prosodic cues do play a decisive role in sentence processing, this both involves and requires a core brain region supporting syntax: the left IFG.

The notion of prosody as an influential cue in sentence comprehension has long been evident in linguistic, psycholinguistic, and electrophysiological research. Yet, in functional neuroimaging studies, it has often proven a challenge to investigate prosodic cues in what is arguably their most influential capacity during auditory language processing: as cues that steer grammatical processing. The work in this thesis therefore emphasises the necessity to study the effects that prosody exerts on sentence processing in parallel to studying the perceptual aspects of prosody. Clearly, it requires investigations of perceptual processing as well as of sentence-level effects to provide a complete account of the neuroanatomical network supporting prosody, and, ultimately, language.

To conclude, this thesis provided novel insights into the effects of prosody during sentence comprehension. Crucially, in the paradigms presented here, sentence comprehension could not have occurred in the absence of the prosodic cue without resorting to a default analysis of the syntactic or information structure. In both paradigms, results suggested a key role for the left inferior frontal gyrus, a core area for sentence processing. Consequently, it can be concluded that prosody makes a central contribution to auditory sentence processing, as is reflected both on the behavioural and neural level.

Zusammenfassung

Einleitung

In alltäglichen Gesprächen bedient sich der jeweils gerade Zuhörende verschiedener linguistischer Anhaltspunkte, um zu verstehen, was gesagt wird. Neben der Syntax (Grammatik) und der Semantik (Inhalt) bietet die Art und Weise in der gesprochen wird weitere wichtige Anhaltspunkte für das Verständnis des Zuhörers. Veränderungen in der Sprechmelodie, dem Rhythmus, sowie der Lautstärke werden unter dem Begriff *Prosodie* zusammengefasst und spielen eine entscheidende Rolle bei der Interpretation eines Satzes. Die Auswirkungen von prosodischen Elementen auf das Verständnis von Sätzen sind vielseitig: Ein solcher prosodischer Anhaltspunkt ist die sogenannte Intonationsphrasengrenze (engl. *intonational phrase boundary*, IPB; akustisch realisiert durch einen Anstieg der Tonhöhe und Dehnung der Silbe, gefolgt von einer Pause), welche die syntaktische Struktur eines Satzes drastisch verändern kann. Zum Beispiel ergibt sich, in gesprochener Sprache, der Unterschied zwischen den Sätzen *„Der Gutachter sagte: Der Autor irrt sich."* und *„Der Gutachter, sagte der Autor, irrt sich."* ausschließlich durch die unterschiedliche Anordnung der prosodisch markierten Phrasengrenzen. Ein weiterer prosodischer Anhaltspunkt, der sogenannte Tonhöhenakzent (engl. *pitch accent*), kann sogar Auswirkungen auf die syntaktische als auch die semantische Verarbeitung eines Satzes haben. Zum Beispiel wird im Satz *„Anna kaufte ÄPFEL am Markt."* das Wort ÄPFEL durch einen Tonhöhenakzent (d.h. einen Anstieg in Tonhöhe und Lautstärke) markiert, wodurch der Teil des Satzes, welcher wesentliche oder wichtige Information enthält, hervorgehoben wird. Der Tonhöhenakzent verändert demnach durch die Hervorhebung eines Wortes die Informationsstruktur des Satzes (in diesem Fall wird somit betont, dass Anna eben Äpfel und kein anderes Obst gekauft hat).

Obwohl sich die psycholinguistische und kognitiv-neurowissenschaftliche Forschung schon lange mit dem Thema Prosodie beschäftigt, sind viele wichtige Fragen nach wie vor offen. Auf der neuronalen Ebene ist unklar welche Hirnregionen in die Verarbeitung von prosodischer Information involviert sind, wenn ebendiese Information die grammatikalische Struktur eines Satzes bestimmt. Aus verhaltenswissenschaftlicher Perspektive ist bereits bekannt, dass Tonhöhenakzente eine wichtige Rolle bei der syntaktischen als auch semantischen Verarbeitung von

Sätzen spielen. Jedoch ist nach wie vor ungeklärt, ob Tonhöhenakzente die erzeugte Erwartungshaltung von Zuhörenden, im Bezug auf die syntaktische als auch semantischen Eigenschaften eines Satzes, beeinflussen können. Darüber hinaus ist auch noch nicht geklärt welche Art von linguistischen Anhaltspunkten (prosodisch, syntaktisch, oder semantisch) vom Zuhörer am stärksten Gewichtet und somit vorrangig behandelt wird, für den Fall, dass sich die unterschiedlichen Anhaltspunkte innerhalb eines Satzes konterkarieren. Um diesen Fragen nachzugehen, wurden im Rahmen der vorliegenden Arbeit drei neue experimentelle Paradigmen entwickelt, welche es möglich machen die Auswirkungen von Prosodie auf die syntaktische Struktur sowie die Informationsstruktur von Sätzen zu untersuchen. Durch die Kombination dieser experimentellen Paradigmen mit neurowissenschaftlichen Methoden konnten zudem diese Auswirkungen von Prosodie auf der neuronalen Ebene untersucht werden. Die experimentelle Arbeit in der vorliegenden Dissertation lässt sich wie nachfolgend dargestellt zusammenfassen.

Studie 1: Eine fMRT-Studie zur Verarbeitung von Intonationsphrasengrenzen

Allgemein wird angenommen, dass prosodische Informationen im Gehirn in einem bilateralen fronto-parietalen Netzwerk verarbeitet werden. Welche Regionen innerhalb dieses Netzwerks am stärksten in die Verarbeitung von Prosodie involviert sind hängt jedoch sehr stark von der Beschaffenheit des Stimulusmaterials, sowie der verwendeten experimentellen Aufgabe ab. Insbesondere die mögliche hemisphärische Lateralisierung der Verarbeitung von prosodischen Informationen ist Gegenstand laufender wissenschaftlicher Diskussionen. In der vorliegenden Studie wurden den Probanden unter Verwendung der funktionellen Magnetresonanztomografie (fMRT) Sätze präsentiert, welche die Verarbeitung eines prosodischen Anhaltspunktes—einer IPB—erforderten, um im jeweiligen Satz zu verstehen *wer was mit wem gemacht hat* (engl. *who did what to whom*). In einer weiteren Bedingung wurde die Struktur des Satzes hingegen durch einen grammatikalischen Anhaltspunkt (in Form einer morphosyntaktischen Markierung des grammatikalischen Kasus) angezeigt. Diese ausschlaggebenden Bedingungen wurden mit grundlegenden Sätzen in sogenannten Baseline-Bedingungen verglichen, in welchen die Probanden sowohl prosodische als auch grammatikalische Anhaltspunkte zum Verständnis heranziehen konnten. Die Teilnehmer hörten dabei gesprochene Sätze und antworteten per Knopfdruck auf Verständnisfragen.

Die Ergebnisse der Untersuchung zeigten verstärkte funktionelle Aktivität in der linken unteren Stirnwindung, dem *Gyrus frontalis inferior* (engl. *inferior frontal gyrus*; IFG), immer dann, wenn die prosodische Information im Vergleich zur Baseline-Bedingung essentiell für das Verständnis eines Satzes war. Wenn jedoch ein grammatikalischer Anhaltspunkt ausschlaggebend für das Verständnis eines Satzes war, wurde die Aktivierung einer überlappenden Region im linken IFG sowie einer Region im posterioren temporalen Kortex festgestellt. Eine weiterführende Analyse zeigte, dass die Lateralisierung der Verarbeitung der prosodischen Information von ihrer Relevanz für die syntaktische Verarbeitung des Satzes abhängt: Die Aktivität im IFG war linkslateralisiert, wenn die IPB den einzigen Anhaltspunkt bot um die grammatikalische Struktur eines Satzes zu Verstehen. Hingegen war die Aktivität im IFG rechtslateralisiert, wenn die IPB keinen Anhaltspunkt für das Verständnis eines Satzes bot.

Diese Ergebnisse unterstreichen die Ähnlichkeit im Hinblick auf die Auswirkungen, die prosodische und morphosyntaktische Elemente auf die Rekonstruktion der grammatikalischen Struktur im Rahmen der Verarbeitung eines Satzes haben können. Diese Ähnlichkeit spiegelt sich auf der neuronalen Ebene in der funktionellen Aktivität des linken IFG wieder und zeigt somit die wesentliche Rolle dieser Hirnregion in der Verarbeitung von prosodischen als auch grammatikalischen Anhaltspunkten im Kontext der Satzverarbeitung auf. Zu guter Letzt unterstützen diese Ergebnisse die Annahme, dass die Lateralisierung der Verarbeitung von prosodischen Informationen von der jeweiligen linguistischen Funktion derselben abhängt.

Studie 2: Verhaltenswissenschaftliche Experimente zum Tonhöhenakzent

Die vorangegangene fMRT-Studie hob die grundlegende Rolle, welche prosodische Anhaltspunkte bei der Rekonstruktion der syntaktischen Struktur eines Satzes spielen können, hervor. Es gilt jedoch zu bedenken, dass die IPB als prosodischer

Anhaltspunkt bereits auf der konzeptuellen Ebene zwingend eine starke Verbindung zur syntaktischen Verarbeitung aufweist, da sie als prosodischer Anhaltspunkt vorwiegend syntaktische Phrasengrenzen in einem Satz markiert. Die vorliegende verhaltenswissenschaftliche Studie beschäftige sich deswegen mit einem anderen prosodischen Phänomen: Den Auswirkungen des Tonhöhenakzents auf das Verständnis von Sätzen. Generell spielt der Tonhöhenakzent sowohl in der syntaktischen als auch der semantischen Verarbeitung von Sätzen eine wichtige Rolle. Eine bislang noch unbeantwortete Forschungsfrage war, ob ein einzelner Tonhöhenakzent gleichzeitig die Erwartungshaltung von Probanden in beiden dieser linguistischen Domänen beeinflussen kann. Darüber hinaus war unklar, welche Art von linguistischen Anhaltspunkten vom Zuhörer am stärksten gewichtet und somit vorrangig behandelt wird, wenn sich unterschiedliche Anhaltspunkte innerhalb eines Satzes konterkarieren.

Um diese Fragen zu beantworten, verwendeten wir Sätze als Stimulusmaterial, in denen eine von zwei Nominalphrasen in einer kontrastiven Fokusposition zu einer dritten Nominalphrase steht. Alle Nominalphrasen beinhalteten dabei klar ersichtliche syntaktische Information in der Form von Kasusmarkierung durch das Artikelwort sowie semantische Information, welche in der Regel die thematische Rolle des Nomens anzeigte. Zwei Experimente (eine Satzverständnis- und eine Satzvervollständigungsaufgabe) zeigten, dass die Markierung der Fokusposition durch Tonhöhenakzente bei den Probanden eine Erwartungshaltung sowohl in der syntaktischen als auch der semantischen Domäne hervorrief. Allerdings führte lediglich die Inkongruenz mit den erzeugten syntaktischen Erwartungshaltungen zu einer verzögerten Reaktion der Probanden bei der Satzverständnisaufgabe. Darüber hinaus wurde der lokale syntaktische Anhaltspunkt (Kasusmarkierung) stärker gewichtet als der semantische Anhaltspunkt (thematische Rolle) und überschrieb somit vorangegangene Information in Form von prosodischen Anhaltspunkten für den Fall, dass sich die unterschiedlichen Anhaltspunkte innerhalb eines Satzes konterkarierten. In Summe deuten diese Ergebnisse demnach drauf hin, dass Tonhöhenakzente bei den Probanden eine Erwartungshaltung in der syntaktischen und der semantischen

Domäne hervorriefen. Bemerkenswerterweise hatten jedoch lediglich Inkongruenzen mit diesen Erwartungshaltungen in der syntaktischen Domäne eine direkte Auswirkung auf das Satzverständnis. Diese Ergebnisse deuten demnach drauf hin, dass das menschliche Sprachverarbeitungssystem während der Verarbeitung von gesprochenen Sätzen Informationen aus syntaktischen, semantischen sowie prosodischen Anhaltspunkten extrahiert und integriert, wobei jedoch die syntaktische Information am stärksten gewichtet und somit vorrangig behandelt wird.

Studie 3: Eine TMS-Studie zur Verarbeitung von grammatikalischen Rollen die durch Tonhöhenakzente markiert sind

Anbetracht des Ergebnisses, dass der linke IFG in die Verarbeitung von Sätzen involviert ist, wenn prosodische Anhaltspunkte ausschlaggebend für die Rekonstruktion der syntaktischen Struktur eines Satzes sind (**Studie 1**) sowie dem Umstand, dass prosodische Anhaltspunkte Erwartungshaltungen im Bezug auf die syntaktischen und semantischen Eigenschaften von nachfolgenden Satzelementen während der Verarbeitung erzeugen können (**Studie 2**), lag das Ziel von **Studie 3** darin diese beiden Forschungsergebnisse und ihre Implikationen miteinander zu verbinden. Das Hauptziel dieses Experimentes war demnach das Erforschen der kausalen Rolle des linken IFG in der Satzverarbeitung, wenn diese von prosodischen Anhaltspunkten maßgeblich beeinflusst wird. Ein weiteres Ziel war es außerdem eine mögliche kausale Rolle verschiedener Subregionen des IFG bei der syntaktischen und semantischen Verarbeitung von prosodischen Informationen zu untersuchen. Dieses zweite Ziel des vorliegenden Experiments basiert dabei auf einem gut abgesicherten Ergebnis aus der Literatur zu Untersuchungen der Sprachverarbeitung mit funktioneller Bildgebung, der bekannten funktionellen Spezialisierung des anterioren IFG für semantische und des posterioren IFG für syntaktische Prozesse. Um diese Spezialisierung zu überprüfen, wurden örtlich und zeitlich beschränkte Störungen des Sprachverarbeitungssystems mittels wiederholter transkranieller Magnetstimulation (engl. *repetitive transcranial magnetic stimulation*; rTMS) hervorgerufen, um die kausale Rolle des posterioren IFG in der Verarbeitung von syntaktischen und des anterioren IFG in der Verarbeitung von semantischen Informationen zu festzustellen. Das hier verwendete experimentelle Paradigma entsprach dabei der Satzverständnisaufgabe aus **Studie 2**, in welcher die Teilnehmer in den verschiedenen Durchläufen des Experiments gezwungen sind syntaktische und semantische Entscheidungen zu treffen. Da in diesem Paradigma die Interpretation des Tonhöhenakzents in einem Satz ausschlaggebend für das erfolgreiche Bewältigen der Aufgabe war, war es dadurch gleichzeitig auch möglich die kausale Rolle des linken IFG bei der Satzverarbeitung, wenn wesentliche Informationen von prosodischen Anhaltspunkten markiert werden, zu untersuchen.

Demnach wurden den Probanden im Rahmen dieses Experimentes abgeschnittene gesprochene Sätze präsentiert, in denen ein Tonhöhenakzent einen Anhaltspunkt dafür bat, welches Artikelwort und Nomen (visuell präsentiert) das am besten passende Ende für den präsentierten Satz darstellen würde. Die Teilnehmer wählten das präferierte Ende per Knopfdruck aus. Das Versuchsdesign sah vor, dass jeder Teilnehmer insgesamt drei Sitzungen absolvierte, in denen 10-Hz-rTMS-Pulse jeweils entweder über dem anterioren oder posterioren IFG oder aber dem Hirnscheitelpunkt (als Kontrollregion) appliziert wurden. Die Ergebnisse zeigten, dass eine Störung der Sprachverarbeitung über dem posterioren IFG sowohl eine Zerrüttung syntaktischer als auch semantischer Prozesse zur Folge hatte, wohingegen die Stimulation über dem anterioren IFG kein eindeutiges Ergebnis mit sich brachte. Da sowohl die syntaktische als auch semantische Verarbeitung bei dieser Aufgabe vom Verständnis von grammatikalischen Rollen, die durch den Tonhöhenakzent markiert werden, erfordern, lassen die vorliegenden Ergebnisse darauf schließen, dass der posteriore IFG eine kausale Rolle in der Verarbeitung von ebendiesen durch prosodische Anhaltspunkte markierten grammatikalischen Rollen spielt.

Diskussion

Zusammengenommen unterstreichen die hier vorgelegten Studien generell die wesentliche Rolle von Prosodie bei der Verarbeitung von gesprochenen Sätzen und—im Detail—die zentrale Rolle des linken IFG als einen der wichtigsten Knotenpunkte des Sprachnetzwerks in ebendiesem Prozess. Die im Rahmen der vorliegenden Arbeit durchgeführten Experimente beschäftigten sich mit zwei unterschiedlichen Situationen, in denen prosodische Anhaltspunkte eine entscheidende Rolle beim Verständnis von Sätzen haben: Das Markieren der syntaktischen Struktur eines Satzes sowie das Erzeugen einer Erwartungshaltung im Bezug auf nachfolgende syntaktische und auch semantische Informationen in einem Satz. Die Ergebnisse zeigen, dass die Rolle von Prosodie vor allem bei mehrdeutigen Satzstrukturen am stärksten ist. Wenn sich aber die im Satz vorhandenen prosodischen und morphosyntaktischen Anhaltspunkte konterkarieren, dann werden morphosyntaktische Anhaltspunkte am stärksten gewichtet und vorrangig verarbeitet. Von zentraler Bedeutung ist hier, dass in Situationen wo prosodische Anhaltspunkte eine wesentliche Rolle für die Rekonstruktion der Struktur eines Satzes während der Satzverarbeitung spielen, die Aktivierung des linkem IFG (als eine für syntaktische Prozesse wesentliche Hirnregion) nicht nur beobachtbar, sondern auch kausal notwendig ist.

Innerhalb der linguistischen, psycholinguistischen und elektrophysiologischen Forschung wurde der Prosodie bereits seit längerem eine wichtige Rolle als Anhaltspunkt bei der Verarbeitung von Sätzen beigemessen. In funktionellen Studien mit bildgebenden Verfahren stellte die Untersuchung von prosodischen Phänomenen, insbesondere in ihrer wohl wichtigsten Rolle als Anhaltspunkte für die Rekonstruktion der syntaktischen Struktur eines gesprochenen Satzes, bislang eine besondere Herausforderung dar. Die hier vorgelegten Untersuchungen unterstreichen demnach die wissenschaftliche Notwendigkeit die Auswirkungen von Prosodie auf die Satzverarbeitung parallel zu ihren perzeptuellen Aspekten zu untersuchen. Zweifellos bedarf es sowohl der Untersuchung der perzeptuellen Aspekte von Prosodie, als auch der ihrer Auswirkung auf der Ebene der Satzverarbeitung, um ein vollständiges Bild des neuroanatomischen Netzwerks, welches der Verarbeitung von Prosodie und letztendlich der Verarbeitung von Sprache an sich, zu Grunde liegt.

Abschließend lässt sich somit folgern, dass die vorliegende Arbeit neue Einblicke in die Auswirkungen von Prosodie auf die Verarbeitung von Sätzen bietet.

Entscheidend ist dabei, dass in allen hier vorgelegten Untersuchungen das Verstehen von Sätzen nicht ohne die im Stimulusmaterial enthaltenen prosodischen Anhaltspunkte hätte erfolgen können, ohne dass die Probanden dabei auf eine standardmäßige Analyse der syntaktischen Struktur oder Informationsstruktur zurückgreifen. In beiden experimentellen Paradigmen deuten die Ergebnisse klar auf eine zentrale Rolle der linken unteren Stirnwindung, also den IFG hin—eine Hirnregion, die gemeinhin als ein wichtiger Knotenpunkt für die Verarbeitung von Sätzen gilt. Dies lässt darauf schließen, dass Prosodie einen wesentlichen Beitrag zur Verarbeitung von gesprochenen Sätzen leistet, welcher sich sowohl im Verhalten als auch auf neuronaler Ebene widerspiegelt.

List of abbreviations

abbreviation	**meaning**
ANOVA	Analysis Of Variance
ATL	Anterior Temporal Lobe
BA	Brodmann Area
BOLD	Blood Oxygen-Level Dependent
CPS	Closure Positive Shift
ECoG	Electrocorticography
EEG	Electroencephalography
ERP	Event-Related Potential
fMRI	Functional Magnetic Resonance Imaging
GLM	General Linear Model
GLMM	Generalised Linear Mixed Model
IFG	Inferior Frontal Gyrus
IPB	Intonational Phrase Boundary
MEG	Magnetoencephalography
MNI	Montreal Neurological Institute
MTG	Middle Temporal Gyrus
N400	Negative ERP component around 400ms
NMR	Nuclear Magnetic Resonance
P600	Positive ERP component around 600ms
rTMS	Repetitive Transcranial Magnetic Stimulation
SMA	Supplementary Motor Area
SMG	Supramarginal Gyrus
STG/S	Superior Temporal Gyrus/Sulcus
TMS	Transcranial Magnetic Stimulation

Appendices

Appendix A

Supplementary material to **Chapter 3** *Intonation guides sentence processing in the left inferior frontal gyrus*

Supplementary table 1 Reaction times. Pair-wise comparisons (Wilcoxon signed-rank tests) between reaction times in all experimental conditions. Table shows *z*-scores followed by the *p*-value per comparison. *P*-values smaller than 0.0033 (Bonferroni-corrected) are marked with an †. BL stands for baseline.

Condition B							
		ProsSyn1	ProsSyn2	Gram-Only	BL-Pros-Only	BL-Gram-Only	BL-Pros-NoChoice
Condition A	ProsSyn1						
	ProsSyn2	-0.597; 0.551					
	Gram-Only	-1.283; 0.200	-2.121; 0.034				
	BL-ProsOnly	-4.457; <0.001†	-4.457; <0.001†	-4.432; <0.001†			
	BL-GramOnly	-3.594; <0.001†	-3.060; 0.002†	-4.026; <0.001†	-4.432; <0.001†		
	BL-Pros-NoChoice	-4.203; <0.001†	-4.178; <0.001†	-4.203; <0.001†	-2.197; 0.028	-3.822; <0.001†	

Supplementary table 2 Accuracy rates. Pair-wise comparisons (Wilcoxon signed-rank tests) between accuracy rates in all experimental conditions. Table shows *Z*-scores followed by the *p*-value per comparison. *P*-values smaller than 0.0033 (Bonferroni-corrected) are marked with †. BL stands for baseline.

	Condition B						
Condition A		ProsSyn1	ProsSyn2	GramOnly	BL-ProsOnly	BL-GramOnly	BL-Pros-NoChoice
	ProsSyn1						
	ProsSyn2	-1.939; 0.053					
	GramOnly	-0.633; 0.527	-2.331; 0.020				
	BL-ProsOnly	-3.523; <0.001†	-2.578; 0.010	-3.526; <0.001†			
	BL-GramOnly	-3.023; 0.003†	-1.882; 0.259	-3.760; <0.001†	-1.882; 0.060		
	BL-Pros-NoChoice	-4.270; <0.001†	-3.816; <0.001†	-3.936; <0.001†	-2.024; 0.043	-2.908; 0.004	

Appendix B

Supplementary material to **Chapter 4** *Pitch accents create dissociable syntactic and semantic expectations during sentence processing*

Supplementary table 1: Analysis of log response times (Experiment 1). Results from linear mixed effects model including the fixed effects violation type (baseline, semantic, syntactic), focus position (subject, object) and comprehension question target (main clause, ellipsis). Random effects included intercepts for participants and items. Model formula: log(RT) ~ violation type * focus position * comprehension question target + (1 | subject) + (1 | verb)

fixed effect		*estimate*	*SE*	*t*
intercept		7.343	0.032	226.182
violBaseline		-0.012	0.006	-1.967
violSyntactic		0.016	0.006	2.527
probeEllipsis		-0.002	0.004	-0.377
focObject		0.008	0.004	1.881
violBaseline * probeEllipsis		0.002	0.006	0.314
violSyntactic * probeEllipsis		0.025	0.006	3.981
violBaseline * focObject		-0.013	0.006	-2.037
violSyntactic * focObject		-0.027	0.006	-4.269
probeEllipsis * focObject		-0.035	0.004	-7.961
violBaseline * probeEllipsis * focObject		0.010	0.006	1.643
violSyntactic * probeEllipsis * focObject		0.034	0.006	5.399
random effect			*variance*	*SD*
verb	intercept		0.001	0.034
subj	intercept		0.036	0.191
residual			0.067	0.259

Supplementary table 2: Analysis of response counts (Experiment 1). Results from generalized linear mixed effects model including the fixed effects violation type (baseline, semantic, syntactic), focus position (subject, object) and comprehension question target (main clause, ellipsis). Random effects included intercepts for participants and items, and by-participant slopes for the factor violation type. Model formula: accuracy ~ violation type * focus position * comprehension question target + (1 + violation type | subject) + (1 | verb)

fixed effect	*estimate*	*SE*	*z*	*p*
intercept	2.788	0.152	18.290	<.001
violBaseline	0.284	0.133	2.130	0.033
violSyntactic	-0.175	0.113	-1.543	0.123
focObject	-0.285	0.070	-4.061	<.001
probeEllipsis	0.447	0.070	6.348	<.001
violBaseline * focObject	0.269	0.104	2.594	0.009
violSyntactic * focObject	0.472	0.095	4.987	<.001
violBaseline * probeEllipsis	-0.369	0.104	-3.563	<.001
violSyntactic * probeEllipsis	-0.088	0.095	-0.934	0.350
focObject * probeEllipsis	0.277	0.070	3.937	<.001
violBaseline * focObject * probeEllipsis	0.032	0.104	0.306	0.759
violSyntactic * focobject * probeEllipsis	-0.436	0.095	-4.585	<.001

random effect			*variance*	*SD*
verb	intercept		0.031	0.177
subj	intercept		0.565	0.752
	violBaseline		0.090	0.300
	violSyntactic		0.018	0.135
	intercept	violBaseline	-0.057	-0.251
	intercept	violSyntactic	0.030	0.299
	violBaseline	violSyntactic	-0.021	-0.509

Supplementary table 3: Estimated marginal means contrasts for planned pair-wise comparisons between conditions (Experiment 1). bl = baseline; se = semantic; sy = syntactic. P-values are Bonferroni-Holm-corrected. Note that the high number of degrees of freedom is due to single-trial information on which the estimated marginal means are based.

REACTION TIMES

Comprehension question target	*focus position*	*contrast*	*estimate*	*SE*	*df*	*t*	*p*
main clause	subject	bl - se	-0.013	0.012	10225	-1.025	0.916
		se - sy	-0.048	0.012	10225	-3.820	0.001
		bl - sy	-0.060	0.012	10225	-4.847	<.001
	object	bl - se	-0.008	0.012	10225	-0.629	0.970
		se - sy	-0.034	0.012	10225	-2.689	0.036
		bl - sy	-0.041	0.012	10225	-3.318	0.006
ellipsis	subject	bl - se	-0.037	0.012	10225	-2.981	0.017
		se - sy	0.069	0.012	10225	5.564	<.001
		bl - sy	0.032	0.012	10225	2.583	0.039
	object	bl - se	0.009	0.012	10225	0.699	0.970
		se - sy	-0.051	0.012	10225	-4.103	<.001
		bl - sy	-0.043	0.012	10225	-3.406	0.005

ACCURACY

Comprehension question target	*focus position*	*contrast*	*estimate*	*SE*		*z*	*p*
main clause	subject	bl - se	0.215	0.251		0.855	1
		se - sy	0.227	0.224		1.015	1
		bl - sy	0.442	0.245		1.807	0.566
	object	bl - se	-0.386	0.227		-1.699	0.566
		se - sy	0.299	0.223		1.341	0.900
		bl - sy	-0.087	0.216		-0.402	1
ellipsis	subject	bl - se	0.889	0.176		5.065	<.001
		se - sy	-0.822	0.164		-5.005	<.001
		bl - sy	0.067	0.198		0.339	1
	object	bl - se	0.416	0.233		1.787	0.566
		se - sy	0.995	0.180		5.524	<.001
		bl - sy	1.411	0.212		6.643	<.001

Supplementary table 4: Analysis of log response times (Experiment 2). Results from linear mixed effects model including the fixed effects decision type (semantic, syntactic) and focus position (subject, object). Random effects included intercepts for participants and items, and by-participant and by-item slopes for the interaction decision type x focus position. Model formula: log(RT) = decision type * focus position + (1 + decision type + violation type | subject) + (1 | verb)

fixed effect	***estimate***	***SE***	***t***
intercept	6.861	0.036	190.693
decisionSyntactic	-0.131	0.016	-8.033
focusObject	-0.009	0.005	-1.829
decisionSyntactic * focusObject	0.018	0.004	4.607

random effect		***variance***	***SD***
verb	intercept	0.001	0.037
subj	intercept	0.045	0.212
	decisionSyntactic	0.009	0.095
	focusObject	0	0.015
	intercept, decisionSyntactic	0.005	0.246
	intercept, focusObject	-0.001	-0.410
	decisionSyntactic, focusObject	0	-0.327
residual		0.106	0.326

Supplementary table 5: Analysis of response counts (Experiment 2). Results from generalized linear mixed effects model including the fixed effects decision type (semantic, syntactic) and focus position (subject, object). Random effects included intercepts for participants and for items. Model formula: accuracy ~ decision type * focus position + (1 | subj) + (1 | verb)

fixed effect	***estimate***	***SE***	***z***	***p***
intercept	1.307	0.200	6.545	<.001
decisionSyntactic	0.030	0.030	1.029	0.303
focusObject	0.036	0.030	1.217	0.224
decisionSyntactic * focusObject	-0.187	0.030	-6.326	<.001

random effect		***variance***	***SD***
verb	intercept	0.012	0.108
subject	intercept	1.376	1.173

Supplementary table 6: Estimated marginal means contrasts for planned pair-wise comparisons between conditions (Experiment 2). Correction: Bonferroni-Holm method for comparing a family of 4 estimates.

REACTION TIMES

contrast	***estimate***	***SE***	***df***	***t***	***p***
syntactic,subject - semantic,subject	-0.226	0.034	41.438	-6.643	<.001
syntactic,object - semantic,object	-0.299	0.034	41.446	-8.770	<.001
syntactic,subject - syntactic,object	0.019	0.012	107.978	1.561	0.121
semantic,subject - semantic,object	-0.053	0.012	108.546	-4.329	<.001

ACCURACY

contrast	***estimate***	***SE***	***z***	***p***
syntactic,subject - semantic,subject	-0.313	0.084	-3.735	<.001
syntactic,object - semantic,object	0.435	0.083	5.223	<.001
syntactic,subject - syntactic,object	-0.302	0.084	-3.607	<.001
semantic,subject - semantic,object	0.446	0.083	5.351	<.001

Appendix C

Stimulus list **Chapter 3**: *Intonation guides sentence processing in the left inferior frontal gyrus*. The stimuli of condition ProsOnly1 are listed. The intonational phrase boundary in each sentence is indicated with #.

	Stimulus sentence
1	Peter befiehlt Jost # dafür zu bezahlen
2	Martin befiehlt Jost # danach zu fragen
3	Martin befiehlt Jost # darüber zu informieren
4	Rudolf befiehlt Jost # davor zu warnen
5	Franz bestätigt Erik # dafür zu bezahlen
6	Klaus bestätigt Erik # danach zu fragen
7	Klaus bestätigt Erik # darüber zu informieren
8	Hans bestätigt Erik # davor zu warnen
9	Stephan droht Gerd # danach zu fragen
10	Dieter droht Gerd # darüber zu informieren
11	Jürgen droht Gerd # davor zu warnen
12	Peter empfiehlt Falk # dafür zu bezahlen
13	Rudolf empfiehlt Falk # danach zu fragen
14	Rudolf empfiehlt Falk # darüber zu informieren
15	Dieter empfiehlt Falk # davor zu warnen
16	Peter erlaubt Mark # dafür zu bezahlen
17	Rudolf erlaubt Mark # danach zu fragen
18	Rudolf erlaubt Mark # darüber zu informieren
19	Stephan erlaubt Mark # davor zu warnen
20	Thomas rät Kurt # dafür zu bezahlen
21	Martin rät Kurt # danach zu fragen
22	Martin rät Kurt # darüber zu informieren
23	Jürgen rät Kurt # davor zu warnen
24	Thomas schwört Dirk # dafür zu bezahlen
25	Rudolf schwört Dirk # danach zu fragen
26	Rudolf schwört Dirk # darüber zu informieren
27	Martin schwört Dirk # davor zu warnen
28	Franz versichert Rupert # dafür zu bezahlen
29	Franz versichert Rupert # danach zu fragen
30	Klaus versichert Rupert # darüber zu informieren
31	Hans versichert Rupert # davor zu warnen
32	Thomas verspricht Nick # dafür zu bezahlen
33	Dieter verspricht Nick # danach zu fragen
34	Dieter verspricht Nick # darüber zu informieren
35	Martin verspricht Nick # davor zu warnen

36	Dieter bittet Manfred # darauf zu antworten
37	Dieter bittet Manfred # darüber zu berichten
38	Hans bittet Manfred # dafür zu danken
39	Hans bittet Manfred # dabei zu helfen
40	Martin drängt Arnd # darauf zu antworten
41	Martin drängt Arnd # darüber zu berichten
42	Peter drängt Arnd # dafür zu danken
43	Rudolf drängt Arnd # dabei zu helfen
44	Thomas mahnt Bernd # darauf zu antworten
45	Thomas mahnt Bernd # darüber zu berichten
46	Peter mahnt Bernd # dafür zu danken
47	Klaus veranlasst Hartmut # darauf zu antworten
48	Klaus veranlasst Hartmut # darüber zu berichten
49	Franz veranlasst Hartmut # dafür zu danken
50	Franz veranlasst Hartmut # dabei zu helfen

Appendix D

Stimulus list **Chapter 4**: *Pitch accents create dissociable syntactic and semantic expectations during sentence processing*

	Verb	Agent 1	Agent 2	Patient 1	Patient 2	Agent$^{\text{FEM}}$	Patient$^{\text{FEM}}$
1	verhaftet	Polizist	Kommissar	Dieb	Mörder	Kommissarin	Mörderin
2	gefeuert	Manager	Chef	Sekretär	Hausmeister	Chefin	Hausmeisterin
3	gefilmt	Kameramann	Reporter	Politiker	Star	Reporterin	Diva
4	eingestellt	Manager	Chef	Mitarbeiter	Volontär	Chefin	Volontärin
5	trainiert	Besitzer	Trainer	Hund	Hengst	Trainerin	Stute
6	angeleitet	Meister	Betriebsleiter	Azubi	Schüler	Betriebsleiterin	Schülerin
7	ausgeraubt	Gauner	Rüpel	Fußgänger	Urlauber	Diebin	Urlauberin
8	gegessen	Fisch	Vogel	Wurm	Käfer	Katze	Ameise
9	getadelt	Lehrer	Schulleiter	Schüler	Referendar	Schulleiterin	Referendarin
10	verhaftet	Polizist	Offizier	Bürger	Gauner	Offizierin	Gaunerin
11	gejagt	Kater	Hund	Hamster	Vogel	Hündin	Maus
12	durchsucht	Polizist	Wärter	Dieb	Landstreicher	Wärterin	Landstreicherin
13	gefangen	Fischer	Urlauber	Fisch	Krebs	Urlauberin	Muschel
14	gefüttert	Besitzer	Besucher	Kater	Hund	Besucherin	Hündin
15	beraten	Professor	Tutor	Prüfling	Bewerber	Tutorin	Bewerberin
16	gesegnet	Priester	Papst	Schüler	Büßer	Nonne	Büßerin
17	porträtiert	Fotograf	Maler	Herzog	König	Malerin	Königin
18	eingekleidet	Schneider	Designer	Kaiser	König	Designerin	Königin
19	gebissen	Hund	Kater	Bäcker	Metzger	Katze	Metzgerin
20	gerissen	Bär	Wolf	Hahn	Bock	Tigerin	Ziege
21	gewaschen	Angehörige	Pfleger	Rentner	Pflegefall	Pflegerin	Kranke
22	erschreckt	Geist	Vampir	Diener	Bewohner	Vampirin	Bewohnerin
23	interviewt	Reporter	Redakteur	Politiker	Schauspieler	Redakteurin	Schauspielerin
24	behandelt	Arzt	Pfleger	Rentner	Schüler	Pflegerin	Schülerin
25	getestet	Prüfer	Ausschuss	Bewerber	Mitarbeiter	Managerin	Mitarbeiterin
26	angebettelt	Landstreicher	Bettler	Verkäufer	Bewohner	Bettlerin	Bewohnerin

27	bedient	Kellner	Koch	Gast	Kritiker	Köchin	Kritikerin
28	belehrt	Chef	Manager	Neuling	Azubi	Managerin	Azubine
29	gezeichnet	Grafiker	Maler	Sänger	Schauspieler	Malerin	Schauspielerin
30	verfolgt	Fan	Stalker	Schauspieler	Fußballer	Stalkerin	Fußballerin
31	Ausgezeichnet	Präsident	König	Wissenschaftler	Künstler	Königin	Künstlerin
32	gesegnet	Mönch	Priester	Sünder	Bettler	Priesterin	Bettlerin
33	gefressen	Löwe	Tiger	Fisch	Vogel	Tigerin	Maus
34	geführt	Bergführer	Reiseleiter	Urlauber	Forscher	Reiseleiterin	Forscherin
35	gejagt	Polizist	Detektiv	Dieb	Mörder	Detektivin	Mörderin
36	unterdrückt	König	Kaiser	Diener	Wirt	Kaiserin	Wirtin
37	beaufsichtigt	Wächter	Bewährungshelfer	Häftling	Besucher	Bewährungshelferin	Besucherin
38	gerettet	Feuerwehrmann	Sanitäter	Bergsteiger	Skifahrer	Sanitäterin	Skifahrerin
39	geprüft	Professor	Betreuer	Lehrling	Bewerber	Betreuerin	Bewerberin
40	beraten	Experte	Verkäufer	Auftraggeber	Käufer	Verkäuferin	Käuferin
41	belustigt	Komiker	Clown	Zuschauer	Teilnehmer	Clownin	Teilnehmerin
42	instruiert	Coach	Chef	Anfänger	Facharbeiter	Chefin	Facharbeiterin
43	angehalten	Polizist	Tramper	Autofahrer	Motorradfahrer	Tramperin	Motorradfahrerin
44	vorgestellt	Moderator	Quizmaster	Teilnehmer	Zuschauer	Quizmasterin	Zuschauerin
45	verurteilt	Richter	Diktator	Verbrecher	Bürger	Diktatorin	Bürgerin
46	gespielt	Schauspieler	Amateur	Bösewicht	Retter	Amateurin	Retterin
47	benotet	Lehrer	Direktor	Erstklässler	Schulabgänger	Direktorin	Schulabgängerin
48	eingeholt	Autofahrer	Reiter	Fußgänger	Rollstuhlfahrer	Reiterin	Rollstuhlfahrerin

Appendix E

Stimulus list **Chapter 5** *Disruption of the left inferior frontal gyrus impairs grammatical processing guided by prosodic cues*

	Verb	Agent 1	Agent 2	Patient 1	Patient 2	Agent$^{\text{FEM}}$	Patient$^{\text{FEM}}$
1	angeschossen	Jäger	Förster	Hirsch	Wolf	Försterin	Rehe
2	verhaftet	Polizist	Kommissar	Dieb	Mörder	Kommissarin	Mörderin
3	gesattelt	Reiter	Jockey	Schimmel	Gaul	Tierpflegerin	Stute
4	geschlachtet	Schlachter	Fleischer	Stier	Eber	Fleischerin	Kuh
5	eingewechselt	Trainer	Coach	Torwart	Stürmer	Coachin	Stürmerin
6	geimpft	Tierarzt	Besitzer	Hund	Kater	Besitzerin	Katze
7	gefüttert	Besitzer	Besucher	Kater	Hund	Besucherin	Hündin
8	gefahren	Chauffeur	Kutscher	Scheich	Sultan	Kutscherin	Prinzessin
9	geschoren	Bauer	Scherer	Hammel	Bock	Schererin	Ziege
10	gepflegt	Helfer	Pfleger	Rentner	Opa	Pflegerin	Oma
11	gebändigt	Wärter	Dompteur	Puma	Tiger	Dompteurin	Tigerin
12	trainiert	Besitzer	Trainer	Hund	Hengst	Trainerin	Stute
13	angehalten	Polizist	Tramper	Fahrer	Trucker	Tramperin	Truckerin
14	gerissen	Bär	Wolf	Hahn	Bock	Löwin	Henne
15	angebettelt	Landstreicher	Bettler	Verkäufer	Bewohner	Bettlerin	Bewohnerin
16	verbannt	König	Kaiser	Mörder	Dieb	Kaiserin	Diebin
17	eingekleidet	Designer	Schneider	Popstar	Rockstar	Schneiderin	Sängerin
18	gefangen	Fischer	Urlauber	Fisch	Krebs	Urlauberin	Krabbe
19	porträtiert	Fotograf	Maler	Herzog	König	Malerin	Königin
20	bedient2	Kellner	Koch	Kritiker	Gast	Köchin	Gästin
21	gebissen	Hund	Kater	Bäcker	Metzger	Katze	Metzgerin
22	gefressen1	Löwe	Tiger	Fisch	Vogel	Tigerin	Maus
23	geheilt	Therapeut	Psychiater	Trinker	Spieler	Psychiaterin	Spielerin
24	bewertet	Juror	Kritiker	Tänzer	Akteur	Kritikerin	Akteurin
25	gefilmt	Kameramann	Reporter	Politiker	Star	Reporterin	Sportlerin
26	unterwiesen	Fachmann	Profi	Stümper	Neuling	Meisterin	Anfängerin

27	gesegnet	Priester	Papst	Schüler	Büßer	Nonne	Büßerin
28	instruiert	Coach	Chef	Anfänger	Azubi	Chefin	Azubine
29	beschlagen	Bursche	Schmied	Hengst	Esel	Schmiedin	Eselin
30	gefasst	Polizist	Gendarm	Räuber	Gauner	Gendarmin	Gaunerin
31	ausgezeichnet	Präsident	König	Forscher	Künstler	Königin	Künstlerin
32	ausgeraubt	Gauner	Rüpel	Fußgänger	Urlauber	Diebin	Urlauberin
33	karikiert	Witzbold	Komiker	Minister	Kanzler	Komikerin	Kanzlerin
34	erforscht	Forscher	Angler	Stör	Hecht	Anglerin	Forelle
35	gewählt	Arbeiter	Rentner	Minister	Senator	Rentnerin	Senatorin
36	geprüft1	Prüfer	Tutor	Schüler	Bewerber	Tutorin	Bewerberin
37	getraut	Priester	Pfarrer	Freund	Schuster	Pfarrerin	Schusterin
38	bejubelt2	Groupie	Fan	Trommler	Star	Anhängerin	Sängerin
39	abgehorcht	Spitzel	Spion	Staatsmann	Kanzler	Spionin	Kanzlerin
40	entlarvt	Ermittler	Detektiv	Lügner	Blender	Detektivin	Betrügerin
41	verfolgt1	Fan	Stalker	Schauspieler	Musiker	Stalkerin	Musikerin
42	beliefert	Brauer	Metzger	Gastwirt	Gastronom	Metzgerin	Gastronomin
43	gegessen	Fisch	Vogel	Wurm	Käfer	Henne	Ameise
44	getauft	Mönch	Priester	Sünder	Bettler	Ärztin	Bettlerin
45	beaufsichtigt	Wärter	Pförtner	Häftling	Besucher	Pförtnerin	Besucherin
46	gejagt	Kater	Hund	Hamster	Vogel	Hündin	Maus
47	gerufen	Hirte	Schäfer	Bock	Hund	Schäferin	Hündin
48	belehrt	Chef	Manager	Neuling	Azubi	Managerin	Azubine

Selbständigkeitserklärung

Hiermit versichere ich, Constantijn Laurens van der Burght, geboren am 2. November 1990 in Rotterdam,

1. dass die vorliegende Arbeit ohne unzulässige Hilfe und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt wurde und dass die aus fremden Quellen direkt oder indirekt übernommenen Gedanken in der Arbeit als solche kenntlich gemacht worden sind;
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Constantijn Laurens van der Burght

Leipzig, 24. Juli 2020

Curriculum Vitae

Constantijn Laurens van der Burght

2 November 1990

Rotterdam

Academic Education

2013 - 2014	MSc Clinical neuroscience University College London, London, United Kingdom
2010 - 2013	BSc Liberal Arts and Sciences *Cognitive neuroscience, Human and animal physiology, Linguistics* University College Utrecht, Utrecht, Netherlands

Career

2015 – *present*	PhD Student Department of Neuropsychology, Lise Meitner Research Group “Cognition and Plasticity” Max Plank Institute for Human Cognitive and Brain Sciences Leipzig, Germany *supervision: Prof. Dr. Angela D Friederici, Dr. Gesa Hartwigsen*
2014	Research intern Sobell Institute for Motor Neuroscience and Movement Disorders, Institute of Neurology, University College London London, United Kingdom *supervision: Prof. Dr. John C Rothwell, Dr. Ricci Hannah*
2013	Research intern Department of Neuroscience, Erasmus MC Rotterdam, Netherlands *supervision: Prof. Dr. Chris I de Zeeuw*
2012	Research intern Experimental Psychology, Helmholz Institute, Utrecht University Utrecht, Netherlands *supervision: Prof. Dr. Leon J Kenemans*

List of publications

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Acknowledgements

Firstly, I would like to express my gratitude to Prof. Angela Friederici for having taken me on as a PhD student. Your support in giving the time and space for carrying out these studies has been truly generous. The meetings in your office (which admittedly never cease to be slightly nerve-wracking to prepare) have always been very enjoyable. It has been a great pleasure to witness your outstanding and seemingly effortless command of the literature, as well as the many wonderful anecdotes from your scientific career.

Großen Dank geht an Gesa Hartwigsen, die mich während dieser Jahre betreut hat. Gesa, die Tür deines Büros stand immer offen, auch als sich deine Gruppe im Laufe der Zeit stark ausgebreitet hat. Weiterhin warst du gefühlt Tag und Nacht bereit, um Feedback oder einen Ratschlag zu geben. Wie du immer einen Weg vorwärts oder eine pragmatische Lösung findest, bewundere ich sehr. Zum Schluss habe ich mit dir Fragen, Ergebnisse, und Probleme immer mit viel Freude diskutiert. Danke vielmals für die wunderbare Betreuung.

Tomás, this thesis is in many ways shaped by your scientific approach. You have taken me along as cognitive neuroscience and language research tutee with great patience and pizzazz. Although your "final" push for an explanation, justification, or improvement may at times have felt frustrating, it has always been fair and, ultimately, rewarding. I have enjoyed our collaboration immensely. Thank you.

Discussions with and help from senior colleagues: many thanks to Alfred Anwander, Thom Gunter (voor de gezelligheid en behulpzaamheid bij het bespreken van experimenten én voor de lekkere koffie), Maren Grigutsch, Jens Kreitewolf (thank you for holding my hand while MATLABing during the very early days), Claudia Männel, Lars Meyer, Karsten Müller, Nicole Neef, and, my prosody mentor, Daniela Sammler.

Brilliant students and postdocs I am lucky to have been surrounded with: thank you, Anna, Astrid, Caro, Charlotte, Curtiss, Jana (du hast meine R- und Mixed Models-Entwicklung gekickstRtet, wofür mein ewiger Dank), Leon, Ole, Philipp Kuhnke, and Vincent (I value your expertise in sonatas, symphonies, and statistics in equal measures).

Lieben Dank für die Unterstützung bei Messungen und Herstellung der Stimuli geht an Isabel Gebhardt, Lisa Kunz, Rebekka Luckner, Laura Nieberlein, Lisa Reimund, Dana Richter, Carolin Wipfler, und besonders Benito Schlaak.

Durch eine unermüdliche Unterstützung vieler MTAs wird Messungen durchführen am MPI einem so leicht wie möglich gemacht. Dafür möchte ich mich bei Ulrike Barth, Conny Henschel, Mandy Jochemko, Ina Koch, Anke Kummer, und vor allem Heike Boethel, herzlich bedanken.

Auch das Grafikteam stand immer zur Verfügung, um bei kleinen sowie größeren Aufgaben Unterstützung zu bieten. Vielen Dank an Kerstin Flake, Andrea Gast-Sandmann, Stephan Liebig, und Heike Schmidt-Duderstedt.

Liebe Margund und Melanie, danke schön für die liebevolle Unterstützung während der vergangenen Jahre.

My tireless proofreaders: Thom Gunther, Samuel, Patrick (und vielen lieben Dank für die deutsche Zusammenfassung), and Ser.

Friends at the MPI, who have made going to "work" over the past years almost suspiciously enjoyable: Clara (*Team*), Giorgio, Jana, Matteo, Patrick, and Philipp Paulus.

Here, Tomás, you must be featured another time. Thank you for the social avenues you've travelled with me over the years. Zusammen mit dir, Charlotte—*die Dame*, and with you, Helyne—*sailor*. Es war traumhaft mit euch, and Leipzig has been home because of you.

Emiliano, amico mio. Sempre per sempre.

To Rosemary Orr, who planted the seed of my fondness for linguistics. Rosemary is in my memory as the most wonderful teacher there ever was.

Mijn thuisfront: Marijke, Jeroen, Caramay, Michiel, Samuel & Maria. Een scriptie bestaat niet als het wel en wee van de scriptie—en alles daarbuiten—niet gedeeld kan worden. Dank jullie wel.

Mevrouw Mastero en Alexandra: de verbinding tussen taal en de hersenen is voor u misschien net iets anders vormgegeven dan voor mij. Echter, de enige verbinding die er eigenlijk toe doet, die van muziek, heeft u mij laten zien. Stan is Stan mede door u, en daarmee ook dit proefschrift.

Ser & Tintin. Ja met mij. Zonder wat gebliep tussendoor was het niet gegaan. Hoe een mens een PhD kan doen, zonder een broer die tegelijkertijd hetzelfde doet—ik heb geen flauw idee. Ik ga jullie dan wel niet achterna naar Cambridge, maar dat geeft niet, want gevoeld zijn jullie altijd om de hoek.

Lieve pappa en mamma, jullie hebben me hier gebracht. Na een leven lang halen en brengen naar toneel, piano, en wat voor nieuwe stad of land dan ook, hebben jullie me tot en met een PhD in de watten gelegd. Met de vanzelfsprekendheid waarmee jullie altijd klaar staan, hebben jullie me misschien nog wel het meest verwend. Dank jullie wal.