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Rhythmic parsing

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Abstract: A controlled reading experiment reveals that stress-based linguistic rhythm impinges on syntactic ambiguity resolution in silent and oral reading. The results suggest that, at points of syntactic underspecification, the accruing prosodic representation may affect even the earliest stages of structure building, viz. the analysis of syntactic features of an ambiguous word. Such an effect remains inexplicable in the context of (psycho-)linguistic theories that assume a strictly unidirectional relationship between syntactic and phonological processes, the latter merely interpreting the conditions the syntactic component imposes on it. Here, a performance compatible grammar in the framework of Optimal Parsing is presented that is capable of capturing the reading data. The model integrates syntactic parsing and prosodification in reading and predicts that, at points of syntactic indetermination, weak prosodic constraints alone may guide syntactic structure assignment. This suggests a bidirectional relationship between syntax and phonology in grammar and processing while, at the same time, confirming a tight coupling of language production and comprehension.

Keywords: sentence processing, Optimality Theory, implicit prosody, syntax-phonology interface, linguistic rhythm

1 Introduction

Readers generate from the graphemic string an intrinsic auditory version of the text entailing rich prosodic structure. Various reading studies have revealed that the silent prosodic rendition, called “implicit prosody,” may affect the syntactic analysis of written text. Several studies on “implicit prosody” suggest that readers’ preferences concerning the prosodic representation compete with preferences with respect to the syntactic analysis. Prosodic preferences may be particularly forceful when there are no strong syntactic preferences. As an example, Fodor (1998) argues that the preference for roughly equal-sized prosodic phrases affects readers’ attachment decisions in ambiguous environments like (1). In order to achieve a balanced output, a prosodic phrase boundary

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would separate *teacher's* and *mother* in (1-a) while, in (1-b), the genitive NP and the head noun are phrased together. Via syntax-prosody mapping constraints, this difference in prosodic phrasing impinges on the syntactic interpretation, with the adjective attaching to the genitive NP in (1-a) but attaching to the NP_{Gen}-NP complex in (1-b).

(1) a. (the cheerful teacher's) (mother-in-law)
b. (the very cheerful) (teacher's mother)

However, the role of implicit prosody has been described as paradoxical (Fodor, 2002): on the one hand, it is assumed that prosody is shaped according to the syntactic structure assigned to the word string, suggesting that the syntactic analysis predetermines much of the prosodic representation; on the other hand, experimental evidence attests a clear influence of "implicit prosody" on the syntactic analysis proper. Research on implicit prosody has therefore concentrated on the question concerning at what stage of the syntactic analysis phonological factors constrain the parse. Clearly, the balance principle responsible for the attachment preferences in (1) may only apply once all relevant words are in the parser's processing window. Correspondingly, Bader (1998) suggests a late influence of the prosodification on the syntactic analysis in reading. In his *Prosodic Constraint on Reanalysis*, it is proposed that prosodic factors add to the burden of syntactic reanalysis during sentence processing when the revised syntactic structure necessitates prosodic adjustments, too. Similarly, Augurzky (2006) claims that readers leave the prosodic rendition of the sentence underspecified during the initial processing stage, relying on purely syntactic cues. Only later are the syntactic parse and the prosodic rendition integrated. Hirose (2003) and Hwang and Steinhauer (2011) suggest that already during first pass parsing, syntactic analysis and prosodic representation are integrated, advocating early interaction of these domains in processing. Their experiments concern prosodic balance with respect to syntactic attachment preferences for long versus short phrases. It has to be noted, though, that the evaluation of phrase length by the parser requires the syntactic formation of these phrases in the first place. In this respect, the prosodification is dependent on at least limited syntactic pre-processing in these studies.

In the following section (Section 2), we review experimental evidence that challenges the idea that readers build prosodic structure only on the basis of syntactic pre-processing. Conversely, the experiments suggest that, at points of syntactic underspecification, phonological constraints alone may guide syntactic structure assignment in reading. Beyond its psycholinguistic importance, such evidence has repercussions for the architecture of the competence grammar that the parser consults during processing. We argue that the grammar has to be devised in such a way as to allow phonological influence on syntactic structure assignment. On the basis of the empirical evidence, we propose and advocate a parsing model which makes explicit reference to an optimality theoretic competence grammar integrating constraints from the domains of syntax, phonology and the corresponding interface (Section 3). We compare this competence-based model to other parsing models in Section 4. The paper ends with a conclusion in Section 5.

2 Experiment

Germanic languages have a general preference for the alternation of strong and weak syllables (e. g. Hayes, 1995; Liberman and Prince, 1977; Selkirk, 1984). It has been shown that a clash of two stressed syllables is avoided whenever more rhythmic alternatives are available. Faced with a potential stress clash, speakers might resort to stress shift (Bohn et al., 2011; Kiparsky, 1966; Visch, 1999) or they might choose a word order that prevents stress clash in the first place (Anttila et al., 2010; Ingason, 2015; Schlüter, 2005; Shih et al., 2015). If, in silent reading, readers indeed generate a speech-like prosodic representation of the text, as proposed in Ashby and Martin (2008), clash avoidance should also hold in the written modality. That is, stress clash avoidance should have consequences for the syntactic processing of the written string: in the face of an ambiguous structure that involves a stress clash in one reading but not in the other, there should be a preference for the version without stress clash. This hypothesis has recently been confirmed in two reading experiments (Kentner, 2012), which we summarize briefly.[1]

The object of investigation was temporarily ambiguous structures, with two possible interpretations of the word *mehr* and specific prosodic representations for each of the syntactic interpretations (2). The word *mehr* is either the unaccented part of the temporal adverbial *nicht mehr* (Engl.: “no longer”) (TEMP) or the obligatorily accented, comparative quantifier (Engl.: “more”) (COMP). In order to test the rhythmic influence on syntactic parsing, the prosodically ambiguous word *mehr* was followed by a tri-syllabic verb with either initial (INI) or medial (MED) stress, yielding four experimental conditions. The sentences are disambiguated in the phrase that ends the sentence. In the TEMP-conditions, the disambiguating material is an extraposed sentential complement of the verb, introduced by a complementizer or wh-pronoun.

1 For a detailed depiction of the results, the reader is referred to Kentner (2012). Comparable effects of linguistic rhythm on sentence comprehension in reading have since been reported by McCurdy et al. (2013), Kentner (2015), and Kentner and Vasishth (2016).

The COMP-conditions are invariably disambiguated by the *als*-phrase, serving as the standard of comparison (i. e. the argument to the comparative *mehr*).

(2) Der Polizist sagte, dass man...
The policeman said that one ...
a. ... NICHT mehr NACHweisen kann, wer der Täter war. TEMP-INI
... *couldn't prove anymore who the culprit was.*
a. NICHT mehr erMITteln kann, wer der Täter war. TEMP-MED
... *couldn't determine anymore who the culprit was.*
c. ... nicht MEHR nachweisen kann, als die Tatzeit. COMP-INI
... *couldn't prove more than the date of the crime.*
d. ... nicht MEHR ermitteln kann, als die Tatzeit. COMP-MED
... *couldn't determine more than the date of the crime.*

In the case of the temporal adverbial *nicht mehr* (TEMP), the two graphemic words form a single lexical item since the meaning cannot be decomposed any further. Lexical stress (marked by single underlines) falls on *nicht*, and *mehr* remains unstressed. Correspondingly, the phrasal accent (marked by small caps) assigned to the adverb falls onto the stressed *nicht*. In adverb–verb sequences, the verb bears the main or nuclear accent (marked by small caps and double underlines) (Truckenbrodt, 2006). As for the COMP-conditions, *mehr* receives main phrase accent as it serves as a (comparative) complement to the verb; the verb itself may remain unaccented (Truckenbrodt, 2006).

Comparative, and thus accented, *mehr* followed by initial stress on the verb engenders a stress clash (COMP-INI). It was hypothesized that, without disambiguating information, readers should initially favor the unaccented, temporal interpretation of *mehr* in order to avoid the stress clash. Hence, in the clash-condition, readers should be forced to reanalyze when encountering the disambiguating region (the phrase at the end of the sentence) and thus experience increased processing demand.

First, an oral reading experiment (unprepared reading) was set up with 24 sets of sentences like (2). Twenty-four participants were asked to read single sentences from a screen without preparation. In order to prevent look-ahead to the disambiguating material at the end of the sentence, readers were asked to start reading out loud as soon as the sentence was displayed on screen. The accentuation patterns were evaluated by two student assistants, who were presented the sound files up to the verb. Their judgments confirmed the hypothesis that readers, as long as they were unaware of the disambiguating information, avoided accentuation of *mehr* when it was followed by a verb with initial stress. Specifically, readers accented 28 % of *mehr* that were followed by a verb with medial stress but significantly fewer cases of *mehr* (19 %) when a verb with initial stress followed. These numbers also reveal a strong general preference for the unaccented version of *mehr*.

Further analysis demonstrated that readers significantly slowed down in speech at the disambiguating region (i. e. in the phrase after the verb complex) when their accentuation of *mehr* turned out to be inappropriate relative to the disambiguating information. This slowdown is indicative of a garden path effect, suggesting that the readers' decision for accentuation of *mehr* involved a syntactic commitment to the relevant reading.

In a second experiment, 48 participants read the same set of sentences silently on screen with an eye-tracking device monitoring the fixation patterns. The evaluation of the eye-movement record in the disambiguating region attests significantly higher reading costs for the COMP- conditions. Arguably, the difficulties associated with the COMP-conditions reflect the general preference for the unaccented, temporal version of *mehr* that was observed in the oral reading experiment. On top of this main effect, the experiment yielded a significant interaction: reading times were significantly increased in the stress clash condition COMP-INI as compared to the other, rhythmically innocuous conditions (see Figure 1).

The results are interpreted with recourse to the preference for rhythmic alternation, which apparently prevails even in silent reading. That is, the general preference for the unaccented, temporal-adverbial reading is reinforced by the rhythmic environment in the COMP-INI condition. In order to avoid a potential stress clash, readers avoid an "implicit" accent on *mehr* and, correspondingly, follow the generally preferred temporal-adverbial reading. The temporal-adverbial reading, however, is incompatible with the disambiguating information, which causes the observed reading difficulties in the COMP-INI condition. Since, in the COMP-MED condition, there is no danger of stress clash, the preference for the temporal-adverbial reading is significantly weaker. The results support the claim that the direct rhythmic environment, i. e. the lexical stress on the verb, affects the earliest stage of syntactic processing, viz. the determination of the syntactic category of the preceding ambiguous item *mehr*.

2.1 Discussion

The processing data on the *nicht mehr* ambiguity present a challenge for standard sentence processing models. The evidence suggests that prosodic planning, and more specifically the avoidance of stress clash, makes readers systematically leave a potentially accentable word (implicitly or explicitly) unaccented when adjacent syllables in neighboring words already require prosodic prominence. It was further shown that leaving the (syntactically and prosodically)

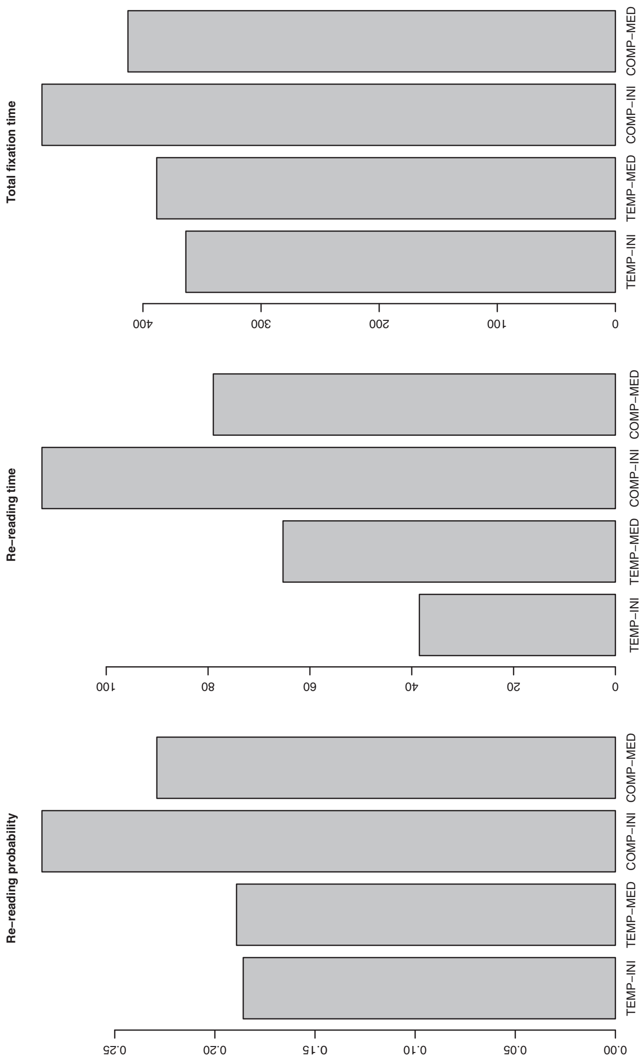


Figure 1: Re-reading probability, re-reading time and total fixation time within the disambiguating region broken down by condition. The highest reading times and fixation probabilities were obtained for the stress clash condition COMP-INI.

ambiguous word unaccented has consequences for the parsing process. If disambiguating material later in the sentence requires an accent on the preceding ambiguous word, various measures of reading behavior point to processing difficulties, indicating that the syntactic analysis is directly conditioned by the prosodic rendition of the sentence in reading.

The prosodic effect on syntactic structure building seems to be immediate in the sense that it affects the earliest imaginable stage of syntactic analysis, namely the retrieval of the word's lexical-syntactic category. This state of affairs is incompatible with strictly feed-forward or unidirectional models of sentence processing and reading, in which prosodification is thought to occur only on the basis of the syntactic analysis (Kondo and Mazuka, 1996; Koriat et al., 2002; Wheeldon, 2000).

The findings also trigger questions about the architecture of the grammar that the processing mechanism consults. Since "a performance model must certainly incorporate a grammar" (Chomsky, 1965: 141), the grammar should be devised in such a way that it can be incorporated into a performance model. Correspondingly, a grammar that offers "operational plausibility" (Lamb, 1998) should a priori be favored over one that draws hard boundaries between linguistic knowledge and its application in performance (Jackendoff, 2003; Sag and Wasow, 2011).

In the following, I will outline a model of language competence that allows at least limited interaction of syntax and phonology and, at the same time, is capable of reproducing the principal results of the above reading experiments as an incremental parsing process. This model is, in effect, an optimality theoretic grammar (Prince and Smolensky, 1993, 2004) that is applied to sentence processing.

3 Integrating comprehension and production in an Optimal Parsing account

Optimality Theory (OT) as a theory of grammar was originally designed to explain the relation between assumed underlying structures (INPUT) and surface structures (OUTPUT) in phonology. Input and output can be construed in various ways, however, depending on the nature of the task the grammar is used for.

Crucially, the same grammar can be applied to all kinds of linguistic performance. The grammar is independent of input and output modality but it is central to both. For example, in OT accounts that deal with language comprehension, the input is understood as the phonetic signal the listener is exposed to and the output is the mental representation he builds or accesses on the basis of the signal (e. g. Smolensky, 1996; Beaver and Lee, 2004). Similarly, OT can be applied to reading. In reading, the written string of lexical items can be construed as input and the output might be a syntactic description assigned to the string or the phonological representation thereof, which could be used for oral reading.

The OT grammar is thus a device that interprets (in the case of syntactic structure assignment) and generates (in the case of phonologization) linguistic objects; it is parser and synthesizer at the same time.

The principle of constraint violability, which is central to OT, implies that the *degree* of adherence to the grammar can be evaluated for complete sentences as well as for partial, uncompleted, even ungrammatical candidate structures. This is a most desirable feature for any system of linguistic competence that aspires to have explanatory power for language performance. After all, being engaged in sentence comprehension or production means dealing with partial and imperfect linguistic objects at least as long as the sentence being processed is unfinished, arguably most of the time.

OT has the capability to build outputs for incremental input. It has been applied to sentence parsing and proven to have the capacity to model a wide range of sentence processing phenomena (Fanselow et al., 1999; Hoeks and Hendriks, 2011; Stevenson and Smolensky, 2006). The rationale is simple: scanning the input incrementally from left to right (or in chronological order, in the case of auditory language comprehension), for any given piece of input, the OT parser would favor the analysis that best satisfies the constraint hierarchy.

Processing difficulty arises when high ranking constraints become relevant with additional input and force the parser to drop the currently optimal candidate in favor of a previously suboptimal one. The idea that constraints might become relevant with new input in parsing implicates that the order in which information is assessed by the parser is determined by the input stream. Depending on the structure of the input, constraints from different linguistic domains may interact freely at any time during the parse. That is, the evaluation process is cross-modular if the output is cross-modular. For example, constraints regulating the well-formedness of prosodic structure may interact with syntactic requirements in determining the structure of a linguistic object. In this respect, OT crucially differs from models of sentence processing that assume a fixed order in which different kinds of information are considered by the language processor at any given step of the analysis. For example, it is not the case in cross-modular OT that semantic and contextual information is only consulted after a first syntactic analysis of the input has been completed (as has been suggested in some models of sentence processing, e. g. Garden Path Theory, Frazier 1987, Friederici 2002) and a great deal of psycholinguistic evidence supports the parallel engagement of contextual semantic and syntactic knowledge in sentence parsing (e. g. Garnsey et al., 1997; Trueswell et al., 1994).

For the present case, the simultaneous application of constraints of various linguistic domains (syntax and phonology), the capability of evaluating incremental input, and the possibility to integrate both parsing and synthesizing of linguistic objects within a single framework are well suited for modeling the interaction of prosodification and syntactic structure building in reading performance. The OT model used for this endeavor has the following characteristics:

- The written string of lexical items serves as input.
- The output consists of both a syntactic description of the input and its prosodic rendition.
- The relevant constraints evaluate syntactic well-formedness, phonological well-formedness, and the agreement between syntactic and phonological structure.

The general method for testing whether OT can be used to model the parsing facts is as follows:

First, we determine the constraints relevant for the type of ambiguity under consideration. We make sure that the constraints are well motivated and have independent support. Second, we ascertain the ranking among the constraints as established in the relevant literature or on the basis of grammaticality judgments. Third, we verify the validity of the model by reference to the reading performance on the *nicht mehr*-ambiguity detailed in the previous section.

We assume that the model simultaneously generates two kinds of structured representations which are combined: a syntactic interpretation and a prosodic rendition. The written input provides information about the lexical items and their sequence. The combination of syntactic and prosodic structure is evaluated against the constraint hierarchy. The syntactic descriptions used here conform to standard assumptions concerning phrase structure, i. e. syntactic parses may generally be represented by a fully connected predicate argument structure with a single root representing the phrase or the sentence.

3.1 Motivating the constraints

In the case of the *nicht mehr*-ambiguity, the parser has the choice between the comparative reading of *mehr* and the adverbial reading of *nicht mehr*. In order to formulate the relevant constraints and their respective ranking, it is necessary to be clear about the syntax and prosody of the target structures to be evaluated.

3.1.1 The syntax of comparative *mehr* and adverbial *nicht mehr*

As is assumed for *more* in English, German comparative *mehr* is construed as a suppletive formation of an adjectival stem (*viel*, Engl.: *much*) and a degree marker (cf. Hendriks and De Hoop, 2001, for the relevant terminology), a.k.a. the comparative morpheme (*-er* in morphologically transparent forms).

Lechner (2003) notes that nominal comparatives like *mehr* in (3) display hybrid characteristics: they behave like DPs with respect to constituent distribution (as argument to the verb), but, at the same time, they have adjectival properties in providing the gradability necessary for comparatives. Obviously, the fused adjective-comparative morpheme selects a complex complement: As a prenominal adjective, it licenses the (optional) NP *Bier* (cf. Abney, 1987). In its function as degree marker, it selects the (obligatory) *als*-phrase containing the standard of comparison. Thus the relatively complex syntactic representation that follows Abney's and Lechner's analysis.

(3)	Peter hat [$_{DP}$ [$_{DegP}$ [$_{AP}$	mehr [$_{NP}$	(Bier)]]	als	Susanne]]	getrunken.
	Peter has	more	(beer)	than	Susanne	drunk
	'Peter drank more (beer) than Susanne.'					

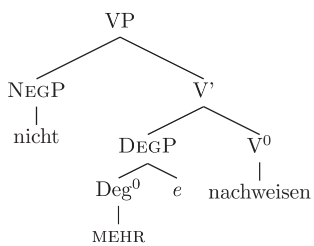
The fused adjective-comparative simultaneously serves as the head of the DegP, which is complemented by the *als*-phrase, and of the AP, which may take an NP as argument. Note that the NP within the AP does not necessarily need to be expressed in order for the sentence to be interpretable, cf. (3). On the other hand, the degree phrase introduced by *als* is required as the complement to the degree morpheme. Without a standard of comparison, the comparative cannot be interpreted, cf. (4). That is, leaving the standard of comparison unexpressed renders the sentence infelicitous if the context does not provide the information about the comparison.

(4)	#Peter	hat	mehr	getrunken.
	Peter	has	more	drunk.
	'Peter drank more.'			

In (5) the comparative *mehr* is the head of the DegP complement to the following transitive verb. Example (6) depicts the syntactic analysis of the region starting with *nicht* up to and including the verb. The negation is analyzed as an adjunct to the VP containing the DegP as complement to V^0. The DegP itself is elliptic as it lacks the degree phrase selected by the degree features of *mehr*, hence the empty sister node to Deg^0 (marked with *e*). The phrasal complement to the comparative head furnishing the standard of comparison in (5) is extraposed and surfaces only after the verb.

(5) Peter konnte nicht mehr nachweisen als die Blutwerte.
Peter could not more determine than the blood values
'Peter couldn't determine more than the blood values.'

(6)

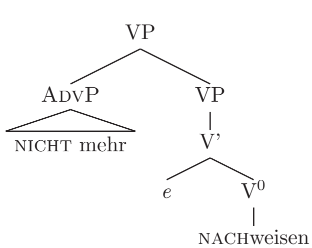


The adverbial counterpart of (5) has different syntactic properties. In this case (7), *mehr* is not gradable, and therefore cannot serve as the head of a degree phrase. Instead, *mehr* is part of a larger lexical unit, i.e. the adverb *nicht mehr*, which cannot be analyzed compositionally.

(7) Peter konnte nicht mehr nachweisen, dass die Werte erhöht waren.
Peter could not more determine, that the values increased were
'Peter couldn't determine anymore that the values were increased.'

As an adverb, *nicht mehr* adjoins to the VP. VP adjuncts, however, are not proper constituents of the core VP since, contrary to arguments, they are not selected by V^0. To reflect the fact that VP adjuncts are not exhaustively dominated by, but are nevertheless part of the VP, an intermediate maximal projection is introduced in (8). This syntactic difference will be especially relevant for the prosodification of the phrase.

(8)



Observe that the representation in (8) lacks the argument that is required by the transitive V^0 (and hence marked by *e*). The argument is only realized postverbally as a sentential complement introduced by the complementizer *dass* in (7).

Comparing the two analyses in (6) and (8), they violate syntactic requirements at different points in the syntactic representation as long as they are unfinished. Focusing on the region up to, and including, the main verb, the comparative structure (6) lacks the complement of the degree head *mehr*, i. e. the degree phrase. It thus violates a syntactic constraint that demands that complements of heads, or arguments, surface. We will call this constraint FILL-ARG.[2]

(9) FILL-ARG: argument slots must be filled.

Note that, in the comparative reading, FILL-ARG is satisfied for the VP in providing the argument in the form of the DegP already pre-verbally. In the adverbial reading (7), again focusing on the material up to and including the VP, FILL-ARG is violated since the transitive verb lacks its argument. The argument to the verb appears only after the verb complex in the form of an extraposed sentential complement.

The violation of FILL-ARG is only relevant for the incomplete, unfinished representations in (6) and (8). In both structures, the postverbal material can be coindexed with the respective gap position (marked by *e*). That is, once the postverbal material is considered, the FILL-ARG violation will be suspended. However, it should be clear that the syntactic features of the postverbal material have to match the required features of the gap.

3.1.2 Prosodic properties of comparative *mehr* and adverbial *nicht mehr*

The comparative *mehr* is accented (as indicated by small caps in the tree diagram in (6)). Accentuation is regulated by the syntax-phonology interface constraint STRESSXP (Féry and Samek-Lodovici, 2006; Truckenbrodt, 1995, 2007; Truckenbrodt and Darcy, 2010). STRESSXP interprets the syntactic structure assigned to the input and requires that maximal projections (XPs) of lexical heads receive prosodic prominence on the level of the Phonological Phrase (PhP) by way of accentuation.

(10) STRESSXP: Each lexically headed XP contains a phrasal stress.

2 Applied to VPs, FILL-ARG has also been dubbed a violable version of the θ-criterion and accordingly been called ASSIGN-θ (Stevenson and Smolensky, 2006).

Though standardly understood as a functional projection, the DegP in (5) is headed by a degree operator *mehr* that has lexical content (due to its fusion with adjectival material). Therefore, StressXP applies and assigns accent to *mehr*. Note that with an accent on *mehr*, StressXP is satisfied for both the (lexical) DegP and the VP because the DegP is a proper constituent of the VP. Consequently, the verb may remain unaccented without violating StressXP. According to standard assumptions about X-bar structure, both VP adjuncts and VP arguments are considered maximal projections. However, adjuncts and arguments differ with respect to their affiliation to the VP: while VP arguments are proper constituents of the VP, adjuncts are not exhaustively dominated by the VP, as represented by the intermediate maximal projection in (8). StressXP is sensitive to this syntactic difference (see also Truckenbrodt, 2006, 2007). Prosodic prominence on a VP argument, in the present case on *mehr* in (5), implies prominence for the whole VP thus satisfying StressXP for the VP. Prosodic prominence on a VP adjunct, however, does not suffice to satisfy StressXP for the VP: the lower maximal projection, that is the core VP, also calls for an accent. Therefore, both adjunct and verb receive an accent in (8).[3] The adverb *nicht mehr* features lexical stress[4] on *nicht* so accent is correspondingly realized, leaving *mehr* without prosodic prominence in the temporal reading. StressXP is violated if the above conditions are not met, e. g. if adjunct or argument or the whole VP remain unaccented. This may happen under certain information structural conditions that will be briefly discussed in the following section.

In addition to StressXP, relative prominence of accents is regulated by Rightmost. This constraint simply requires that among the accents assigned to XPs the rightmost accent is strongest. Rightmost is equivalent to HeadPhrase (HP/HI) (Féry and Samek-Lodovici, 2006), which demands that heads of prosodic or intonational phrases appear close to the right edge. Accordingly, the accent on the adverbial *nicht mehr* in (8) is weaker than the accent on the verb (e. g. Féry and Samek-Lodovici, 2006; Truckenbrodt, 2007).

(11) Rightmost: The rightmost accent within a prosodic or intonational phrase is strongest.

3 Matters are probably more complicated than described here: Féry and Herbst (2004) attest unaccented verbs in adjunct-verb sequences. The general tendency, however, is captured by the above account.

4 As a temporal adverbial, *nicht mehr*, although it incorporates two graphemic words, is considered a single lexical entry as its meaning cannot be computed compositionally from its two constituents.

Three more constraints are relevant for the present case. These impose restrictions on the prosodic-phonological representation independent of its syntactic structure. The requirements of StressXP are in conflict with a purely phonological constraint, *Accent. This constraint penalizes prevalent accentuation by assigning each accent a violation mark. It is motivated by the fact that a sentence like (12) is not normally uttered with accent on each word. An accentuation pattern of this type may only be licensed under very strong pragmatic conditions.

(12) L*H L*H L*H H*L%
Peter wollte die Kosten ermitteln.
'Peter wanted to calculate the costs.'

In addition, two further constraints play a role in deriving the prosodic structure of phrases and sentences. *Clash (Prince, 1983; Selkirk, 1984) militates against adjacent stressed syllables within a phonological phrase. The workings of *Clash are exemplified in (13). The accented monosyllabic *Hemd* is adjacent to *anziehen*, which bears main stress on the initial syllable in its citation form (13-a) (relative prominence is indicated by underscoring). According to Bohn et al. (2011), Giegerich (1985), Kiparsky (1966), and Visch (1999), the stress position of the trisyllabic main verb may shift away from the first syllable to the second in such a situation, yielding the stress pattern in (13-b). Stress shift warrants avoidance of stress clash, satisfying *Clash.[5] However, this procedure violates another constraint that requires faithfulness to the citation form stress pattern, which, in the case of *anziehen*, would demand initial stress. The latter constraint will be called IdentStress.

(13) a. #... das Hemd anziehen.
b. ... das Hemd anziehen.
... the shirt on-take
'... to put on the shirt.'

Note that stress clashes cannot always be resolved. In (14), there is simply no other syllable to which stress could shift, so (14) will always incur a violation of *Clash.

(14) ...weil er das Hemd holt.
...because he the shirt pick-up.
'...because he is picking up the shirt.'

5 The important point here is the prominence relation between the syllables involved. Whether, in the case of stress clash, it is changed by literally shifting the stress or by stress deletion (Horne, 1990) is beyond the scope of this paper and does not affect the analysis.

Taken together, the constraints relevant for the present case are of three types: Fill-Arg regulates syntactic structure building. StressXP supervises the syntax-phonology interface. Finally, four further constraints are responsible for the prosodic-phonological representation, namely Rightmost, *Accent, *Clash, and IdentStress.

3.2 Determining the constraint hierarchy

In the previous section, the relevant constraints and their requirements were introduced. This section motivates the constraint hierarchy which ultimately governs the parsing process. It is customary in most applications of Optimality Theory to determine the ranking of constraints on the basis of the empirical facts alone. In our case, the empirical facts correspond to the parsing preferences as evidenced by the reading experiments on the *nicht mehr*-ambiguity. However, we need independent motivation for the constraint ranking since we are not only interested in showing that OT can be used to model the parsing and prosodification facts in reading, but also that the processing facts can be modeled with the same grammar that describes and explains the structure of linguistic objects in general. We therefore consult the grammar to ascertain the constraint hierarchy and test this ranking against the performance data from the reading experiment.

The syntactic constraint Fill-Arg is, in essence, one side of the θ-criterion, demanding that argument slots or θ-roles be filled. For a sentence to be grammatical, the θ-criterion has to be fulfilled (Chomsky, 1981). Correspondingly, this constraint is undominated.

We turn now to the constraints regulating the syntax-prosody interface and the phonological representation.

StressXP may be violated under certain conditions without automatically inducing ungrammaticality. As an example, a VP may lack accentuation if it is already given in the discourse. This is the case in (15-b), where the locative adjunct *unter der Dusche* receives accent but the VP proper may remain unaccented due to discourse givenness. A pattern of this type may emerge as a result of high ranking constraints that guide the interface between information structure and prosody such as StressFocus and DestressGiven (Féry and Samek-Lodovici, 2006).

(15) Where did Julie sing?
a. #Julie hat unter der DUSCHE GESUNGEN.
b. Julie hat unter der DUSCHE gesungen.
Julie has under the shower sung
'Julie sang under the shower.'

A violation of RIGHTMOST is tolerated under similar circumstances, i. e. if information structural requirements govern the prosodification. Consider the elliptical coordination structure in (16). Owing to the contrast, the verb *loves* in (16) is assigned strongest accentuation. The object to the right may be accented, too, but its accent is certainly weaker. Generally, post-nuclear accents violate RIGHTMOST.

(16) Mary DESPISES and Peter LOVES fruity CREAM tarts.

The OT literature on sentence intonation has established that STRESSXP dominates RIGHTMOST in German and English (Féry and Samek-Lodovici, 2006). We will stick to this independently motivated hierarchy.

The constraint *CLASH will be violated whenever the adjacency of two prominent or strong syllables cannot be resolved. Adjacency of strong syllables is a widespread phenomenon, as may be exemplified by the very conventionality of phrases like (17) consisting of three consecutive stressed syllables.

(17) … weil Linn BROT kauft.
… because Linn bread buys
'*… because Linn is buying bread.*'

This suggests a rather low rank for *CLASH. IDENTSTRESS must be ranked even lower, otherwise stress shift in the face of a potential stress clash, as in (13) above, would remain inexplicable. *ACCENT is necessarily violated by every utterance if we subscribe to the assumption of the prosodic hierarchy according to which every utterance entails a phonological phrase which, by definition, is headed by an accent. *ACCENT will therefore hold the lowest rank among the relevant constraints.

The above considerations establish the ranking in (18).

(18) FILL-ARG » STRESSXP » RIGHTMOST » *CLASH » IDENTSTRESS » *ACCENT

This ranking will be used throughout in the following demonstration of the model.

3.3 Putting the model to work

The constraint hierarchy will be applied to the *nicht mehr*-ambiguity introduced above. The OT-parser/synthesizer, going from left to right, takes as input the written lexical items and GEN incrementally assigns the string a set of syntactic and prosodic candidate descriptions.[6] For each parsing step, EVAL choses among the candidate outputs the one that best harmonizes with the constraint hierarchy. According to OT convention, the optimal candidate will be marked with a pointing finger. For the application of OT to incremental processing, this convention will be expanded in the following way:

Incremental candidates that are optimal throughout the parsing process collect pointing fingers for each parsing step. That is, if the optimal candidate structure of parsing step *n-1* is consistent with the optimal candidate at parsing step *n*, that candidate will be marked with two pointing fingers. Conversely, once previously optimal candidates become suboptimal, the corresponding candidate is flagged with a hash mark. Candidates marked with a hash mark may still take part in the competition and new input may revive them as optimal candidates.

There are two ways to predict processing costs on the basis of this OT formalism. First, a parse incurs processing costs at parsing step *n* if the optimal candidate Φ is inconsistent with the optimal candidate at *n-1*; the costs increase with every previous parsing step *n-1…n-k* for which a partial structure consistent with Φ was suboptimal ("digging in" effect, cf. Tabor and Hutchins, 2004).

Secondly, and more importantly, the higher the rank of the constraint responsible for the failure of a previously optimal candidate, the higher the processing costs associated with it (Stevenson and Smolensky, 2006).

In what follows, we depict an incremental OT processing model that makes falsifiable predictions for reading performance. Crucially, the OT model integrates syntactic parsing (comprehension-oriented optimization) and prosodification (production-oriented optimization) using a single constraint hierarchy. The constraints of the model have their basis in grammar, so the reason for the preference of one output over the other is a grammatical one. Also, the interplay of production and comprehension is thus rooted in the OT grammar.[7]

For illustration, the model will be applied to the four conditions of the *nicht mehr*-ambiguity in (19).

6 In some models that use OT in language comprehension, the function generating the candidates is called INT for "interpretation" (Stevenson and Smolensky, 2006). We keep using GEN and understand it as a cover term for both production oriented as well as comprehension oriented candidate generation.

7 This is not to deny that performance constraints have a role to play in parsing; however, the purely grammatical model is more economical and thus yields a more comprehensive explanation of the processing results.

(19) Peter konnte…
‘Peter could…’
a. …nicht mehr ausrechnen, dass… TEMP-INI
…not more calculate that…
‘…not calculate anymore that…’
b. …nicht mehr berechnen, dass… TEMP-MED
…not more calculate than…
‘…not calculate anymore that…’
c. …nicht mehr ausrechnen, als… COMP-INI
…not more calculate than…
‘…not calculate more than…’
d. …nicht mehr berechnen, als… COMP-MED
…not more calculate than…
‘…not calculate more than…’

Three parsing steps will be considered, starting in the ambiguous region, namely with the two graphemic words *nicht mehr*. As shown in Tableau 1, the adverbial reading (candidates a–d) is preferred as it satisfies the high ranking Fill-Arg in contrast to the competing comparative reading. The latter reading is suboptimal as it lacks the complement to the comparative head *mehr*, thus incurring a violation of Fill-Arg (candidates e–h).

As for the prosodification there are four logical possibilities concerning the distribution of accents: accent on either *nicht* or *mehr* or accent on both or accent on neither (accents are marked by small caps).[8]

StressXP requires accentuation of the adverbial phrase. Accordingly, the accentless candidate (d) is out of bounds. Double accentuation in (c) and (f) is prohibited by *Clash and also incurs a gratuitous violation of *Accent. Candidate (b) features accent on *mehr*, violating the lexical-phonological prominence pattern of the adverbial *nicht mehr*, which bears stress on the initial syllable. Candidate (b) thus founders on IdentStress. The optimal candidate (a) only incurs a single violation of *Accent.

The suboptimal comparative candidates all founder on Fill-Arg for lack of the comparative phrase (missing argument marked by $e_?$),[9] but it is still possible to

8 For ease of exposition, the relative strength of accentuation is not evaluated at this parsing step, i. e. Right-most is ignored in Tableau 1. We simply assume that, in the case of accent on both *nicht* and *mehr* (candidates c and f), Rightmost requires nuclear accent to fall on *mehr*. Note that doubly accented candidates are also suboptimal due to their violating *Clash and *Accent.
9 An anonymous reviewer points out that the preference for the adverbial parse may also be explicable in terms of usage frequency.

Tableau 1: First parsing step.

/nicht mehr/		Fill-Arg	StressXP	Rightmost	*Clash	IdentStress	*Accent
a. ☞	[$_{VP}$ [$_{AdvP}$ NICHT mehr]						*
b.	[$_{VP}$ [$_{AdvP}$ nicht MEHR]					*!	*
c.	[$_{VP}$ [$_{AdvP}$ NICHT MEHR]				*!	*	**
d.	[$_{VP}$ [$_{AdvP}$ nicht mehr]		*!			*	
e.	[$_{VP}$ nicht [$_{DegP}$ MEHR $e_?$]	*!					*
f.	[$_{VP}$ NICHT [$_{DegP}$ MEHR $e_?$]	*!			*		**
g.	[$_{VP}$ NICHT [$_{DegP}$ mehr $e_?$]	*!	*				*
h.	[$_{VP}$ nicht [$_{DegP}$ mehr $e_?$]	*!	*				

determine the best among the bad ones: candidate (e), featuring a single accent on *mehr*, fares best. Leaving comparative *mehr* unaccented incurs a violation of StressXP (g and h); double accentuation violates *Clash and *Accent (f).

Tableau 2: Second parsing step (candidates violating StressXP are ignored).

/nicht mehr ausrechnen/		Fill-Arg	Rmost	*Clash	IdStress	*Acc
a. ☞☞	[$_{VP}$ [$_{AdvP}$ NICHT mehr] [$_{VP}$ $e_?$ AUSrechnen]]	*				**
a'.	[$_{VP}$ [$_{AdvP}$ NICHT mehr] [$_{VP}$ $e_?$ AUSrechnen]]	*	*!			**
e.	[$_{VP}$ nicht [$_{DegP}$ MEHR $e_?$] ausrechnen]	*		*!		*
e'.	[$_{VP}$ nicht [$_{DegP}$ MEHR $e_?$] ausrechnen]	*			*!	*
/nicht mehr berechnen/						
a. ☞#	[$_{VP}$ [$_{AdvP}$ NICHT mehr] [$_{VP}$ $e_?$ beRECHnen]]	*				*!*
a'.	[$_{VP}$ [$_{AdvP}$ NICHT mehr] [$_{VP}$ $e_?$ beRECHnen]]	*	*!			**
e. ☞	[$_{VP}$ nicht [$_{DegP}$ MEHR $e_?$] berechnen]	*				*
e'.	[$_{VP}$ nicht [$_{DegP}$ MEHR e?] berechnen]	*		*!	*	*

Turning to the second parsing step (Tableau 2), the OT processor considers *nicht mehr* together with the following verb. Given that the verb is obligatorily transitive, it incurs a violation of Fill-Arg in those candidate structures that do not provide a direct object. This holds for the adverbial reading since the adverb cannot occupy the argument slot. The nominal comparative *mehr*, however, may step in as argument to the verb. Still, the comparative parse continues to violate Fill-Arg as it lacks the complement of the degree head. Therefore, the adverbial and comparative readings both fail to satisfy Fill-Arg, albeit for different reasons. As a result, both syntactic analyses are on equal footing concerning the high ranking syntactic constraints. The competition is therefore decided by lower ranking phonological constraints. In the case of a verb with lexical stress on the initial syllable (upper half of Tableau 2), the adverbial reading wins. The comparative reading with accented *mehr* and an initially stressed verb founders on *CLASH (candidate e). The stress shift candidate (e') fails due to a violation of IDENTSTRESS.

As for the cases with the verb featuring medial stress (cf. lower panel of Tableau 2), the situation changes. In contrast to the corresponding candidate in the upper half of Tableau 2, candidate (e) with a stressless initial syllable does not incur a violation of *CLASH because of the favorable stress pattern on the verb. Instead, the adverbial candidate with accent on both *nicht* and the verb (candidate a) incurs one more violation of *ACCENT than the optimal comparative candidate (e), which turns out to be fatal. The predecessor of the adverbial candidate (a) was the optimal candidate of the previous parsing step and is correspondingly flagged with the # mark. This change of parsing preferences from step 1 to step 2 hinges on a very low ranking constraint. It may therefore be all but a weak preference. Accordingly, processing costs associated with the preference change will be relatively low.

In the third parsing step (cf. Tableaux 3 and 4), the parser encounters the disambiguating material, i. e. the complementizer phrase introduced by *dass* or the comparative phrase with *als*. As discussed above, the complementizer phrase may fill the up to now open VP argument by providing a sentential complement to the transitive verb in the adverbial reading; at the same time, the complementizer is incompatible with the comparative version. Conversely, the *als*-phrase may be interpreted as the argument to the comparative DegP but it is impermissible in the context of the adverbial reading, which demands a complement to the VP. The outcome of the competition between the syntactic analyses therefore depends on the high ranking constraint FILL-ARG. To maintain

Tableau 3: Third parsing step (disambiguation towards adverbial reading). Candidates violating STRESSXP, RIGHTMOST and *CLASH are ignored.

TEMP-INI: /nicht mehr ausrechnen... dass/		FILL-ARG	IDSTRESS	*ACC
a. ☞ ☞ ☞	[$_{VP}$ [$_{AdvP}$ NICHT mehr] [$_{VP}$ e_i AUSrechnen]] [$_{CPi}$ dass			**
e'.	[$_{VP}$ nicht [$_{DP}$ MEHR $e_?$] ausRECHnen] [$_{CP}$ dass	*!	*	*
TEMP-MED: /nicht mehr berechnen... dass/				
a. ☞# ☞	[$_{VP}$ [$_{AdvP}$ NICHT mehr] [$_{VP}$ e_i beRECHnen]] [$_{CPi}$ dass			**
e. ☞ #	[$_{VP}$ nicht [$_{DP}$ MEHR $e_?$] berechnen] [$_{CP}$ dass	*!		*

Tableau 4: Third parsing step (disambiguation towards comparative reading). Candidates violating StressXP, Rightmost and *Clash are ignored.

comp-ini: **/nicht mehr ausrechnen … als/**			Fill-Arg	IdStress	*Acc
a.	☞ ☞ #	[$_{VP}$ [$_{AdvP}$ NICHT mehr] [$_{VP}$ $e_?$ AUSrechnen]] [$_{ComP}$ als	*!		**
e'.	☞	[$_{VP}$ nicht [$_{DP}$ MEHR e_i] ausrechnen] [$_{ComPi}$ als		*	*
comp-med: **/nicht mehr berechnen… als/**					
a.	☞# #	[$_{VP}$ [$_{AdvP}$ NICHT mehr] [$_{VP}$ $e_?$ beRECHnen]] [$_{ComP}$ als	*!		**
e.	☞ ☞	[$_{VP}$ nicht [$_{DP}$ MEHR $e_?$] berechnen] [$_{ComPi}$ als			*

clarity, we will only be considering the best candidates of each reading for the two parses.

In the case of the initially stressed verb followed by the complementizer phrase (Tableau 3, upper panel), the parser may simply maintain the analysis established in both previous parsing steps; the complementizer phrase introducing the VP complement can simply be coindexed with the VP argument slot. Fill-Arg is thus satisfied and no processing difficulty is predicted in this case. The best of the significantly worse candidates featuring the comparative reading was suboptimal throughout the parse and founders on Fill-Arg. The CP cannot legally fill the still open argument slot within the DegP, as *mehr* obligatorily selects the comparative phrase introduced by *als*.

Encountering the complementizer after a verb featuring medial stress (Tableau 3, lower panel), however, leads to another change of parsing preferences. Again, the high ranking syntactic constraints decide about the winning candidate. Observe that in the previous parsing step, the comparative reading was preferred over the adverbial analysis, albeit weakly. The very weakness of the parsing preference in step 2, together with the brevity of the period in which this preference has held, may alleviate the processing costs that the repeated preference change would predict for parsing step 3. Assuming a ranked parallelism in OT parsing, the temporarily suboptimal adverbial reading might still be active to a relatively high degree.

In the face of a comparative *als*-phrase preceded by the initially stressed verb (upper panel of Tableau 4), the parser is forced to revoke the previously preferred analysis (candidate a) due to the requirements of Fill-Arg. The processing costs associated with this change of preference towards candidate (e') should be high for two reasons: First, the now discarded adverbial analysis was established over both preceding parsing steps, suggesting relative stability of this parse. Second, the constraint responsible for the failure of the previously optimal candidate is a high ranking one. Note that this parsing step involves a stress shift on the verb that is required by *Clash.

The OT parser predicts decidedly less difficulty in the case of the medially stressed verb (lower panel of Tableau 4). In the previous parsing step, a weak preference for the comparative reading has already been established. The new input simply confirms this preference for candidate (e).

4 Discussion

The performance differences the model predicts for the four conditions at parsing step 3 do indeed appear to reflect the reading data obtained in the experiments. Little processing difficulty is predicted for both conditions with the adverbial reading (Tableau 3). This is obvious for the condition with the initially stressed verb. The optimal candidate is syntactically and prosodically consistent with the optimal candidates at both previous parsing steps (hence the three pointing fingers). In the case of the verb with medial stress, the deviating parsing preference that is predicted for the second parsing step is a very weak one. It hinges on a low ranking constraint and might thus be easily overwritten in the third step.

Turning to the two conditions featuring the comparative reading (Tableau 4), a clear difference in processing difficulty is predicted between cases with initial and medial stress on the verb. In the latter condition, a weak preference that had been established at the second parsing step is confirmed. The structure should therefore be processed relatively easily compared to the comparative *mehr* followed by a verb with initial stress. It is this condition that is predicted to produce the highest processing costs: the competitor that was the optimal candidate in the two previous parsing steps founders on a high ranking constraint.

This prediction of the model is borne out in the actual data of the reading experiment. In the disambiguating region, several dependent variables reveal an interaction between the factors "syntactic reading" and "verbal stress pattern" that is mainly due to the striking reading difficulty observed for the condition that forces a stress clash (or else a deviation from the lexically determined stress pattern), i. e. comparative *mehr* followed by initial stress on the verb.

The model is also compatible with the general prevalence of unaccented readings of *mehr* that was observed in the oral reading experiment (only 25 % of cases accented; cf. summary of oral reading experiment). The avoidance of accent on *mehr* can be explained with recourse to the model's first parsing step (cf. Tableau 1), in which the adverbial reading was established as the optimal interpretation, and the competing comparative version ruled out by strong syntactic constraints. Since, in the oral reading experiment, readers were encouraged to read as fluently as possible without self-corrections, this initial analysis may have been only mildly affected by the incoming verb in the second parsing step.[10]

Generally, the proposed OT parser accounts for the prosodic effects that were shown to act upon syntactic ambiguity resolution in reading. The OT model makes direct use of the grammar in determining its parsing preferences. The assumption is that grammatical restrictions are applied to incremental structure building and that preferences at points of ambiguity reflect these grammatical requirements. The constraint ranking that derives the parsing preferences has a sound and independent grammatical motivation and, in the present case, it can do without additional extra-grammatical processing constraints. Moreover, not only the constraints but also the specific ranking employed for this performance theory hold for the ordinary competence grammar. Importantly, this model is cross-modular in that it integrates constraints from different modules of grammar, namely syntax, phonology and the corresponding interface.

With that said, we shall briefly return to the problem of the syntax-phonology interface in grammar touched upon in the introduction. The present model is a performance-compatible grammatical device that allows phonological constraints to act upon syntactic structure building. This is especially evident in parsing step 2 (cf. Tableau 2, lower panel), in which the optimal candidate, complete with a syntactic description, is selected as optimal because it fares better than the relevant syntactic competitor only with respect to phonological constraints. Given that it is the OT grammar proper that produces this result, this parsing step constitutes an offense against the notion of phonology-free syntax as forcefully advocated by Pullum and Zwicky (1988). If this incremental model and its constraint hierarchy is realistic, the idea of a merely unidirectional relation between syntax and phonology is once more invalidated (see Inkelas and Zec, 1995; Rice and Svenonius, 1998; Schlüter, 2003; Zec and Inkelas, 1990, for more evidence against phonology-immune constituent structure building). Rather, this phenomenon is reminiscent of the idea that Bierwisch (1966) put forward referring to the role of prosody in language production:

10 This explanation – which is based on the incremental application of grammatical constraints – is orthogonal to the one offered by Bader (1998) in the context of a similar syntactic/prosodic ambiguity. He states that those readings are difficult to parse in which function words have to be assigned accent. That is, in contrast to the grammatical account defended here, Bader (1998) ascribes the attested preference pattern to the lexicon when stating that function words should preferably remain unaccented. As noted above, comparative *mehr*, even though it may project a functional XP, is not an indisputable function word as it clearly features adjectival properties.

> *Es ist sehr wohl möglich, dass ein Sprecher sich durch ein begonnenes Intonationsmuster zur Wahl einer bestimmten syntaktischen Struktur veranlasst fühlt* [...].
> It is very well possible that a speaker feels himself prompted to choose a certain syntactic structure owing to the intonation pattern that he has started.
> Bierwisch (1966), 105.; translation by the author

A grammar and/or processing model that does justice to phonological interference of this type must surely allow for at least limited interaction of syntax and prosody. Without further justification, I submit that situations of the kind found here (and formulated by Bierwisch, 1966) are not uncommon in incremental sentence processing. For the assignment of a syntactic description to a full sentence, however, recourse to phonology might be the exception rather than the rule.

In the following section I will compare the OT approach to other models of sentence processing.

4.1 Comparison to other sentence processing models

4.1.1 Other constraint-based approaches

The proposed OT processor has a lot in common with the family of constraint satisfaction models that have been formulated for sentence comprehension (MacDonald et al. 1994; Trueswell et al. 1994 and the computer implemented variants such as McRae et al. 1998; Tabor et al. 1997). Just as the subsymbolic variant of OT (cf. Smolensky and Legendre, 2006), constraint satisfaction models of information processing are based on the idea of spreading activation in neural networks. Together with these models, OT assumes that multiple constraints from various domains may interact during ambiguity resolution.

As opposed to the present model, the standard constraint satisfaction models generally deemphasize grammatical influences on parsing (cf. Stevenson and Smolensky, 2006), focusing on extra-grammatical factors such as lexical or structural frequency. Models like the Competition-Integration Model (McRae et al., 1998) do not provide an explicit testable competence grammar but rely on unspecified modules providing the syntactic alternatives to be evaluated. It is questionable what the cognitive equivalent of such modules is and what their relation to competence grammar might be. In short, the relationship between competence grammar and the processing component is underspecified in these models.

The architectures of the standard constraint satisfaction models seem to be task specific. In the psycholinguistic arena, distinct connectionist models have been proposed for speech processing (e. g. McClelland and Elman, 1986), sentence comprehension (Tabor et al., 1997; Tabor and Tanenhaus, 1999; McRae et al., 1998), reading aloud (on the word level only: Seidenberg and Plaut, 1998; Rastle and Coltheart, 1998), and language production (e. g. Dell et al., 1999; Bock and Griffin, 2000). As Christiansen and Chater (2001) point out, it is far from clear whether and how these models will eventually be integrated to cover full-scale human language performance. OT as a theory of grammar "at least has the explicit aim of developing a general set of constraints that applies to all sentences in a language" (Archangeli, 1997, as cited by Hoeks and Hendriks 2011); this general set of constraints and its ranking should be central to all kinds of linguistic tasks.

Owing to the strict constraint domination approach taken here, the present model does not generate numerical predictions of processing difficulty that could be evaluated against numerical processing data. The lack of this ability is clearly detrimental to the OT model in comparison to other constraint-based approaches. The relation of the model's prediction to the experimental data is discussed in more detail below (cf. 4.2).

4.1.2 Two-stage parsing accounts

Together with other constraint satisfaction models, OT assumes that multiple constraints from various domains may interact during ambiguity resolution. The kind of information assessed in constraint satisfaction models depends on the nature of the input alone. Whichever constraint is responsive to a given piece of input will be active in ambiguity resolution – independent of its grammatical domain. That is, constraint-based approaches assume parallel evaluation of several structural descriptions of the input.

This behavior contrasts with so-called *syntax-first* serial accounts like the Garden Path model in which syntactic structure is given temporal priority in evaluation (Frazier, 1987; Friederici, 1995, 2002). According to these models, comprehending a sentence involves several (at least two) stages, each of which is dedicated to the processing of a certain kind of information. Due to limited memory, it is assumed that the parser first pursues only a single rather sketchy candidate analysis on the basis of simple syntactic heuristics. The resulting syntactic skeleton is fleshed out in the following parsing stage(s), in which other types of information are furnished to yield a full semantic, contextually integrated representation. If, however, additional information conflicts with the first-stage syntactic sketch, the parser has to revise the structure in a cognitively costly second step dedicated to reanalysis. Other two-stage accounts assume that the parser already uses non-syntactic information during the first pass (Crocker, 1996; Van Gompel et al., 2001; Pritchett, 1992, among others), but, crucially, parallel processing is prohibited and only a single analysis is pursued at any given parsing stage.

Since, in these models, the role of phonological information is not well accounted for, prosodic effects on syntactic structure building are not easily explained. The situation becomes worse if one considers effects of prosodic structure that is not explicitly provided in the input (as in the case of reading), especially if prosody affects the initial stages of structure building (i. e. the computation of the syntactic category of ambiguous words).

A division between first pass parsing (syntactic pre-processing) and reanalysis (integration of other information) is not assumed in the current OT model. Rather, the model adopts the notion of Stevenson and Smolensky (2006), who state that if reanalysis is understood as a change in the parser's representation of what the preferred interpretation of the input is, any addition of input necessarily constitutes some kind of reanalysis. That is, focusing on the interpretation of syntactic structure, every new piece of input requires the processing mechanism to revise the current analysis either by filling empty slots in the structure (e. g. missing heads or arguments) or by actually changing syntactic relations that had been established in previous parsing steps. The latter process is costly if the change is forced by high ranking constraints. The revision will incur only mild costs if low ranking constraints are responsible for it. That is, the degree of difficulty is determined by the change in the constraint violation pattern of the optimal candidate at word *w* relative to the previous word *w-1*. Thus, instead of two qualitatively different parsing stages as assumed in serial parsing architectures, OT envisions a single interpretation mechanism that integrates all knowledge sources for which there is relevant information in the input and, at the same time, may still account for largely differing processing costs.

4.2 A deterministic model for gradient data?

Even though the OT model makes clear and testable predictions of processing preferences, those predictions are rather coarse-grained. In its current format, the model is not suited for making numerical predictions but it yields an ordinal estimate of processing difficulty at most. Note also that this OT model produces deterministic parsing results. There is only one candidate structure for each parsing step that wins the competition. The parsing data are certainly gradient rather than deterministic and not all participants in the experiments behave in exactly the way the model predicts. However, the model may well reflect the overall preferences that hold for the population of participants in the experiment.

The notion of the strict ordinal constraint domination in classic OT implies a “winner-take-all” system and thus excludes fine-grained modeling of gradient data on principled grounds (Gibson and Broihier, 1998). Some extensions of the OT framework, particularly stochastic OT (Boersma, 1998; Boersma and Hayes, 2001; Jäger, 2004), consider ranking the constraints on a continuous scale instead of the strict ordinal ranking. That way, the position of a given constraint in the hierarchy is not only defined by the relative order of constraints but also by the distance between the constraints on that scale. For the stochastic evaluation procedure, the constraint hierarchy is modified by adding normally distributed noise to each constraint position in the hierarchy such that its rank is not fixed but dwells in the area defined by the normal distribution. Depending on the proximity of the constraints on the scale, their Gaussian distributions may overlap to a certain degree. The overlap of the normal distributions then determines the probabilistic dominance relationship between the constraints and the degree to which their ranking may be reversed, yielding variable outputs.

However, applying stochastic OT to the case at hand is non-trivial. The two reading experiments that confirm the prosodic effect on syntactic ambiguity resolution have a variety of dependent variables: in the case of oral reading, the number of accentuations on the ambiguous *mehr* and the pause duration before the disambiguating phrase were chosen; for silent reading, we examined several standard reading times and fixation probabilities derived from the eye-tracking record.

Even though the results of these dependent variables are complementary, they naturally differ numerically. It is far from obvious which dependent variable should be chosen as the reference mark for the assignment of the numerical rank to the constraints and what amount of noise should be added to that value. Without a clearly defined link between a dependent variable and the higher-level linguistic processes it might reflect, the choice of the reference variable remains an arbitrary one. Also, since we seek to bring together grammar and processing as close as possible, the numerical ranking should be established independently of the processing data as well. We have good reason for the ordinal ranking, but it is unclear how to motivate the constraint hierarchy on a continuous scale without recourse to the processing data.

Unless and until a highly articulated model linking dependent variables of the experiments with higher-level linguistic processes is formulated, we abstract away from the gradience in the data and have to make do with modeling the systematic parsing preferences with a deterministic OT processor.

5 Conclusion

The OT account of sentence reading outlined here has several advantages over other theories: First, the OT approach makes direct use of grammatical principles to determine parsing preferences at any given parsing step. The constraints and the ranking used to model the performance data have independent support from the general competence grammar. For the kind of ambiguity studied here, the OT grammar suffices to make clear and testable processing predictions. The present model achieves this goal without making reference to extra-grammatical features of the input (such as word frequency) or working memory constraints. Nevertheless, it might be possible to formulate extra-grammatical requirements in optimality theoretic terms that could be integrated into this framework to explain processing facts that are not reducible to core grammar. The architecture of the model is parsimonious and establishes clarity: a very small set of grammatical constraints allows the model's predictions to be derived. Still, the present OT approach allows complex, non-trivial interactions of various grammatical modules in that it integrates constraints from syntax, phonology and the respective interface. That way, it allows the modeling of prosodic effects on syntactic ambiguity resolution that cannot easily be modeled in frameworks that assume a merely unidirectional syntax-phonology interface. Moreover, the model is easily scalable; it can be flexibly adapted and enlarged to fit phenomena in which semantic or contextual constraints interact with syntactic and phonological ones. What sets it apart from other constraint-based models is its modality independence. None of the constraints used here is specifically designed for the task the model was tested on, viz. reading. The same constraint hierarchy can potentially be used to make predictions about performance in listening, speaking or writing. That is, the model answers the call for a more integrative account of language production and comprehension – a demand that has been voiced again and again in psycholinguistics (e. g. Cutler and Norris, 1999; Ferreira, 2003; Garrett, 2000; Levelt et al., 1999; Pickering and Garrod, 2007).

Certainly, fundamental issues remain unresolved: For one thing, as discussed above, it is not trivial to relate the merely ordinal expression of processing preferences derived from the OT model to numerical data from psycholinguistic experiments. In addition, it is undisputed that factors like word frequency or the limitations of working memory are important forces in sentence comprehension and production. It would be far-fetched to assume that these factors are reducible to the workings of purely grammatical constraints. At this stage, it is unclear how frequency or memory effects could be integrated in the present OT model. In spite of these desiderata, the success of this model and its predecessors suggests that the general approach of applying OT to language performance is a fruitful one. The model introduced here can be seen as an extension of existing OT parsing accounts (Fanselow et al., 1999; Hoeks and Hendriks, 2011; Stevenson and Smolensky, 2006). The model shows how cross-modular effects in sentence processing and effects of production-driven comprehension may be captured within a unified model of linguistic competence and performance.

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