A Probabilistic Parser as a Model of Global Processing Difficulty

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Abstract
We present a model of global processing difficulty in human parsing. This model is based on a probabilistic context-free grammar and is trained on a realistic corpus sample. It achieves broad coverage and good parsing accuracy on unseen text, and its predictions are significantly correlated with experimental data on word order preferences in German. The model makes predictions about the differential behavior of verb final and verb initial sentences and provides evidence for the importance of lexical information in sentence processing.

Introduction
The human sentence processor is constantly confronted with ambiguous input, i.e., with linguistic material that is compatible with more than one syntactic analysis. The question of how such ambiguities are resolved has generated considerable debate in the psycholinguistic literature, and a variety of approaches have been proposed to address this question (see Crocker, 1999 for an overview).

One of these approaches is the Tuning Hypothesis (Mitchell, Cuetos, Corley, & Brysbaert, 1996), which states that the sentence processor extracts frequency information from its environment. In the case of ambiguity, the processor adopts the most frequent structure. This predicts that more frequent structures are easier to process than less frequent ones, as the processor is more likely to have encountered them before, and can choose the correct analysis. A number of experimental studies confirm this prediction for PP attachment and relative clause attachment (e.g., Brysbaert & Mitchell, 1996).

The aim of the present paper is to generalize the Tuning Hypothesis from local processing difficulty (as it occurs with attachment ambiguities) to global processing difficulty. By this we mean processing difficulty that persists even when the whole sentence has been read in by the parser, and a unique reading should be available. Standard examples include center embedding constructions and constructions that induce ‘strong’ garden paths, i.e., garden paths from which the parser fails to recover. The Tuning Hypothesis predicts a link with frequency for these cases: if the globally correct analysis of a sentence is infrequent, then this sentence will lead to strong processing difficulty.

In this paper, we test prediction with respect to word order variation in German, a phenomenon for which global processing difficulty can be observed. The paper is structured as follows. We first give an overview of the two experimental data sets that our modeling studies are based on. Then the relationship between frequency and processing difficult is discussed and a parsing model based on probabilistic context-free grammars is proposed. We train and test the model on a standard corpus and demonstrate that it achieves broad coverage and good parsing accuracy on an unseen test set. Then the model is evaluated by correlating its predictions with the two experimental data sets. The model makes predictions about the differential behavior of verb final and verb initial sentences and provides evidence for the importance of lexical information in sentence processing.

Experimental Data
Keller (2000a, 2000b) presents experimental results on word order variation in subordinate clauses in German. These data form the basis for our modeling studies, and will be summarized in the following section.

Experiment 1
Keller’s (2000a) experiment included transitive verbs such as kaufen ‘buy’ which take an animate subject and an inanimate object. Four different word order patterns were investigated: SOV, OSV, VSO, VOS (we use ‘S’ for subject, ‘O’ for object, and ‘V’ for verb). The object and the subject were realized as either a full NP or as a pronoun. The target word order was presented as a subordinate clause embedded by verbs like glauben ‘believe’.

(1) illustrates the SOV order with two full NPs.

(1) Maria glaubt, dass der Vater den Wagen kauft.
Maria believes that the [nom] father the [acc] car buys
‘Maria believes that the father is buying the car.’

In the syntactic literature on German (e.g., Müller, 1999) SOV is generally regarded as the basic word order for subordinate clauses. Verb initial orders are regarded as ungrammatical, while scrambling (the permutation of subject and object) is regarded as marked, i.e., of reduced grammaticality, but it not outright ungrammatical.

Keller (2000a) used magnitude estimation (ME; Bard, Robertson, & Sorace, 1996) to test these theoretical claims. He elicited acceptability judgments for 16 word orders, each of which as represented by eight lexicalizations, yielding a total set of 128 sentences. Twenty native speakers of German were used as subjects. Under the assumption that ME judgments provide an index of global processing difficulty, Keller’s (2000a) results support the following generalizations:

(2) a. Verb initial orders are harder to process than verb final orders.
   b. Object initial orders are harder to process than subject initial orders.
   c. Orders in which non-pronouns precede pronouns are harder to process than orders in which pronouns precede non-pronouns.

There is a range of experimental results that were obtained using different paradigms that confirm these processing preferences. This includes eye-movement and self-paced reading data (Bader & Meng, 1999; Scheepers, 1997), and a range of other comprehension and production paradigms (Pechmann, Uszkoreit, Engelkamp, & Zerbst, 1994).

Experiment 2
Keller (2000b, Experiment 6) extends these results to ditransitive verbs such as vorstellen ‘introduce’ that can
take three animate arguments. Six word order patterns were tested: SIOV, SÖIV, ISOV, ISOV, OSIV, OISV, either with three full NPs or with two full NPs and one pronounalized NP (‘O’ denotes the direct object, ‘I’ the indirect object). Again, the word order was presented as a subordinate clause. (3) gives an example for the order SIOV with three full NPs.

(3) Ich weiß, dass der Manager dem Projektleiter den Mitarbeiter vorstellt. 
I know that the manager project leader staff member introduces 'I know that the manager is introducing the staff member to the project leader.'

ME judgments were elicited for 24 orders; each order was presented in eight lexicalizations, yielding an overall set of 192 stimuli. Twenty-five native speakers were used as subjects. The results support claims (2b) and (2c), and yield the additional finding in (4) (verb initial orders were not included, hence the result in (2a) could not be tested).

(4) Orders in which the direct object precedes the indirect object are harder to process than orders in which the indirect object precedes the direct object.

We will use the data sets from Experiments 1 and 2 to test a model of global processing difficulty. The underlying assumption is that the ME score of a sentence can serve as a measure of processing difficulty: the harder a sentence is to process, the more unacceptable it is in an ME judgment task. Evidence for this assumption is provided by Bard, Frenck-Mestre, Kelly, Kilborn, and Sorace’s (1999) study which shows that ME data are correlated data from self-paced reading and eye-tracking experiments.

Frequency and Processing Difficulty

The aim of the present study is to test the Tuning Hypothesis, i.e., the claim that there is a correlation between the frequency of a structure in the linguistic environment and global processing difficulty, as measured by magnitude estimation studies. Before we can test this claim, we have to find a way of approximating the linguistic environment of a speaker, i.e., we need a sample of the linguistic input that the speaker is exposed to. Such samples are readily available for a number of languages in the form of corpora, large computerized collections of text or speech. In the remainder of the paper, we will assume that the frequency distributions in the linguistic environment can be approximated by frequency distributions in a corpus.

For German, a suitable corpus is available in the form of Negra (Skut, Krenn, Brants, & Uszkoreit, 1997), a 350,000 word corpus of newspaper text. Negra is annotated with (a) part of speech labels (e.g., KOUS for complementizer), ART for article, NN for count noun, and VVFIN for finite verb; (b) syntactic information in the form of syntactic trees and phrase structure labels (e.g., NP for noun phrase, S for sentence); (c) grammatical function labels (e.g., HD for head, SB for subject, OA for accusative object). Figure 1 shows a Negra-style structure for the sentence in (1) (subordinate clause only; a subset of the Negra function labels is displayed).

A corpus annotated with syntactic structure affords a straightforward way of testing the Tuning Hypothesis: We extract all instances of a given structure from the corpus and then correlate the resulting frequencies with a measure of processing difficulty.

This naive approach, however, is not feasible due to data sparseness: many of the word orders tested in Experiments 1 and 2 are rare in the corpus, which makes it difficult to obtain reliable frequency counts for these structures. As an example consider the frequency data that Kurz (2000) extracted from Negra. Kurz (2000) investigated the word order patterns of certain ditransitive verbs, such as geben ‘give’ vorstellen ‘present’, and zur Verfügung stellen ‘make available’. All instances of these verbs were extracted from Negra and then classified with respect to the order of their objects. The resulting frequencies are given in Table 1. The column headed Total lists the overall frequency of a given verb in the corpus; the IO column contains the number of cases where the indirect object (dative NP) precedes the direct object (accusative NP), the OI column lists the counts for the inverse order. The frequencies in these two columns only take into account cases in which both objects are realized as full NPs; Kurz (2000) does not report data on pronounalized word orders.

In principle, we could now correlate the frequencies in Table 1 with the results of Experiment 2, in which it was found that OI orders are harder to process than IO orders (see (4)). However, as the corpus counts are too sparse for such a comparison: three out of six counts are zero, and also the other three orders are very rare. This means that no reliable claims can be derived from these counts.

This example indicates that data sparseness makes it impossible to directly correlate corpus frequency and processing difficulty, at least for the particular syntactic construction we are interested in here, and for the corpus we are using. In cognitive terms, this means that it is implausible to assume that the human parser directly keeps track of structural frequencies in its environment to determine word order preferences; it simply does not encounter the relevant structures often enough to derive reliable statistics.
Probabilistic Context-Free Grammars

In the last section, we argued that data sparseness makes it implausible that the human parser directly records structural frequencies. We will therefore pursue an alternative hypothesis: that the parser keeps track of the frequencies of grammar rules.

More specifically, we will assume that global processing difficulty can be modeled using a probabilistic context-free grammar (PCFG). Models of syntactic disambiguation (i.e., of local processing difficulty) based on PCFGs have been proposed by a variety of authors and have been shown to account for experimental findings on human disambiguation preferences (Jurafsky, 1996; Lotocky, 1997). More specifically, we will assume that global processing difficulty, i.e., that improbable structures are harder to process than probable ones.

Figure 2: Example of a PCFG

<table>
<thead>
<tr>
<th>Rule</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>S → KOUS NP NP VVFIN</td>
<td>.9</td>
</tr>
<tr>
<td>S → KOUS NP VVFIN</td>
<td>.1</td>
</tr>
<tr>
<td>NP → ART NN</td>
<td>1.0</td>
</tr>
<tr>
<td>VVFIN → kauft</td>
<td>1.0</td>
</tr>
<tr>
<td>KOUS → dass</td>
<td>1.0</td>
</tr>
<tr>
<td>ART → der</td>
<td>.8</td>
</tr>
<tr>
<td>ART → den</td>
<td>.2</td>
</tr>
<tr>
<td>NN → Vater</td>
<td>.6</td>
</tr>
<tr>
<td>NN → Wagen</td>
<td>.4</td>
</tr>
</tbody>
</table>

Figure 3: Example of tree generated by a PCFG

\[
P(t) = .9 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot .8 \cdot .6 \cdot .2 \cdot .4 = .03456
\]

Lexicalization can be seen as a way of approximating linguistic information that is not explicit in the corpus (and in the grammar). An example is morphological information: the label NP[Vater] implicitly contains the information that the NP is nominative, third person, and singular, i.e., the morphological features of Vater ‘father’. Lexicalization is also a way of incorporating co-occurrence information into the grammar. The rule S[kauft] → KOUS NP[Vater] NP[Wagen] VVFIN contains the information that the verb kauft ‘buys’ co-occurs with the nouns Vater ‘father’ and Wagen ‘car’, thus capturing the semantic relationship between these three words. There is evidence in the psycholinguistic literature showing that the human parser makes use of morphological information (e.g., Trueswell, 1996) and semantic plausibility (e.g., Garnsey, Pearlmutter, Myers, & Lotocky, 1997).

Modeling Broad Coverage

We developed three models of global processing difficulty, as outlined in the previous section: (a) a baseline model using a standard PCFG, the (b) a lexicalized model.
using a lexicalized PCFG, and (c) a functional model based on a PCFG that includes grammatical function labels. In all three cases both the grammar rules and the probabilities were derived from the Negra corpus.

Method

Negra was split into three subsets: the first 90% of the corpus were used as training set, the remainder was divided into a 5% test set and a 5% development set (for parameter tuning). Sentences with more than 40 words were removed (to increase parsing efficiency).

The baseline model was realized using the probabilistic left-corner parser Lopar (Schmid, 2000), running in unlexicalized mode. A grammar and a lexicon were read off the Negra training set, after empty categories and function labels had been removed from the corpus. The lexicalized model was also realized using Lopar, which in lexicalized mode implements Carroll and Rooth’s (1998) model. Lexicalization requires that each rule in a grammar has one of the categories on its righthand side annotated as the head. For the categories S, VP, AP, and AVP, the head is marked in Negra. For the other categories, we used rules to heuristically determine the head. The functional model was implemented by introducing a new grammar from the training set: the function labels SB, OA, and DA were kept, but all other function labels were removed. The model was again implemented by running Lopar in unlexicalized mode.

The parameters for all three models were estimated using maximum likelihood estimation. This means that \( P(LHS \rightarrow RHS) \), the probability of rule \( LHS \rightarrow RHS \), is estimated as \( P(LHS \rightarrow RHS) = f(LHS \rightarrow RHS)/N \), where \( f(LHS \rightarrow RHS) \) is the number of times the rule occurs in the training data, and \( N \) is the overall number of rules in the training data. Various smoothing schemes are implemented in Lopar to address data sparseness, see Schmid (2000) for details.

Results

All models were evaluated by running them on the test corpus, which had remained unseen during model development. As is standard in the computational linguistics literature, we measured labeled bracketing: to score a hit, the parser has to predict both the bracket (the beginning or end of a phrase) and the category label correctly. We report labeled recall (LR), i.e., the number of correct labeled brackets found by the parser divided by the total number of labeled brackets in the test corpus, and labeled precision (LP), i.e., the number of correct labeled brackets found by the parser divided by the total number of labeled brackets found by the parser. We also list the F-score, which is defined as \( F = 2 \cdot LP \cdot LR/(LP + LR) \).

The results are given in Table 2. The baseline model achieves an F-score of 71.9%, while the functional model performs slightly worse with an F-score of 70.9%. The lexicalized model performs worse than the baseline with an F-score of 63.9%.

Table 2: Testing the coverage of the models using labeled bracketing scores

<table>
<thead>
<tr>
<th></th>
<th>Failed parses:</th>
<th>constant</th>
<th>removed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( r )</td>
<td>( p )</td>
<td>( N )</td>
</tr>
<tr>
<td>Baseline</td>
<td>.393</td>
<td>.000</td>
<td>128</td>
</tr>
<tr>
<td>Lexicalized</td>
<td>.512</td>
<td>.000</td>
<td>128</td>
</tr>
<tr>
<td>Functional</td>
<td>.137</td>
<td>.123</td>
<td>128</td>
</tr>
</tbody>
</table>

Table 3: Modeling results for Experiment 1

Modeling Global Processing Difficulty

Recall that the aim of this study is to test the hypothesis that there is a correlation between the frequency of a structure in the linguistic environment and global processing difficulty. We have argued that structural frequency cannot be measured directly due to data sparseness. Instead, we hypothesized that the probability of a structure, as computed by a PCFG, is a predictor of processing difficulty. In this section, this hypothesis will be tested against the data sets from Experiments 1 and 2.

Experiment 1

We tested each of the models (baseline, lexicalized, and functional) against the experimental data as follows. The sentences used as experimental materials was parsed by the model, and the probability of the most probable parse was computed. This probability was normalized by sentence length (measured as the number of words in the sentence). This is necessary as a PCFG assigns lower probabilities to longer sentences (all other factors being equal), as longer sentences involve more rule applications.

To compare the models, we conducted a set of correlation analyses: we correlated the log of the probability predicted by the model for each sentence with the log of the mean magnitude estimation score for this sentence. The parser failed on some sentences, i.e., it did not find a parse. There are two ways of dealing with this problem: (a) setting the probability of a failed parse to a small, constant probability, and (b) removing the failed parses from the data. Table 3 lists the correlation coefficients for all three models and for both ways of dealing with failed parses.

The results show that the baseline and lexicalized models obtain significant correlations with the ME data. The functional model only achieves a correlation once the failed parses are removed; however, there are a lot of failed parses here (only 78 data points remain), so this result has to be interpreted with caution. We performed a t-test to compare the correlation coefficients achieved by the baseline model and the lexicalized model (failed parses removed). The correlation of the lexicalized model was significantly higher \( t(109) = 2.454, p < .05 \). The fact that the lexicalized model outperforms the unlexicalized baseline model points to the important role that morphological and semantic information (plausibility) plays for global processing difficulty. Such information is approximated in the lexicalized model, but...
The distinction between verb final and verb initial orders is captured successfully by our model. However, this raises the question if the two word orders are considered separately. In the following, we will further investigate the behavior of the models for verb final orders based on the data from Experiment 2 which only dealt with verb final sentences. Experiment 2 also provides a larger amount of data, viz., 192 items (compared to the 64 verb final items from Experiment 1). Furthermore, Experiment 2 provides a test of the generality of the modeling results, as it included ditransitive verbs, giving rise to additional word orders not included in Experiment 1.

We used the same modeling procedure as for the data from Experiment 1. The results for all three models and for the two ways of treating failed parses (set to a constant or remove) are listed in Table 5. We observe significant correlations for the baseline model and the lexicalized model for both ways of treating failed parses. Note that the lexicalized model again achieves higher correlation coefficients than the baseline model. However, a t-test shows that this difference is not significant.

For the functional model, we find a high correlation if failed parses are set to a constant; however, this correlation disappears if the failed parses are removed from the data set, leaving only 39 items. In other words, the functional model fails to assign a parse in most of the cases; this is probably due to data sparseness: there are not enough instances of ditransitive verbs in the corpus to acquire realistic probabilities for the functional model.

Figure 6 plots the magnitude estimation scores of Experiment 2 against the probabilities predicted by the lexicalized model (failed parses removed). The graph shows that this time all sentences behave in the same way; there is no split into two sentence types (such as the verb final/verb initial split in the model of Experiment 1).

**Table 5: Modeling results for Experiment 2**

<table>
<thead>
<tr>
<th>Failed parses:</th>
<th>constant removed</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>p</td>
<td>N</td>
<td>r</td>
</tr>
<tr>
<td>Baseline</td>
<td>.219</td>
<td>.082</td>
<td>64</td>
<td>.057</td>
</tr>
<tr>
<td>Lexicalized</td>
<td>.233</td>
<td>.064</td>
<td>64</td>
<td>.067</td>
</tr>
<tr>
<td>Functional</td>
<td>.155</td>
<td>.220</td>
<td>64</td>
<td>.296</td>
</tr>
</tbody>
</table>

**Table 4: Modeling results for Experiment 1, separation of verb final and verb initial items**

<table>
<thead>
<tr>
<th>Failed parses:</th>
<th>constant removed</th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>p</td>
<td>N</td>
<td>r</td>
</tr>
<tr>
<td>Baseline</td>
<td>.109</td>
<td>.392</td>
<td>64</td>
<td>.070</td>
</tr>
<tr>
<td>Lexicalized</td>
<td>.123</td>
<td>.333</td>
<td>64</td>
<td>.089</td>
</tr>
<tr>
<td>Functional</td>
<td>.044</td>
<td>.733</td>
<td>64</td>
<td>.011</td>
</tr>
</tbody>
</table>

Figure 5: Correlation for the lexicalized model (failed parses removed) for Experiment 1

Figure 6: Correlation for the lexicalized model (failed parses removed) for Experiment 2

**Experiment 2**

The modeling results for the data from Experiment 1 showed that our models are able to distinguish between verb final and verb initial orders. However, the results also indicated that the models failed to reliably predict processing difficulty if the two word orders are considered separately. In the following, we will further investigate the behavior of the models for verb final orders based on the data from Experiment 2 (which only dealt with verb final sentences). Experiment 2 also provides a larger amount of data, viz., 192 items (compared to the 64 verb final items from Experiment 1). Furthermore, Experiment 2 provides a test of the generality of the modeling results, as it included ditransitive verbs, giving rise to additional word orders not included in Experiment 1.

We used the same modeling procedure as for the data from Experiment 1. The results for all three models and for the two ways of treating failed parses (set to a constant or remove) are listed in Table 5. We observe significant correlations for the baseline model and the lexicalized model for both ways of treating failed parses. Note that the lexicalized model again achieves higher correlation coefficients than the baseline model. However, a t-test shows that this difference is not significant.

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Conclusions
In this paper, we tested the Tuning Hypothesis by applying it to global processing difficulty as measured by magnitude estimation. Two experimental data sets were used, both dealing with word order variation in German. We argued that data sparseness makes it implausible that the human parser directly records structural frequencies; instead, we assumed that it keeps track of rule frequencies. We implemented this hypothesis in a series of models based on probabilistic context free grammars. Sentence probabilities predicted by these models were shown to be significantly correlated with the ME scores obtained experimentally. We also showed that our models make predictions with respect to the differential processing of verb final and verb initial sentences. These predictions were borne out in the ME data.

Three different probabilistic models were tested, each incorporating different types of linguistic information. The baseline model was based on a standard PCFG; it achieved a significant correlation with ME data for both experiments. However, a model that incorporates lexical information into the category labels achieved a better fit with the experimental data than the baseline model. This indicates that the information that is approximated by the lexical model, viz., morphological information and semantic plausibility, plays a role in determining global processing difficulty. We also investigated the behavior of a functional model, in which the categories of the grammar incorporate grammatical function labels (subject, object, etc.). However, this model did not outperform the baseline model. This could be due to sparse data; there are not enough corpus examples available to reliably estimate the parameters of the functional model.

Many models in the psycholinguistic literature are designed to account for ‘pathological’ behavior of the processor, i.e., for cases of processing breakdown (such as garden paths). They are unable to explain why the human parser directly records structural frequencies. Instead, we assumed that it keeps track of rule frequencies. This is borne out in the ME data.

Finally, our approach also presents a methodological innovation. Previous work on probabilistic models of human parsing (Jurafsky, 1996; Crocker & Brants, 2000; Hale, 2001) only contained a simple, qualitative form of evaluation. Typically, the model is applied on a small set of examples to check if it predicts the correct processing pattern for these sentences. The present paper presented a more rigorous form of evaluation: we used two large data sets (128 and 192 sentences, respectively) and performed a quantitative evaluation by correlating model probabilities and ME scores. Model fit was measured using correlation coefficients, making it possible to compare the performance of different models on the same data.

References