

Evaluation of the NLP Components of the OVIS2 Spoken Dialogue System

Gert Veldhuijzen van Zanten¹

Gosse Bouma²

Khalil Sima'an³

Gertjan van Noord²

Remko Bonnema⁴

¹ IPO Eindhoven

² Rijksuniversiteit Groningen

³ Universiteit Utrecht

⁴ Universiteit van Amsterdam

Abstract

The NWO Priority Programme *Language and Speech Technology* is a 5-year research programme aiming at the development of spoken language information systems. In the Programme, two alternative natural language processing (NLP) modules are developed in parallel: a grammar-based (conventional, rule-based) module and a data-oriented (memory-based, stochastic, DOP) module. In order to compare the NLP modules, a formal evaluation has been carried out three years after the start of the Programme. This paper describes the evaluation procedure and the evaluation results. The grammar-based component performs much better than the data-oriented one in this comparison.

1 Introduction

The NWO Priority Programme *Language and Speech Technology* is a 5-year research programme aiming at the development of spoken language information systems. Its immediate goal is to develop a demonstrator of a public transport information system, which operates over ordinary telephone lines. This demonstrator is called OVIS, Openbaar Vervoer Informatie Systeem (*Public Transport Information System*). The language of the system is Dutch.

In this Programme, two alternative NLP modules are developed in parallel: a grammar-based (conventional, rule-based) module and a data-oriented (memory-based, stochastic, DOP) module. Both of these modules fit into the system architecture of OVIS. They accept as their input *word graphs* produced by the automatic speech recognition component, and produce *updates* which are passed on to the pragmatic analysis component and dialogue manager.

A word graph (Oerder and Ney, 1993) is a compact representation for all sequences of words that the speech recogniser hypothesises for a spoken utterance. The states of the graph represent points in time, and a transition between two states represents a word that may have been uttered between the corresponding points in time. Each transition is associated with an *acoustic score* representing a measure of confidence that the word perceived there was actually uttered.

The dialogue manager maintains an information state to keep track of the information provided by the user. An *update* expression is an instruction for updating the information state. The syntax and semantics of such updates are defined in Veldhuijzen van Zanten (1996). The sentence:

- (1) Ik wil op 4 februari van Amsterdam naar Groningen
 I want on 4 February from Amsterdam to Groningen
 I want to travel from Amsterdam to Groningen on February 4th

is translated into the update expression:

- (2) (user.wants.
 (destination.(place.groningen);
 (origin.(place.amsterdam));
 (moment.at.(date.(month.february;day.4))))

which indicates that the destination and origin slots can be filled in, as well as the moment.at slot.

In order to compare the NLP modules, a formal evaluation has been carried out three years after the start of the Programme. In this paper, we first shortly describe the two competing NLP components in section 2. The evaluation measures string accuracy, semantic accuracy and computational resources. This is described in more detail in section 3. The evaluation results are presented in section 4. On the basis of these results some conclusions are drawn in section 5.

2 Two NLP Components

For detailed descriptions of the NLP components, the reader is referred to van Noord et al. (1996a), van Noord et al. (1996b) and van Noord et al. (1999) for the grammar-based NLP module. The data-oriented approach is documented in Scha et al. (1996), Sima'an (1997) and Bod & Scha (1997).

2.1 Data Oriented Parsing

Research in the Data Oriented Parsing framework explores the hypothesis that humans analyse new input by drawing analogies with concrete past language experiences, rather than by applying abstract rules (Scha 1990).

In developing computational models embodying this idea, we have so far focused on one particularly straightforward instantiation of it: our algorithms analyse new input by considering the various ways in which this input might be generated by a stochastic process which combines fragments of trees from an annotated corpus of previously encountered utterances. Formally, these models may be viewed as implementing extremely redundant Stochastic Tree Substitution Grammars (STSG's); the grammar rules are the subtrees extracted from the annotated corpus (Bod 1992).

An important parameter of models of this sort is the way in which the subtree-substitution probabilities in the stochastic process are computed on the basis of the subtree frequencies in the annotated corpus. All current models follow (Bod 1992) in defining the probability of substituting a subtree t on a specific node as the probability of selecting t among all subtrees in the corpus that could be substituted on that node, i.e., as the number of occurrences of t divided by the total number of occurrences of subtrees t' with the same root node label as t :

$$(3) \quad P(t) = \frac{|t|}{\sum_{t': \text{root}(t') = \text{root}(t)} |t'|}$$

Given these subtree substitution probabilities, the probability of a derivation $t_1 \circ \dots \circ t_n$ can be computed as the product of the probabilities of the substitutions that it consists of

$$(4) \quad P(t_1 \circ \dots \circ t_n) = \prod_i P(t_i)$$

The probability of a parse tree is equal to the probability that any of its distinct derivations is generated, which is the sum of the probabilities of all derivations of that parse tree. Let t_{id} be the i -th subtree in the derivation d that yields tree T , then the probability of T is given by:

$$(5) \quad P(T) = \sum_d \prod_i P(t_{id})$$

An efficient polynomial algorithm for computing the Most Probable Derivation is given in Sima'an (1996a). From a theoretical point of view we might expect the computation of the Most Probable Parse to yield better disambiguation accuracies than the Most Probable Derivation, and this expectation was confirmed by certain experiments. However, Sima'an (1996b) has shown that the problem of computing the Most Probable Parse is not solvable by deterministic polynomial time algorithms. For reasons regarding time-complexity, the most probable derivation (MPD) is still the method of choice for a real-world application.

The algorithm presented in Sima'an (1996a) is implemented in the "Data Oriented Parsing and Disambiguation System" (DOPDIS). The algorithm extends a well-known CFG parsing algorithm (the CKY algorithm) in a suitable way in order to deal with STSG's. The extension makes use of the fact that the paths in a parse-tree, which is generated from an STSG derivation for a given sentence, form a regular set that can be easily computed. By computing such sets, DOPDIS generates exactly the necessary trees which the STSG dictates. On top of this mechanism, DOPDIS computes both the most probable derivation and the probability of an input sentence. The construction operates in time-complexity which is cubic in sentence length and linear in STSG size, which is a good achievement in parsing tree grammars (existing tree-parsing techniques have complexity which is square in grammar size).

The extension to parsing and disambiguating word graphs maintains the same time and space complexity (where instead of sentence length here the complexity concerns the numbers of nodes i.e. states the word graph contains). DOPDIS computes the so called Most Probable Intersection-Derivation of a word graph and the

DOP STSG. An intersection-derivation (i-derivation) is a pair $\langle \textit{string}, \textit{derivation} \rangle$ where *string* is the string of words on a path in the input word graph, and *derivation* is an STSG derivation for that string. The probability of the i-derivation is computed through a weighted product of the probabilities on the path in the word graph and the STSG-derivation probability. The probabilities of the word graph paths are obtained from the speech-recognisers likelihoods by a normalisation heuristic. The probabilities resulting from this heuristic combine better with the DOP probabilities than raw speech recogniser likelihoods. The issue of scaling the likelihoods of the speech-recogniser in a well-founded way is still under study. The current method divides the likelihood of every transition by a normalisation factor that is computed from the word graph.

An extension to semantic interpretation. In van den Berg, Bod and Scha (1994), an extension of the model to semantic interpretation is presented. A first implementation of this extension was described in Bonnema (1996). A DOP model as described above can be extended from just syntactic, to semantic analysis, by augmenting the trees in the tree-bank with semantic *rules*. These rules indicate, for each individual analysis in the tree-bank, how its meaning is constructed out of the meaning of its parts. Just as in the purely syntactic version of DOP, we extract all possible fragments from these syntactic/semantic analyses. We then use these fragments to build an STSG. We alter the constraints on tree substitution, by demanding that both the syntactic category and the semantic type of the root node of a subtree match with those at the substitution site. Note that the semantic types restrict the possibility of substitution. The language generated by an STSG created on the basis of a semantically enriched tree-bank, is therefore a subset of the language generated by an STSG created on the basis of the same tree-bank without the semantic annotations. Ideally, the former STSG would exclude exactly the set of semantically ill-formed sentences. The preferred analysis of an utterance will now provide us with both a syntactic and a semantic interpretation. In the current implementation the most probable analysis is taken to be the interpretation given by the most probable derivation.

A corpus of syntactic and semantic analyses of transcribed utterances from the OVIS domain was created to test this model. The OVIS tree-bank currently contains 10.000 analyzed utterances. The top-node semantics of each annotated utterance is an *update-expression* that conforms to the formalism described in Veldhuijzen van Zanten (1996). The semantic label of a node N in an analysis consists of a rule, that indicates how the meaning of N (the *update*) is built-up out of the meanings of N 's daughter nodes. This semantic rule is typed. Its type follows from both the rule itself, and from the types of the semantic labels of the daughter-nodes of N , given the definition of the logical language used. In the present case, the type of an expression is a pair of integers, its *meet* and *join*. The *meet* and *join* correspond to the *least upper bound* and the *greatest lower bound* of the expression in the type-hierarchy, as described in Veldhuijzen van Zanten (1996).

A semantically enriched STSG as described above, must fulfil an important property. It has to be possible to define a function from derivations to logical for-

mulas, that is defined for every derivation that can be produced by the grammar. In other words, the information provided by semantic types and syntactic categories in an analysis must be sufficient. Because the set of subtrees is closed under the operation of subtree extraction, i.e., all subtrees T' that can be extracted from another subtree T , belong to the same set as T , it is easy to establish this property, even for a very large grammar. We only need to look at the subtrees of depth one. If there is a unique semantic rule associated with the root-node of all subtrees of depth one, given the syntactic categories and semantic types of its nodes, it follows that we know the semantic rule at the nonterminal-nodes of every subtree. Fortunately, the nature of the annotated tree-bank is such, that in about 99.9 % of cases we can indeed establish the semantic rule at the root-node of a subtree in this way. The few exceptions are assigned an “exception-type”, to reduce the uncertainty to zero. We exploit the property described above, to construct a rewrite system for the semantic STSG. This rewrite system applies the semantic rules associated with every node in a derivation in a bottom up fashion, and arrives at the complete logical formula.

Methods for word graphs. The evaluation experiments were performed using just the semantic DOP-model as it was described above.

For every word graph the most probable intersection derivation was determined. The leaf-nodes of this derivation constitute the best path through the word graph. The probability of a derivation is calculated on the basis of both the probabilities of the subtrees extracted from the OVIS tree-bank, and the acoustic likelihoods of the words in the word graph.

We created several instances of the semantic DOP-parser, with differing constraints on the form of possible subtrees. Four parameters can be distinguished, whose values determine the constraints on subtrees. Below the parameters are given, with the letters we commonly use to refer to each parameter.

- d** The maximal depth of subtrees.
- I** The maximal number of lexical items in a subtree.
- L** The maximal number of consecutive lexical items in a subtree.
- n** The maximal number of substitution sites in a subtree.

Obviously, the number of possible combinations is huge. We chose to use the parameter settings for which previous experiments yielded the best results.

The results presented in this document are all obtained using the following settings: **I**=9, **L**=3, **n**=2. For the maximum depth we used **d**=2 and **d**=4. No constraints were applied to subtrees of depth 1.

If a word graph contains more than 350 transitions, the maximum depth of subtrees is automatically limited to *two*, to avoid excessive memory requirements. About 3% of word graphs in the testing material do contain more than 350 transitions.

Methods for test sentences. For sentences, we used the same parameter settings, but added an experiment with $d=5$.

In this document, some results on sentences are given with the extra indication *group*. We will now briefly explain what this means.

Non-terminals in the semantic DOP-model consist of a syntactic-category / semantic-type pair. Such a non-terminal imposes a rather rigid constraint on substitution. For the parsing of word graphs, this constraint seems to be beneficiary. For the parsing of sentences, on the other hand, these constraints could be too rigid. A greater degree of freedom results in over-generation, which in turn may lead to better statistics. An algorithm was designed to group semantic types that have a comparable distribution. This results in fewer non-terminals in the tree-bank, and has been shown to lead to a higher semantic accuracy for sentences. The results marked with *group* indicate that this grouping algorithm has been employed.

2.2 Grammar-based NLP

The grammar-based NLP component developed in Groningen is based on a detailed computational grammar for Dutch, and a robust parsing algorithm which incorporates this grammatical knowledge as well as other knowledge sources, such as the acoustic evidence (present in the word graph) and Ngram statistics (collected from a large set of user utterances). It has been argued (van Noord et al. 1999) that robust parsing can be based on sophisticated grammatical analysis. In particular, the grammar describes full sentences, but in doing so, also describes the grammar of temporal expressions and locative phrases which are the crucial concepts for the timetable information application. Robustness is achieved by taking these phrases into consideration, if a full parse of an utterance is not available.

Computational Grammar for Dutch. In developing the grammar the short-term goal of developing a grammar which meets the requirements imposed by the application (i.e. robust processing of the output of the speech recogniser, extensive coverage of locative phrases and temporal expressions, and the construction of fine-grained semantic representations) was combined with the long-term goal of developing a general, computational, grammar which covers all the major constructions of Dutch.

The design and organisation of the grammar, as well as many aspects of the particular grammatical analyses, are based on Head-driven Phrase Structure Grammar (Pollard and Sag 1994). The grammar is compiled into a restricted kind of definite clause grammar for which efficient processing is feasible. The semantic component follows the approach to monotonic semantic interpretation using *quasi-logical forms* presented originally in Alshawi (1992).

The grammar currently covers the majority of verbal subcategorisation types (intransitives, transitives, verbs selecting a PP, and modal and auxiliary verbs), NP-syntax (including pre- and post-nominal modification, with the exception of relative clauses), PP-syntax, the distribution of VP-modifiers, various clausal types (declaratives, yes/no and WH-questions, and subordinate clauses), all temporal ex-

pressions and locative phrases relevant to the domain, and various typical spoken-language constructs. Due to restrictions imposed by the speech recogniser, the lexicon is relatively small (3200 word forms, many of which are names of stations and cities).

Robust and Efficient Parsing. Parsing algorithms for strings can be generalised to parse word graphs (van Noord 1995). In the ideal case, the parser will find a path in the word graph that can be assigned an analysis according to the grammar, such that the path covers the complete time span of the utterance, i.e. the path leads from the start state to a final state. The analysis gives rise to an update of the dialogue state, which is then passed on to the dialogue manager.

However, often no such paths can be found in the word graph, due to:

- errors made by the speech recogniser,
- linguistic constructions not covered in the grammar, and
- irregularities in the spoken utterance.

Even if no full analysis of the word graph is possible, it is usually the case that useful information can be extracted from the word graph. Consider for example the utterance:

- (6) Ik wil van van Assen naar Amsterdam
 I want from from Assen to Amsterdam
 I want to travel from Assen to Amsterdam

The grammar will not assign an analysis to this utterance due to the repeated preposition. However, it would be useful if the parser would discover the prepositional phrases *van Assen* and *naar Amsterdam* since in that case the important information contained in the utterance can still be recovered. Thus, in cases where no full analysis is possible the system should fall back on an approach reminiscent of concept spotting. In van Noord et al. (1999) a general algorithm is proposed which achieves this.

The first ingredient to a solution is that the parser is required to discover all occurrences of major syntactic categories (such as noun phrase, prepositional phrase, subordinate sentence, root sentence) *anywhere in the word graph*. Conceptually, one can think of these categories as edges which are added to the word graph in addition to the transitions produced by the speech recogniser.

For such word graphs annotated with additional category edges, a path can be defined as a sequence of steps where each step is either a transition or a category edge. A transition step is called a 'skip'. For a given annotated word graph many paths are possible. On the basis of an appropriate *weight* function on such paths, it is possible to search for the *best* path. The search algorithm is a straightforward generalisation of the DAG-SHORTEST-PATH algorithm (Cormen et al. 1990).

The weight function is sensitive to the following factors:

- Acoustic score. Obviously, the acoustic score present in the word graph is an important factor.
- The number of skips is minimised in order to obtain a preference for the maximal projections found by the parser.
- Number of maximal projections. The number of maximal projections is minimised in order to obtain a preference for more extended linguistic analyses over a series of smaller ones.
- Ngram statistics.

The grammar-based NLP component is implemented in SICStus Prolog. Below we report on a number of different methods which are all variations with respect to this weight function.

Variants of Grammar-based NLP. The grammar-based NLP methods that have taken part in the evaluation are of two types. The first type, $b(B,N)$, consists of two phases. In the first phase the word graph is made smaller by selecting the N-best paths from the word graph, using the acoustic scores and a language model consisting of bigrams (B=bi) or trigrams (B=tri) (with bigrams for backing-off). Only those transitions of the word graph remain which are part of at least one of those N-best paths. In the second phase the parser is applied, using acoustic scores and a language model of trigrams (again with bigrams for backing-off).

The second type of method is $f(B,N)$. In this case, if the word graph contains less than N transitions, then the full word graph is input to the parser, and acoustic scores and a language model of trigrams (bigrams for backing-off) is applied to select the best analysis. If the word graph contains more than N transitions, then method $b(B,1)$ is applied.

3 Evaluation Procedure and Criteria

3.1 Procedure

An experimental version of the system has been available to the general public for almost a year. From a large set of more recent dialogues a subset was selected randomly for testing. Many of the other dialogues were available for training purposes. Both the training and test dialogues are therefore dialogues with 'normal' users.

In particular, a training set of 10K richly annotated word graphs was available. The 10K training corpus is annotated with the user utterance, a syntactic tree and an update. This training set was used to train the DOP system. It was also used by the grammar-based component for reasons of grammar maintenance and grammar testing.

A further training set of about 90K annotated user utterances was available as well. It was primarily used for constructing the Ngram models incorporated in the grammar-based component.

The NLP components of OVIS2 have been evaluated on 1000 unseen user utterances. The latest version of the speech recogniser produced 1000 word graphs on the basis of these 1000 user utterances. For these word graphs, annotations consisting of the actual sentence ('test sentence'), and an update ('test update') were assigned semi-automatically, without taking into account the dialogue context in which the sentences were uttered. These annotations were unknown to both NLP groups. The annotation tools are described in Bonnema (1996).

After both NLP components had produced the results on word graphs, the test sentences were made available. Both NLP components were then applied to these test utterances as well, to mimic a situation in which speech recognition is perfect.

The test updates were available for inspection by the NLP groups only after both modules completed processing the test material. A small number of errors was encountered in these test updates. These errors were corrected before the accuracy scores were computed. The accuracy scores presented below were all obtained using the same evaluation software.

3.2 Criteria

The NLP components were compared with respect to the following two tasks. Note that in each task, analysis proceeds in isolation from the dialogue context. The first task is to provide an update for the test sentence (in this report we refer to this update as the 'best update'). The second task is to provide an update and a sentence for the word graph ('best update' and 'best sentence'). The quality of the NLP components will be expressed in terms of string accuracy (comparison of the best sentences with the test sentences), semantic accuracy (comparison of the best updates with the test updates) and computational resources. Each of these criteria is now explained in more detail.

String accuracy. String accuracy measures the distance of the test sentence and the best sentence. String accuracy is expressed in terms of sentence accuracy (SA, the proportion of cases in which the test sentence coincides with the best sentence), and word accuracy (WA). The string comparison on which word accuracy is based is defined by the minimal number of substitutions, deletions and insertions of words that is required to turn the best sentence into the test sentence (Levenshtein distance). Word accuracy is defined as

$$(7) \quad WA = 1 - \frac{d}{n}$$

where n is the length of the actual utterance and d is the Levenshtein distance. For example, if the analysis gives 'a b a c d' for the utterance 'a a c e', then the Levenshtein distance is 2, hence the WA is $1 - 2/4$ is 50%.

Semantic accuracy. An update is a logical formula which can be evaluated against an information state and which gives rise to a new, updated information state. The most straightforward method for evaluating concept accuracy in this setting is to compare the update produced by the grammar with the annotated update. One problem with this approach is the fact that the update language does not provide a simple way to compute equivalence of updates (there is no notion of normal form for update expressions). A further obstacle is the fact that very fine-grained semantic distinctions can be made in the update-language. While these distinctions are relevant semantically (i.e. in certain cases they may lead to slightly different updates of an information state), they often can be ignored by a dialogue manager. For instance, the updates below are semantically not equivalent, as the ground-focus distinction is slightly different. In the first update the feature `place` is supposed to be *ground*, whereas in the second update, it is part of the *focus*.

- (8) `user.wants.travel.destination.place`
`([# town.leiden];[! town.abcoude])`
- (9) `user.wants.travel.destination.`
`([# place.town.leiden];[! place.town.abcoude])`

However, the dialogue manager will decide in both cases that this is a correction of the destination town.

Since semantic analysis is the input for the dialogue manager, we have therefore measured concept accuracy in terms of a simplified version of the update language. Following a somewhat similar proposal in Boros et al. (1996), we translate each update into a set of “semantic units”, where a unit in our case is a triple $\langle \textit{CommunicativeFunction Slot Value} \rangle$. For instance, the examples above translate as

- (10) `<denial destination_town leiden>`
`<correction destination_town abcoude>`

Both the updates in the annotated corpus and the updates produced by the system are translated into semantic units of the form given above. The syntax of the semantic unit language and the translation of updates to semantic units is defined in van Noord (1997), but note that the translation of updates to semantic units is relatively straightforward and is not expected to be a source of discussion, because the relation is many to one.

Semantic accuracy can now be defined as follows. Firstly, we list the proportion of utterances for which the corresponding semantic units exactly match the semantic units of the annotation (*exact match*). Furthermore we calculate *precision* (the number of correct semantic units divided by the number of semantic units which were produced) and *recall* (the number of correct semantic units divided by the number of semantic units of the annotation). Finally, following Boros et al. (1996) we also present concept accuracy as

$$(11) \quad CA = \left(1 - \frac{SU_s + SU_I + SU_D}{SU}\right)$$

	graphs	trans	states	words	t/w	max(t)	max(s)
input	1000	48215	16181	3229	14.9	793	151
normalised	1000	73502	11056	3229	22.8	2943	128

Table 1: **Characterisation of test set (1).** This table lists the number of transitions, the number of states, the number of words of the actual utterances, the average number of transitions per word, the maximum number of transitions, and the maximum number of states. The first row provides those statistics for the input word graph; the second row for the so-called normalised word graph in which all ϵ -transitions (to model the absence of sound) are removed. The number of transitions per word is an indication of the extra ambiguity for the parser introduced by the word graphs in comparison with parsing of an ordinary string.

where SU is the total number of semantic units in the corpus annotation, and SU_S , SU_I , and SU_D are the number of substitutions, insertions, and deletions that are necessary to make the (translated) update of the analysis equivalent to (the translation of) the corpus update.

Computational Resources. In order to measure computational efficiency, the total amount of CPU-time, the maximum amount of CPU-time per input, and the total memory requirements will be measured. Due to differences in hardware, details differ between the two NLP components.

For the data-oriented methods, the CPU-time given is the *user-time* of the parsing process, in seconds. This measure excludes the time used for system calls made on behalf of the process (this can be ignored). Time was measured on a Silicon Graphics *Indigo*, with a MIPS R10000 processor, running IRIX 6.2. Memory usage is the maximum number of mega-bytes required, to interpret the 1000 utterances. Regrettably, for a very small percentage (0.02%) of word graphs, the process ran out of memory. This means that the figures for word graph parsing indicate the size of the jobs at the moment the system gave up, which is generally when the physical memory is filled. On the other hand, we should acknowledge the fact that some large word graphs that *did* receive an interpretation, also approached this limit.

For the grammar-based methods, CPU-time is measured in milliseconds on a HP 9000/780 (running HP-UX 10.20). The system uses SICStus Prolog 3 #3. CPU-time include all phases of processing, but does not contain the time required for system calls (can be ignored) and garbage collection (adds at most 15% for a given run). The memory requirements are given as the increase of the UNIX process size to complete the full run of 1000 inputs. At start-up the process size can be as large as 30 megabytes, so this number has been added in order to estimate total memory requirements.

method	WA	SA
speech	69.8	56.0
possible	90.5	83.7
speech_bigram	81.1	73.6
speech_trigram	83.9	76.2

Table 2: **Characterisation of test set (2)**. Word accuracy and sentence accuracy based on acoustic score only (speech); using the best possible path through the word graph, i.e. based on acoustic scores only (possible); and using a combination of bigram (resp. trigram) scores and acoustic scores.

3.3 Test Set

Some indication of the difficulty of the set of 1000 word graphs is presented in table 1. A further indication of the difficulty of this set of word graphs is obtained if we look at the word and sentence accuracy obtained by a number of simple methods. The method *speech* only takes into account the acoustic scores found in the word graph. No language model is taken into account. The method *possible* assumes that there is an oracle which chooses a path such that it turns out to be the best possible path. This method can be seen as a natural upper bound of what can be achieved.

The methods *speech_bigram* and *speech_trigram* use a combination of bigram (resp. trigram) statistics and the speech score. In the latter four cases, a language model was computed from about 50K utterances (not containing the utterances from the test set). The results are summarised in table 2.

During the development of the NLP components of OVIS2, word graphs were typically small: about 4 transitions per word on average. During the evaluation, however, the number of transitions per word for the test set was much larger. It turned out that the NLP components had trouble with very large word graphs (both memory and CPU-time requirements increase rapidly).

Recently, improvements have already been obtained to treat such large word graphs. For example, the grammar-based NLP component has been extended with a heuristic version of the search algorithm which is *not* guaranteed to find the best path. In practice this implementation returns the same answers as the original search algorithm, but much more quickly so (two orders of magnitude faster).

4 Results of the Evaluation

This section lists the results for word graphs. In table 3 we list the results in terms of string accuracy, semantic accuracy and the computational resources required to complete the test.

The total amount of CPU-time is somewhat misleading because typically many word graphs can be treated very efficiently, whereas only a few word graphs require very much CPU-time. In table 4 we indicate the semantic accuracy (concept

Method	Site	String Acc		Semantic Accuracy				CPU		Mem max
		WA	SA	match	prec	recall	ca	total	max	
d2	A'dam	76.8	69.3	74.9	80.1	78.8	75.5	7011	648	619
d4	A'dam	77.2	69.4	74.9	79.1	78.8	75.1	32798	2023	621
f(bi,50)	Gron	81.3	74.6	79.5	82.9	83.8	79.9	215	16	37
f(bi,100)	Gron	82.3	75.8	80.9	83.6	84.8	80.9	297	15	37
f(bi,125)	Gron	82.3	75.9	81.3	83.9	85.2	81.3	340	24	38
b(bi,1)	Gron	81.1	73.6	78.5	82.1	83.1	78.9	175	16	31
b(bi,2)	Gron	82.3	75.7	80.8	83.9	84.8	81.1	255	20	32
b(bi,4)	Gron	82.8	76.0	80.8	83.8	85.0	81.3	479	115	34
b(bi,8)	Gron	83.4	76.5	81.6	84.6	85.6	82.2	780	276	43
b(bi,16)	Gron	83.8	76.4	81.7	84.9	86.0	82.6	1659	757	60
f(tr,50)	Gron	83.9	76.2	81.8	84.9	85.9	82.5	1399	607	64
f(tr,100)	Gron	84.2	76.6	82.0	85.0	86.0	82.6	1614	690	64
f(tr,125)	Gron	84.2	76.5	82.1	85.3	86.3	82.8	1723	755	64
b(tr,1)	Gron	83.9	76.2	81.5	84.5	85.7	82.2	1420	603	64
b(tr,2)	Gron	84.1	76.4	81.8	85.3	86.4	83.0	2802	1405	101
b(tr,4)	Gron	84.3	76.4	82.0	85.4	86.4	83.0	5524	2791	177

Table 3: **Accuracy and Computational Resources for 1000 word graphs.** String Accuracy and Semantic Accuracy is given as percentages; total and maximum CPU-time in seconds, maximum memory requirements in Megabytes.

accuracy) that is obtained if a time-out is assumed (in such cases we assume that the system does not provide an update).

We also present the results for test sentences (rather than word graphs). Such a test indicates what the results are if the speech recogniser would perform perfectly. Obviously, it does not make sense to measure string accuracy in such a set-up. Semantic accuracy and computational resources is presented in table 5. Because the average sentence length is very small, we present the results for concept accuracy versus the length of the input sentence in table 6.

5 Conclusions

The grammar-based methods developed in Groningen perform much better than the data-oriented methods developed in Amsterdam. For word graphs, the best data-oriented method obtains an error-rate for concept accuracy of 24.5%. The best grammar-based method performs more than 30% better: an error-rate for concept accuracy of 17.0%. For sentences, a similar difference can be observed. The best data-oriented method obtains an error rate for concept accuracy of 8.5% whereas the grammar-based method performs more than 40% better with a 5.0% error rate. The differences increase with increasing sentence length.

The grammar-based methods require less computational resources than the data-oriented methods. However, the CPU-time requirements are still outrageous for a small number of very large word graphs¹. For sentences, the grammar-based

¹As mentioned before, a dramatic reduction has been obtained by a heuristic search algorithm.

Method	Site	100	500	1000	5000	10000	>
d2	A'dam	37.0	53.0	58.1	68.1	70.4	75.5
d4	A'dam	24.6	34.5	38.2	50.4	57.3	75.1
f(bi,50)	Gron	46.0	73.7	76.9	80.3	80.3	79.9
f(bi,100)	Gron	44.4	67.9	75.3	81.1	81.2	80.9
f(bi,125)	Gron	44.6	64.9	73.3	81.3	81.7	81.3
b(bi,1)	Gron	58.2	73.1	76.6	79.3	79.2	78.9
b(bi,2)	Gron	54.7	74.1	77.6	81.1	81.5	81.1
b(bi,4)	Gron	49.6	72.3	75.6	80.3	80.5	81.3
b(bi,8)	Gron	45.9	70.2	74.4	80.9	81.5	82.2
b(bi,16)	Gron	42.2	65.5	72.5	78.0	81.0	82.6
f(tr,50)	Gron	45.5	71.2	75.4	81.0	81.7	82.6
f(tr,100)	Gron	44.5	64.2	71.9	80.5	81.8	82.6
f(tr,125)	Gron	44.1	62.2	70.2	80.6	81.9	82.8
b(tr,1)	Gron	52.7	70.9	74.7	80.7	81.2	82.2
b(tr,2)	Gron	49.6	68.8	72.7	79.1	81.4	83.0
b(tr,4)	Gron	48.0	66.6	71.6	78.2	79.5	83.0

Table 4: **Concept accuracy for 1000 word graphs** (percentages), if all results are disregarded with a time-out of respectively 100, 500, 1000, 5000, 10000 milliseconds of CPU-time. The last column repeats the results if no time-out is assumed.

Method	Site	Semantic Accuracy				CPU		Mem max
		match	prec	recall	ca	total	max	
d4	A'dam	92.2	93.8	91.2	90.4	856	14	21
group.d2	A'dam	93.0	94.0	92.5	91.6	91	9	14
group.d4	A'dam	92.7	93.8	91.8	91.0	1614	174	48
group.d5	A'dam	92.6	93.7	92.3	91.4	3159	337	78
nlp	Gron	95.7	95.7	96.4	95.0	27	1	31

Table 5: **Semantic Accuracy and Computational Resources for 1000 test sentences.** Total and maximum CPU-time in seconds; memory in Megabytes.

Method	site	all	≥ 2	≥ 4	≥ 6	≥ 8	≥ 10
# instances		1000	601	344	160	74	38
d4	A'dam	90.4	87.4	84.7	75.9	69.8	65.2
group.d2	A'dam	91.6	89.0	86.7	78.7	69.8	68.3
group.d4	A'dam	91.0	88.2	85.8	77.3	69.4	64.6
group.d5	A'dam	91.4	88.7	86.6	78.9	71.8	67.1
nlp	Gron	95.0	93.4	93.0	88.1	85.9	87.0

Table 6: **Concept Accuracy versus Sentence Length for 1000 test sentences.** The third column repeats the results for the full test set. The remaining columns list the results for the subset of the test set containing the sentences with at least 2 (4, 6, 8, 10) words.

component performs satisfactorily (with a maximum CPU-time of 610 milliseconds).

The by far most important problem for the application consists of disambiguation of the word graph. The evaluation shows that NLP hardly helps here: a combination of speech scores and trigram scores performs much better in terms of string accuracy than the data-oriented methods. The grammar-based methods have incorporated the insight that Ngrams are good at disambiguating word graphs; by incorporating Ngram statistics similar results for string accuracy are obtained. In order to see whether NLP helps at all, we could compare the $b(tr,1)$ method (which simply uses the best path in the word graph as input for the parser) with any of the other grammar-based methods. For instance, the method $b(tr,4)$ performs somewhat better than $b(tr,1)$ (83.0% vs. 82.2% concept accuracy). This shows that in fact NLP is helpful in choosing the best path². If it were feasible to use methods $b(tr,N)$ or $f(tr,N)$ with larger values of N , further improvements might be possible.

Once a given word graph has been disambiguated, then both NLP components work reasonably well: this can be concluded based upon the concept accuracy obtained for sentences. In those cases the grammar-based NLP component also performs better than the data-oriented parser; this indicates that the difference in performance between the two components is not (only) due to the introduction of Ngram statistics in the grammar-based NLP component.

The current evaluation has brought some important shortcomings of the DOP approach to light. Two important problems, for which solutions are in the making, are briefly discussed below.

The first one is the inadequacy of the definition of subtree probability. It turns out that Bod's equation (3) given on page 3 shows a bias toward analyses derived by subtrees from large corpus trees. The error lies in viewing an annotated corpus as the "flat" collection of all its subtrees. Information is lost when the distribution of the analyses that supply the subtrees is ignored. The effect is that a large part of the probability mass is consumed by subtrees stemming from relatively rare, large trees in the tree-bank. A better model has been designed, that provides a more reliable way of estimating subtree probabilities.

The second shortcoming we will discuss is the fact that existing DOP algorithms are unable to generalise over the syntactic structures in the data. Corpus-based methods such as the current implementation of DOP, assume that the tree-bank which they employ for acquiring the parser, constitutes a rich enough sample of the domain. It is assumed that the part of the annotation scheme that is actually instantiated in the tree-bank does not under-generate on sentences of the domain. This assumption is not met by our current tree-bank. It turned out that one can expect the tree-bank grammar to generate a parse-space containing the right syntactic/semantic tree only for approximately 90-91% of unseen domain utterances. This figure constitutes an upper bound on the accuracy for any probabilistic model. Enlarging the tree-bank does not guarantee a good coverage, however. The tree-bank will always represent only a sample of the domain. A solution for this

²This result is (just) statistically significant. We performed a paired T-test on the number of wrong semantic units per graph. This results in a t^* score of 2.0 (with 999 degrees of freedom).

problem is the development of automatic methods for generalising grammars, to enhance their coverage. The goal is to improve both accuracy and coverage by generalising over the structures encountered in the tree-bank.

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