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Processing Crossed and Nested Dependencies: An Automaton Perspective on the Psycholinguistic Results

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PROCESSING CROSSED AND NESTED DEPENDENCIES: AN AUTOMATON PERSPECTIVE ON THE PSYCHOLINGUISTIC RESULTS*†‡

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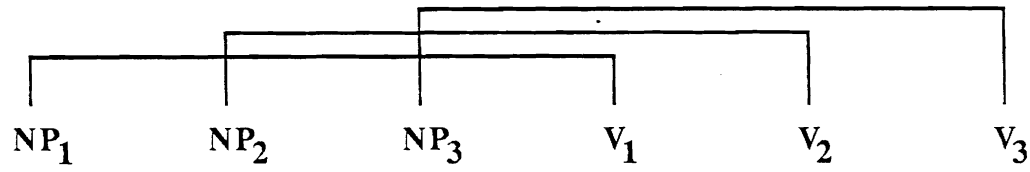
Abstract

The clause-final verbal clusters in Dutch and German (and in general, in West Germanic languages) has been extensively studied in different syntactic theories. Standard Dutch prefers crossed dependencies (between verbs and their arguments) while Standard German prefers nested dependencies. Recently Bach, Brown, and Marslen-Wilson (1986) have investigated the consequences of these differences between Dutch and German for the processing complexity of sentences, containing either crossed or nested dependencies. Stated very simply, their results show that Dutch is 'easier' than German, thus showing that the push-down automaton (PDA) cannot be the universal basis for the human parsing mechanism. They provide an explanation for the inadequacy of PDA in terms of the kinds of partial interpretations the dependencies allow the listener to construct. Motivated by their results and their discussion of these results we introduce a principle of partial interpretation (PPI) and present an automaton, embedded push-down automaton (EPDA) which permits processing of crossed and nested dependencies consistent with PPI. We show that there are appropriate complexity measures (motivated by the discussion in Bach, Brown, and Marslen-Wilson (1986)) according to which the processing of crossed dependencies is easier than the processing of nested dependencies. This EPDA characterization of the processing of crossed and nested dependencies is significant because EPDAs are known to be *exactly* equivalent to Tree Adjoining Grammars (TAG), which are also capable of providing a linguistically motivated analysis for the crossed dependencies of Dutch (Kroch and Santorini 1988). This significance is further enhanced by the fact that two other grammatical formalisms, (Head Grammars (Pollard, 1984) and Combinatory Grammars (Steedman, 1987), also capable of providing analysis for crossed dependencies of Dutch, have been recently shown to be equivalent to TAGs in their generative power. We have also briefly discussed some issues concerning the degree to which grammars directly encode the processing by automata, in accordance with PPI.

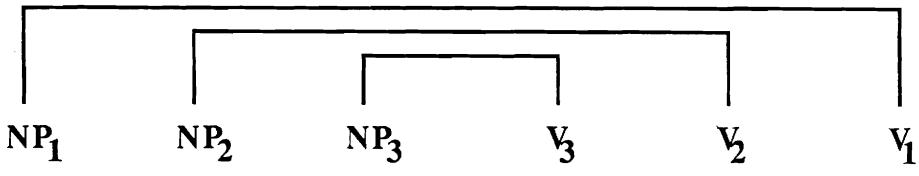
1 Introduction

The clause-final verbal clusters in Dutch and German (and, in general, in West Germanic languages) have been extensively studied in different syntactic theories both from the point of view of their syntactic variation as well as on their own account (Evers, 1975; Zaenen, 1979; den Besten and Edmonson, 1983; Breman, Kaplan, Peters, and Zaenen, 1983; Ades and Steedman, 1985; Haegeman and van Riemsdijk, 1986; Kroch and Santorini, 1988, among others). The main observation for our purpose is that Standard Dutch prefers crossed dependencies (between verbs and their arguments), while Standard German prefers nested dependencies. Thus in Dutch we have



(1)	Jan	Piet	Marie	zag	laten	zwemmen
	Jan	Piet	Marie	saw	make	swim
	(Jan	saw	Piet	make	Marie	swim)

In (1) NP_3 is an argument of V_3, NP_2 and S are arguments of V_2, and NP_1 and S are arguments of V_1. The dependencies between V_1, V_2, V_3 and their NP arguments, NP_1, NP_2, and NP_3 are *crossed* as shown in (1). In contrast, in German we have



(2)	Hans	Peter	Marie	schwimmen	lassen	sah
	Hans	Peter	Marie	swim	make	saw
	(Hans	saw	Peter	make	Marie	swim)

The dependencies between V_1, V_2, and V_3 and their NP arguments, NP_1, NP_2, and NP_3 are *nested* as shown in (2).

Recently Bach, Brown, and Marslen-Wilson (1986) have investigated the consequences of these differences between Dutch and German for the processing complexity of sentences, containing either crossed or nested dependencies. Stated very simply, their results show that Dutch is 'easier' than German. More specifically, in their study "German and Dutch subjects performed two tasks—ratings of comprehensibility and a test of successful comprehension—on matched sets of sentences which varied in complexity from a simple sentence to one containing three levels of embedding." Their results show "no difference between Dutch and German for sentences within the normal range (up to one level of embedding), but with a significant preference emerging for the Dutch crossed order for the more complex strings." Based on these results they argue that "this rules out the push-down stack as the universal basis for the human parsing mechanism." The following table (Table 1) summarizes some of their results. Note that levels in Table 1 refer to the number of verbs in the sentences and thus the level will be one more than the level of embedding in the sentence. The level for sentences (1) and (2) above is 3. Henceforth, this is what we mean by level, which is also in accordance with the notation in Bach, Brown, and Marslen-Wilson.

TABLE 1

Level of embedding	Dutch	German
1	1.14	1.16
2	2.34	2.58
	(0.23)	(0.42)
3	5.42	5.80
	(1.36)	(1.79)
4	7.66	7.86
	(1.72)	(2.04)

Mean rating of comprehensibility (Test)
Difference in mean Test/Paraphrase ratings (numbers in parentheses)

As is evident from Table 1, Dutch is easier than German. At level 1, there is no difference; at level 2, the difference is small, still favoring Dutch; beyond level 2, Dutch is definitely easier than German. These results of Bach, Brown, and Marslen-Wilson confirm the intuitive claim of Evers (1975), in his syntactic study of these structures, that the crossed structures of Dutch are easier to process than the nested structures of German. Hoeksema (1981) made a similar claim in his study of Dutch vis-à-vis Frisian, which has nested dependencies.

These results of Bach, Brown, and Marslen-Wilson thus show that the push-down automaton (PDA) cannot be the universal basis for the human parsing mechanism. Bach, Brown, and Marslen-Wilson offer an explanation for the inadequacy of PDA based on the kinds of partial interpretations

that the crossed and nested dependencies allow the listner to construct. Their main suggestion is "that the most important variable in successful parsing and interpretation is not simply *when* information becomes available, but also *what* you can do with that information when you get it." Thus in (2) (German example), when the deepest NP and V are reached, i.e., NP_3V_3 (Marie schwimmen), we have a verb and its argument, however, we do not know at this stage where this structure belongs, i.e., we do not have a higher structure into which we can integrate this information. Hence, we must hold this information until a higher structure becomes available. The same consideration holds for NP_2V_2. In contrast, in (1) (Dutch example), we can begin to build the matrix of higher verbs as soon as the verb cluster begins and the NP arguments can be integrated, without creating intermediate structures that do not have a place for them to fit into. The nested dependencies in German permit integration of structures (innermost to outermost) in a context-free manner (hence processed by a PDA) but it is not possible to decide what to do with this information until the higher verb(s) becomes available.

Motivated by the results of Bach, Brown, and Marslen-Wilson and their discussion of these results with respect to the inadequacies of PDA, we will introduce a principle of partial interpretation (PPI) which should be obeyed by an automaton if it is to be considered as a possible candidate for a universal mechanism for human sentence processing. PPI, as stated below, is an attempt to make some of the intuitions of Bach, Brown, and Marslen-Wilson more precise.

In an automaton, if a structure is popped, i.e., no longer stored by the automaton but discharged, possibly to another processor for further processing, the following conditions must hold:

1. The structure should be a properly integrated structure (with respect to the predicate-argument structure) and there should be a place for it to go, if it is expected to fit into another structure, i.e., the structure into which it will fit must have been popped already.

2. If a structure which has a slot for receiving another structure has been popped then the structure that will fill this slot will be popped next.

In this paper, we will present an automaton, embedded push-down automaton (EPDA), which will permit processing of crossed and nested dependencies consistent with PPI. We then show that there are appropriate complexity measures (also motivated by the discussion in Bach, Brown, and Marslen-Wilson), according to which the processing of crossed dependencies is easier than the processing of nested dependencies, thus correctly predicting the main results of Bach, Brown, and Marslen-Wilson. This EPDA characterization of the processing of crossed and nested dependencies is significant because EPDAs are known to be *exactly* equivalent to Tree Adjoining Grammars (TAG) in the sense that for any TAG, G, there is an EPDA, M, such that the language recognized by M, $L(M)$ is exactly the language generated by G, $L(G)$, and conversely for any EPDA, M', there is a TAG, G', such that $L(M') = L(G')$. TAGs were first introduced in Joshi, Levy and Takahashi

(1975) and have been actively investigated since 1983 (e.g., Joshi, 1983; Kroch and Joshi, 1987; Joshi, 1987; Kroch, 1987; Vijay-Shanker, 1987; Weir, 1988; Joshi, Vijay-Shanker, and Weir, 1988).

TAGs are more powerful than context-free grammars, but only 'mildly' so, and are capable of providing a linguistically motivated analysis for the crossed dependencies in Dutch (Joshi, 1983; Kroch and Santorini, 1988). The significance of the EPDA characterization of crossed dependencies is enhanced even further because two other grammatical formalisms, (Head Grammars (Pollard, 1984) and Combinatory Categorial Grammars (Steedman, 1985, 1987)), based on principles completely different from those embodied in TAGs, which are also capable of providing analysis for crossed dependencies, have been shown to be equivalent to TAG in their generative power (Vijay-Shanker, Weir, and Joshi, 1985; Weir and Joshi, 1988).

The plan for the rest of the paper is as follows. In Sections 2 and 3, we will present a brief description of a push-down automaton (PDA) and an embedded push-down automaton (EPDA) respectively. In Section 4, we will show how EPDAs can process crossed and nested dependencies. Then in Section 5, we will consider some complexity measures for EPDAs, motivated by some of the discussion in Bach, Brown, and Marslen-Wilson, and show that with respect to both these measures, the crossed dependencies are easier to process than the nested dependencies. In Section 6, we will examine the relationship between EPDAs for processing crossed and nested dependencies, and their associated grammars. We will also briefly discuss some issues concerning the degree to which grammars directly encode the processing by automata, in accordance with PPI.

2 Push-Down Automaton (PDA)

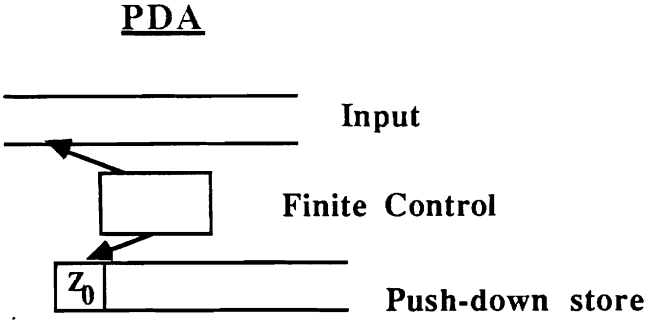
A PDA, M, consists of a finite control (with a finite number of states), an input tape which is scanned from left to right, and a push-down store (pds), or stack for short. The pds or stack discipline is as follows: In a given move of M, a specified string of symbols can be written on top of the stack, or the top symbol of the stack can be popped.

M starts in the initial state S_0 and the input head is on the leftmost symbol of the string on the input tape. The stack head is always on the top symbol of the stack. Z_0 is a special symbol marking the bottom of the stack. The behavior of M is specified by a transition function, δ, which, for some given input symbol and the state of the finite control and the stack symbol (i.e., the topmost symbol on the stack), specifies the new state, and whether the stack is pushed or popped. If pushed, then the transition function specifies the string pushed on the stack. If popped, then the topmost symbol of the stack is removed. The input head either moves one symbol to the right or stays on the current symbol. Thus

$$\delta \text{ (input symbol, current state, stack symbol)} = \text{(new state, push/pop)}$$

If M is nondeterminininistic, then with a given input symbol, current state, and the stack symbol, more than one (new state, push/pop) pairs could be associated.

A string of symbols on the input tape is recognized (parsed, accepted) by M, if starting in the initial state and with the input head on the leftmost symbol of the input string, if there is a sequence of moves, as specified by δ, such that the input head moves past the rightmost symbol on the input tape and the stack is empty. There are alternate ways of defining recognition, e.g., by M entering one of the final states of M after the input head has moved past the leftmost symbol on the input; however, in this paper, we will define acceptance by empty stack. It is well-known that these two definitions are equivalent.



3 Embedded Push-Down Automaton (EPDA)

An EPDA, M', is very similar to a PDA, except that the push-down store is not necessarily just one stack but a sequence of stacks. The overall stack discipline is similar to a PDA, i.e., the stack head will be always at the top symbol of the top stack, and if the stack head ever reaches the bottom of a stack, then the stack head automatically moves to the top of the stack below (or to the left of) the current stack, if there is one (Vijay-Shanker, 1987; Joshi, 1987; Joshi, Vijay-Shanker, and Weir, 1988).

Initially, M' starts with only one stack, but unlike a PDA, an EPDA may create new stacks above and below (right and left of) the current stack. The behavior of M is specified by a transition function, δ', which for a given input symbol, the state of the finite control, and the stack symbol, specifies the new state, and whether the current stack is pushed or popped; it also specifies new stacks to be created above and below the current stack. The number of stacks to be created above and below the current stack are specified by the move. Also, in each one of the newly created stacks, some specified finite strings of symbols can be written (pushed). Thus:

$$\delta' \text{ (input symbol, current state, stack symbol)} =$$

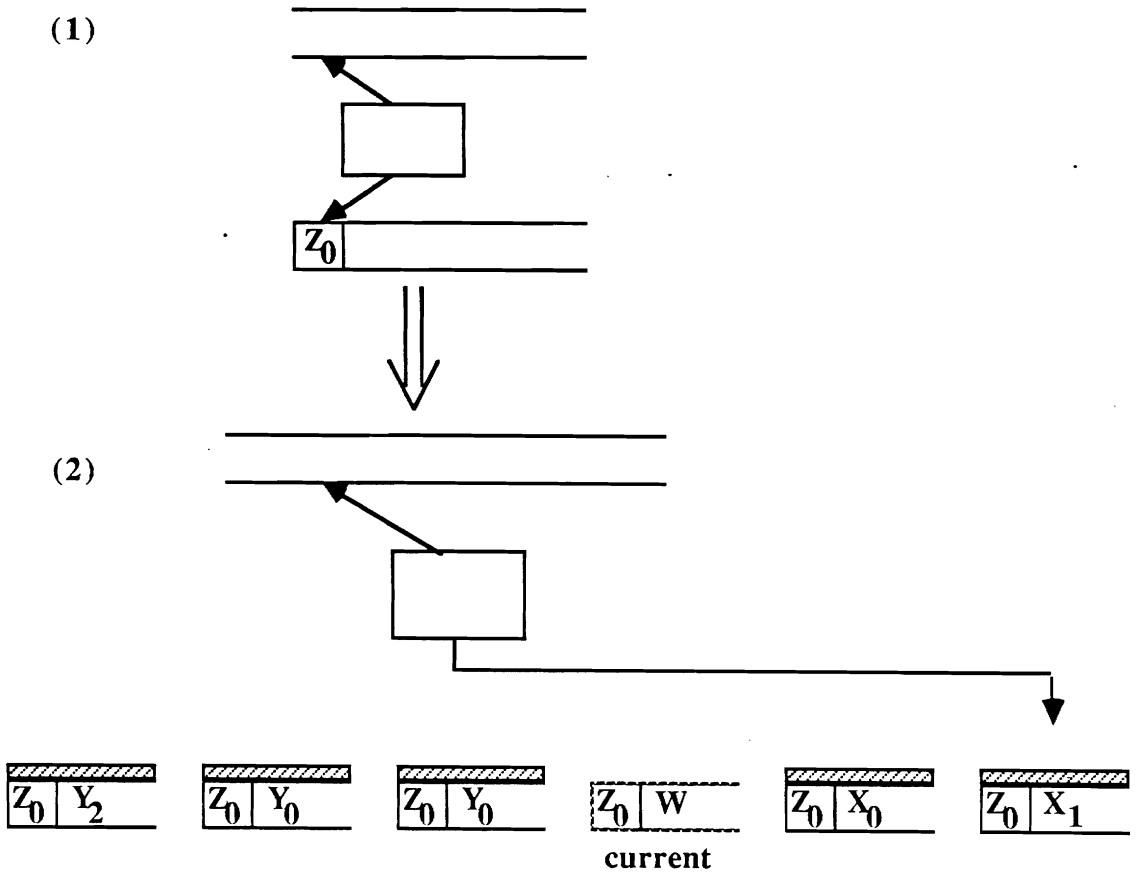
$$(\text{new state}, sb_1, sb_2, \ldots, sb_m, \text{push/pop on current stack}, st_1, st_2, \ldots, st_n)$$

where $sb_1, sb_2, \ldots, sb_m$ are the stacks introduced below the current stack, and $st_1, st_2, \ldots, st_n$ are the stacks introduced above the current stack. As in the case of a PDA, an EPDA can be nondeterministic also.

A string of symbols on the input tape is recognized (parsed, accepted) by M', if starting in the initial state and with the input head on the leftmost symbol of the string on the input tape, if there is a sequence of moves as specified by δ' such that the input head moves past the rightmost symbol on the input tape and the current stack is empty, and there are no more stacks below the current stack.

The following two diagrams illustrate moves of an EPDA, M'.

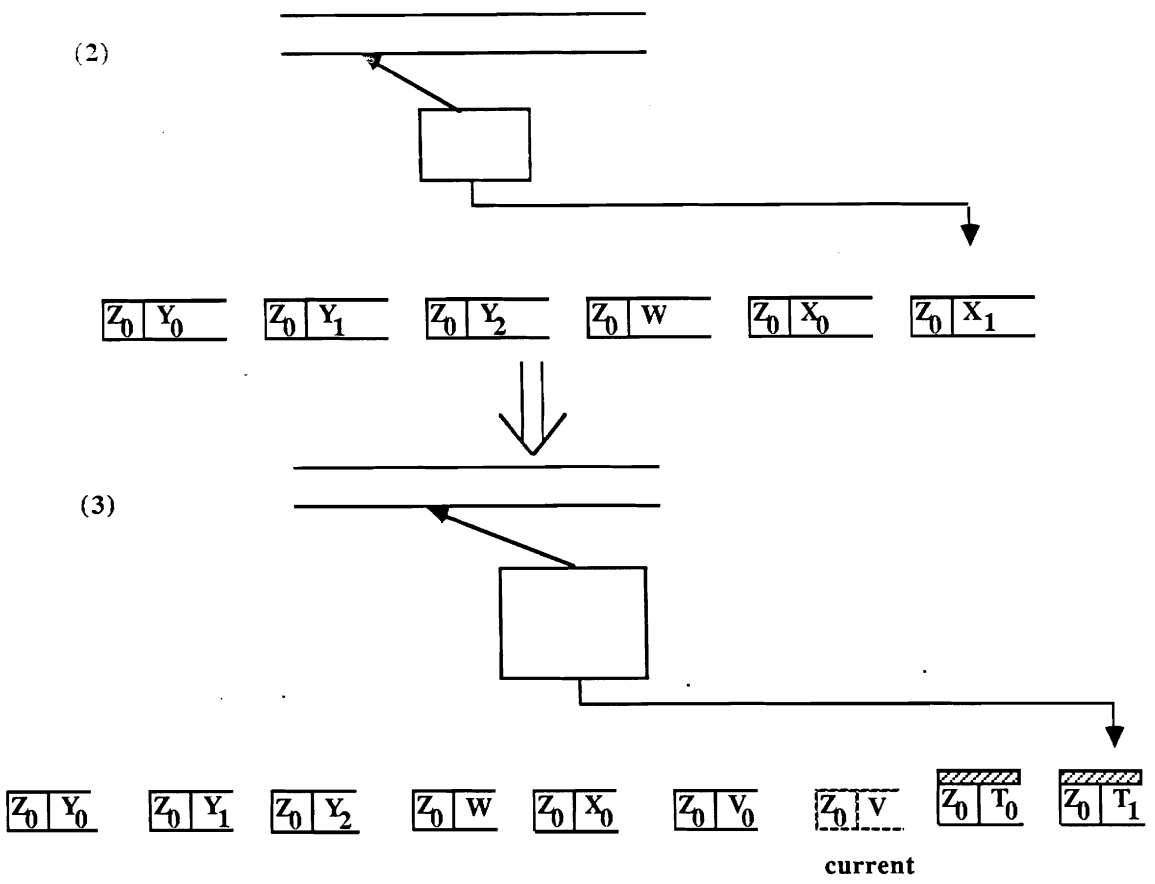
Given the initial configuration as shown in (1), let us assume that for the given input symbol, the current state of the finite control, and the stack symbol, δ' specifies the following move as shown in (2):



In this move, 2 stacks have been created above the current stack (which is shown by dotted lines), and 3 stacks have been created below the current stack. W has been pushed on the current

stack, X_0, X_1 have been pushed on the stacks introduced above the current stack and Y_0, Y_1, Y_2 have been pushed on the stacks created below the current stack. The stack head has moved to the top of top stack, so now the topmost stack is the current stack.

Let us assume that in the next move the configuration is as shown in (3) below:



In this move, 1 stack has been created below the current stack (which is shown by dotted lines) with V_0 pushed on it, 2 stacks have been created above the current stack with T_0, T_1 pushed on them. V is pushed on the current stack. The stack head has again moved to the topmost of top stack.

Thus in an EPDA in a given configuration there is a sequence of stacks; however, the stack head is always at the top of the top stack at the end of a move. Thus although, unlike a PDA, there is a sequence of stack in a given configuration, the overall stack discipline is the same as in a PDA. PDAs are special cases of EPDAs, where in each move no new stacks are created, only a push/pop is carried out on the current stack.

4 Crossed and Nested Dependencies

We will now illustrate how EPDAs can process croseed and nested dependencies consistent with the principle of partial interpretation (PPI) described in Section 1.

Crossed Dependencies (Dutch)

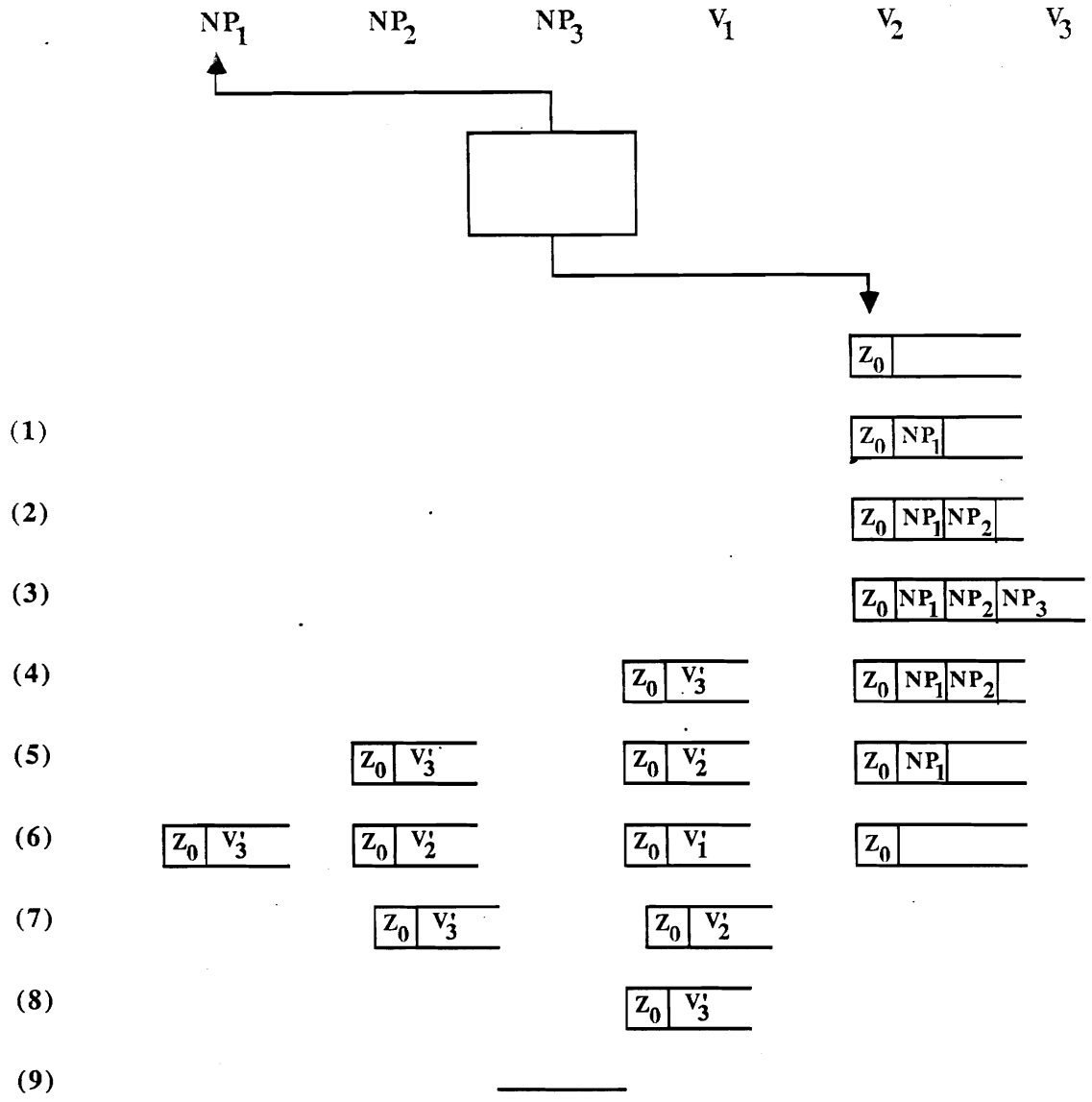


Fig. 1

Rather than defining the EPDA, M_d, formally, (i.e. specifying the transition function completely), we will simply describe the moves M_d goes through during the processing of the input string. The symbols in the input string are indexed so as to bring out the dependencies explicitly and is thus for convenience only. Also NPs are treated as single symbols. In the initial configuration, the input head is on NP_1 and the stack head is on top of the current stack. The first three moves of M_d, i.e., moves 1, 2, and 3, push NP_1, NP_2, NP_3 on the stack. At the end of the third

move, the current stack has NP_1, NP_2, and NP_3 on it and the input head is on V_1. No new stacks have been created in these moves. In move 4, NP_3 is popped from the current stack and a new stack has been created below the current stack and V_3' is pushed on this stack. (The stack symbols have been indexed to show explicitly the relationship between the input symbols and stack symbols, thus this indexing is for convenience only). The symbol V_3' is assumed to encode the NP_3 argument together with the variable of type verb (which takes an NP argument), i.e., to encode a structure $V(NP)$[1]. In move 4, M_d has packaged NP_3 with a variable of type verb whose binding it expects to find later. At the end of move 4, the stack head is on top of the topmost stack, i.e., on NP_2 and the input head stays at V_1. Moves 5 and 6 are similar to move 4. In move 5, NP_2 is popped from the current stack and a new stack with V_2' on it is crated below the current stack. Thus the stack containing V_2' appears between the stack containing V_3' and the current stack. V_3' encodes the NP_2 argument and a variable of type verb (which takes NP and an S as arguments), i.e., it encodes a structure $V(NP, S)$. The input head stays at V_1. Similarly, in move 6, NP_1 is popped from the current stack and a new stack is created below the current stack, and V_1' is pushed on it. V_1' encodes the NP_1 argument and a variable of type verb (which takes NP and S arguments), i.e., it encodes a structure $V(NP, S)$. The input head stays at V_1. The current stack is now empty and since there are stacks below the current stack, the stack head moves to the top of topmost stack below the empty current stack, i.e., it is on V_1'. In move 7, V_1' is popped. In effect, we have matched V_1 from the input to V_1' and the structure $V_1(NP_1, S)$ is now popped and is no longer held by M_d. Note that this structure has its predicate and one argument filled in, and it has a slot for an S type argument, which will be filled in by the next package that is popped by M_d. Thus we are following the principle of partial interpretation (PPI), as described in Section 1. Similarly in move 8, V_2 and V_2' are matched and V_2' is popped, i.e., the structure $V_2(NP_2, S)$ is popped. This structure now fills in the S argument of the structure popped earlier, and it itself is ready to receive a structure to fill its S argument. In move 9, V_3 and V_3' are matched and V_3' is popped, i.e., the structure $V_3(NP_3)$ is popped, which fills in the S argument of the strucutre previously popped. During the moves 7, 8, and 9, the input head moves one symbol to the right. Hence at the end of move 9, the input head is past the rightmost symbol on the input tape; also, the current stack is empty and there are no stacks below the current stack. Hence, the input string has been successfully recognized (parsed).

[1] Although we are encoding a structure, only a bounded amount of information is stored in the EPDA stacks. the symbols NP, S, etc. are all atomic symbols. In an EPDA behaving as a parser, these symbols can be regarded as pointers to relevant structures, already constructed, and outside the EPDA.

Nested Dependencies (German)

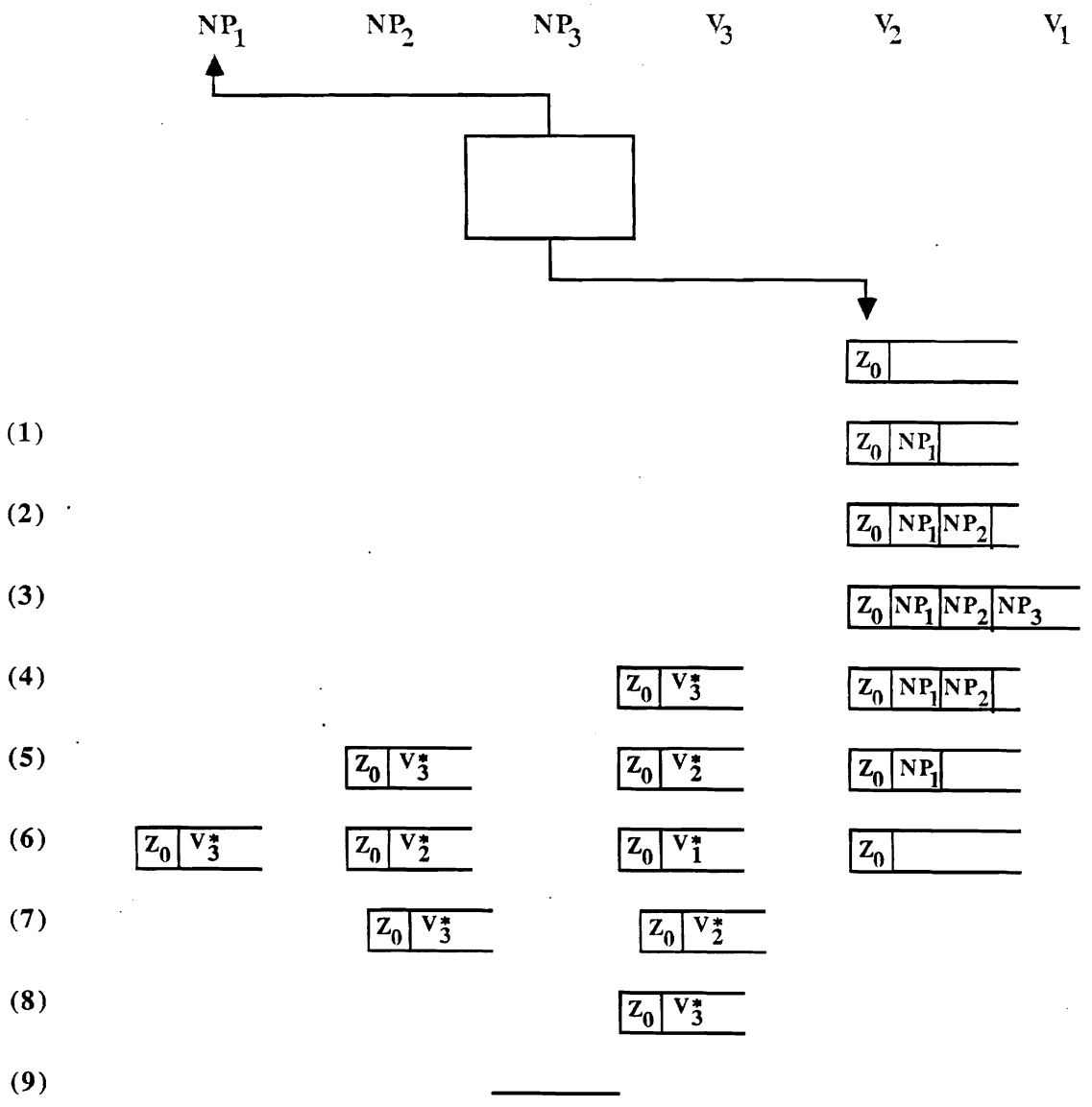


Fig. 2

Once again, we will describe the various moves of the EPDA, M_g, during the processing of the input string. We assume as before that an appropriate transition function has been defined for M_g licensing the moves described below. Note that a PDA can process nested dependencies, but as discussed in Section 1, processing of nested dependencies by a PDA does not obey the principle of partial interpretation (PPI) in Section 1. The EPDA, M_g, described here does obey PPI.

In the initial configuration, the input head is on NP_1 and the stack head is on top of the current

stack. The first three moves of M_g push NP_1, NP_2, and NP_3 on the current stack. No new stacks are created in these moves. During these moves, the input head moves to the right one symbol at a time, so that at the end of move 3, the input head is on V_3. The first three moves of M_g are similar to the first three moves of M_d, described earlier. In move 4, NP_3 is popped from the current stack, a new stack is created below the current stack with V_3^* pushed on it, and the input head moves to V_2 on the input string. V_3^* encoding the NP_3 argument together with the verb V_3 (which takes an NP argument), i.e., it encodes the structure $V_3(NP_3)$. Note that V_3^* is like V_3' in M_d except that in V_3', we had a variable of type verb, while in V_3^*, we have the verb V_3 from the input. Thus in move 4, we have packaged V_3 and its argument and put it on a stack below the current stack. Moves 5, and 6 are similar to move 4. In move 5, NP_2 is popped from the current stack, a new stack is created below the current stack with V_2^* encoding the NP_2 argument and the verb V_2 (which takes NP and S as arguments), i.e., V_2^* encodes the structure $V_2(NP_2, S)$. In move 6, NP_1 is popped from the current stack, a new stack is created below the current stack with V_1^* pushed on it, and the input head moves to the right of V_1. V_1^* encodes the NP_1 argument and the verb V_1 (which takes NP and S as arguments), i.e., V_1^* encodes the structure $V_1(NP_1, S)$. At the end of move 6, the current stack is empty. Since there are stacks below the current stack, the stack head moves to the top of topmost stack below the current stack, i.e., it will be on V_1^*. The input head is to the right of V_1 on the input tape. During moves 7, 8, and 9, the input head will stay where it is, V_1^*, V_2^*, and V_3^* will be popped in that order, the stack head moving from V_1^* to V_2^* to V_3^*. In move 7, V_1^* is popped, i.e., the structure $V_1(NP_1, S)$ is popped and it is no longer held by M_g. This structure has its predicate and one argument filled in, and it has a slot for S type argument, which will be filled in by the next package that is popped by Mg. This is consistent with the PPI. Similarly, in move 8, V_2^* is popped, i.e., the structure $V_2(NP_2, S)$ is popped. This structure has its predicate and one argument filled and it has a slot for an S type argument. This structure itself fills in the S slot in the structure popped in move 7. In move 9, V_3^* is popped, i.e., the structure $V_3(NP_3)$ is popped. This structure has its predicate and its argument filled in, and it itself fills in the S slot in the structure popped in move 8. At the end of move 9, the current stack is empty and there are stacks below the current stack and the input head is to the right of the rightmost symbol in the input tape, hence M_g has successfully recognized (parsed) the input string, and interpretation has been built consistent with PPI.

5 Complexity of Processing

In Section 3, we have shown how an EPDA can process both the crossed and nested dependencies in accordance with PPI. The major result of Bach, Brown, and Marslen-Wilson (1986) as summarized in Section 1, is that the processing of crossed dependencies is 'easier' than the processing of nested

dependencies, as illustrated in Table 1 in Section 1. In this Section, we will show that if a suitable measure of complexity of processing is defined for an EPDA (in the spirit of the discussion in Bach, Brown, and Marslen-Wilson (1986)), the processing of crossed dependencies is indeed, 'easier' than the processing of 'nested' dependencies, thus suggesting that EPDAs can model the processing of crossed and nested dependencies consistent with the experimental results of Bach, Brown, and Marslen-Wilson (1986). The main significance of this result is not just that there is an automaton with the appropriate behavior but rather this behavior is achieved by a class of automata that exactly corresponds to a class of grammars (called Tree Adjoining Grammars (TAG)) which are adequate to characterize both the crossed and nested dependencies. We will discuss this topic later in some detail.

What sort of complexity measure is appropriate? Let us consider the EPDAs M_d and M_g in Figures 1 and 2. If we measure the complexity just in terms of the total number of moves, then there is no distinction between the processing of crossed and nested dependencies. In each case, we have exactly 9 moves, (we have 3 levels of embedding here), and similarly the number of moves for both cases will be the same for other levels of embedding.

Motivated by the discussion in Bach, Brown, and Marslen-Wilson (1986), we will consider a measure which involves only the number of items from the input that the EPDA has to store (we will not attach any cost to the moves themselves, i.e., consider them (nearly) instantaneous). In particular, the measure will be the maximum number of input items stored during the entire computation. Thus in Figure 1, M_d stores 1, 2, and 3 items after moves 1, 2, and 3 respectively. After move 4, the number of items stored is still 3 because although NP_3 is popped, V_3' has NP_3 integrated in it (the V in V_3' is not bound to any input item yet). Thus, after each one of the moves 5 and 6, we also have 3 items from input stored in M_d. After move 7, only 2 items are stored in M_d, after move 8, only 1, and after move 9, none. Thus the maximum number of input times stored during the entire computation is 3.

A similar computation shows that the maximum number of input items stored in the computation of M_g (for the nested case as shown in Figure 2) is 5. After move 3 (as in the case of M_d), M_g has stored 3 input items. After move 4, M_g has stored 4 items because V_3^* not only has NP_3 integrated in it but also V_3 from the input. Thus after move 5, M_g has stored 5 items, and after move 6, 6 items. After move 7, only 4 items are stored, after move 8, only 2, and after move 9, none. Thus the maximum number of items stored is 6. However, it is possible to integrate moves 6 and 7, so that in move 6, we can immediately pop V_1^*, there is no need to first store it and then pop it in the next move. Thus after this newly defined move 6, M_g has stored only 4 items. Hence, the maximum number of input items stored in the entire computation is 5. (We have followed here a strategy of redefining a move of M_g to minimize its complexity. The idea is that by giving all the help which we can to M_g and by not giving any extra help to M_d, if it still turns out that

the complexity of M_d is less than that of M_g, then we will have succeeded in making a stronger argument for our automaton model).

Table 2 below summarizes the complexity of processing as measured by the maximum number of input items stored during the entire computation.

Table 2

Maximum number of input items stored during the computation		
Level of Embedding	**Dutch**	**German**
1	1	1
2	2	3
3	3	5
4	4	7

In Table 2, we have shown the relevant numbers for levels of embedding up to 4 only. It is possible to derive an exact formula for these numbers, but there is not much point in describing that formula because Bach, Brown, and Marslen-Wilson (1986) give their numbers up to level 4 only. It is unlikely that reliable experimental data can be obtained for levels beyond 4. So any complexity numbers beyond level 4 will be only mathematical curiosities.

In Table 2, the complexity numbers for M_d and M_g for level 1 are the same as one would expect. For level 2, the complexity for M_g is greater than the complexity for M_d. In Table 1 (in Section 1), the complexity of processing nested dependencies is only slightly more than that of crossed dependencies. In our case, the difference is not insignificant. Thus in our model, the difficulty of processing nested dependencies shows up even at level 2.

We will now consider a somewhat more fine-grained measure of complexity, still in terms of the number of input items stored. Instead of just counting the number of input items stored, we will also pay attention to the number of time units an input item i is stored, *the time unit is in terms of the movement of the input head* and not in terms of machine operations. (As before, we will not attach any cost to the moves themselves, i.e., consider them (nearly) instantaneous).

Let us consider Figure 1 again. NP_1 is stored in move 1, i.e., after the input head moves past NP_1, it will continue to be stored until the input head is past NP_3. During moves 4, 5, 6, the input stays on V_1. In move 7, V_1' (and therefore NP_1) is popped. Thus if the time unit is measured in terms of the movement of the input head, NP_1 is stored for 3 time units. Similarly NP_2 and NP_3 are each stored for 3 time units. V_1, V_2, and V_3 are each stored for zero units. Hence, $\sum_i T(i) = 9$, where $T(i)$ is the number of time units input item i is stored.

Now consider Figure 2. NP_i is stored in move 1, i.e., after the input head moves past NP_1. It will continue to be stored until the input moves past V_1. During moves 7, 8, and 9, the input head

does not move. Hence, if the time unit is counted in terms of the movement of the input head, NP_1 is stored 6 time units. Similarly NP_2 is stored for 5 time units, NP_3 for 4 unites, V_3 for 3 units, V_2 for 2 units, and V_1 for 1 unit. Thus $\sum_i T(i) = 21$. Once again, we can combine moves 6 and 7, i.e., there is no need to first store V_1^* and then pop it, we can pop it immediately. Thus the number of time units NP_1 is stored is reduced to 5, the number of time units for NP_2, NP_3, V_3, and V_2 are not affected. The number of time units V_1 is stored become zero. Hence, $\sum_1 T(i) = 19$. As before, we have followed the strategy of redefining moves of M_g to help reduce its complexity and not help M_d correspondingly. The reason for doing this is the same as before, i.e., even after helping M_g in this way, if we can show that the complexity of M_d is less than M_g, then we will have succeeded in making a stronger argument for our automaton model. Table 3 summarizes the complexity of processing according to the $\sum_i T(i)$ measure for different levels of embedding up to level 4. Once again, an exact formula for these numbers can be worked out for any level but there is not much point in presenting it, as the experimental data does not go beyond level 4. It can be easily seen that the overall behavior of our automaton model with respect to this somewhat fine-grained complexity measure is about the same as in Table 3.

Table 3

$\sum_i T(i)$, where $T(i)$ is the number of time units an input item i is stored

Level of Embedding	Dutch	German
1	1	1
2	4	8
3	9	19
4	16	34

6 EPDA and the associated grammars

In Section 4, we have shown how crossed and nested dependencies can be processed by EPDAs, in accordance with the principle of partial interpretation (PPI), as described in Section 1. This result has a larger significance because EPDAs are exactly equivalent to the Tree Adjoining Grammars (TAG), which are capable of providing a linguistically motivated analysis for Dutch crossed dependencies (Joshi 1985, Kroch and Santorini 1988).

The fundamental insight on which the TAG formalism is based is that local co-occurence relations can be factored apart from the expression of recursion and unbounded dependencies. A TAG consists of a set of elementary trees on which local dependencies are stated and an adjunction

operation, which composes elementary trees with one another to yield complex structures. The elementary trees of a TAG are divided into initial trees and auxiliary trees (Fig. 3). Initial trees have the form of the tree in α. The root node of an initial tree is labeled S or $\bar{S}$, its internal nodes are all nonterminals (phrasal categories), and its frontier nodes are all lexical categories. Auxiliary trees have the form of the tree β. The root node of an auxiliary tree is a phrasal category, which we have labeled X, a nonterminal. Its frontier nodes are all lexical nodes except for one phrasal node which has the same category label as the root node.

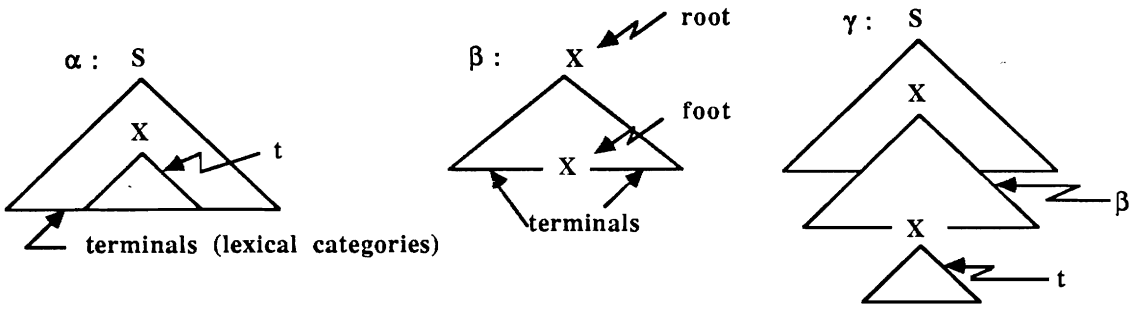


Fig. 3

We now define adjunction as follows. Let α be an elementary tree with a nonterminal node labeled X, and let β be an auxiliary tree with a root node X, the foot node, by definition has the label X also. The tree γ obtained by adjoining β to α at the node labeled X is defined as follows. The subtree at X in α is detached, the auxiliary tree β is attached to X, and then the detached subtree is attached to the foot node of β, in short, β is inserted at X in α. Adjuction, so defined, can be extended to derived trees in an obvious manner. There are other details such as constraints on adjoining, but for our purpose the short description given above is adequate.

The following TAG, G, allows derivations of crossed dependencies. α is a an elementary tree and β is an auxiliary tree. Note that in each tree the verb is "raised." γ_0, γ_1, and γ_2 describe the derivation of (1) in Section 1. Indexing of NPs and Vs are for convenience only. Note that NP_1, NP_2, and NP_3 are crossed with respect to V_1, V_2, and V_3 but nested with respect to V_3', V_2' and V_1' and these in turn are nested with respect to V_1, V_2, and V_3, thus the crossed dependencies between the NPs and (lexical) Vs is achieved by pair of nested dependencies which are coordinated through the (primed) Vs, which can be interpreted as traces. The moves of the EPDA, M_d in Fig. 1 in Section 4 reflects the structure of the grammar G, quite directly.

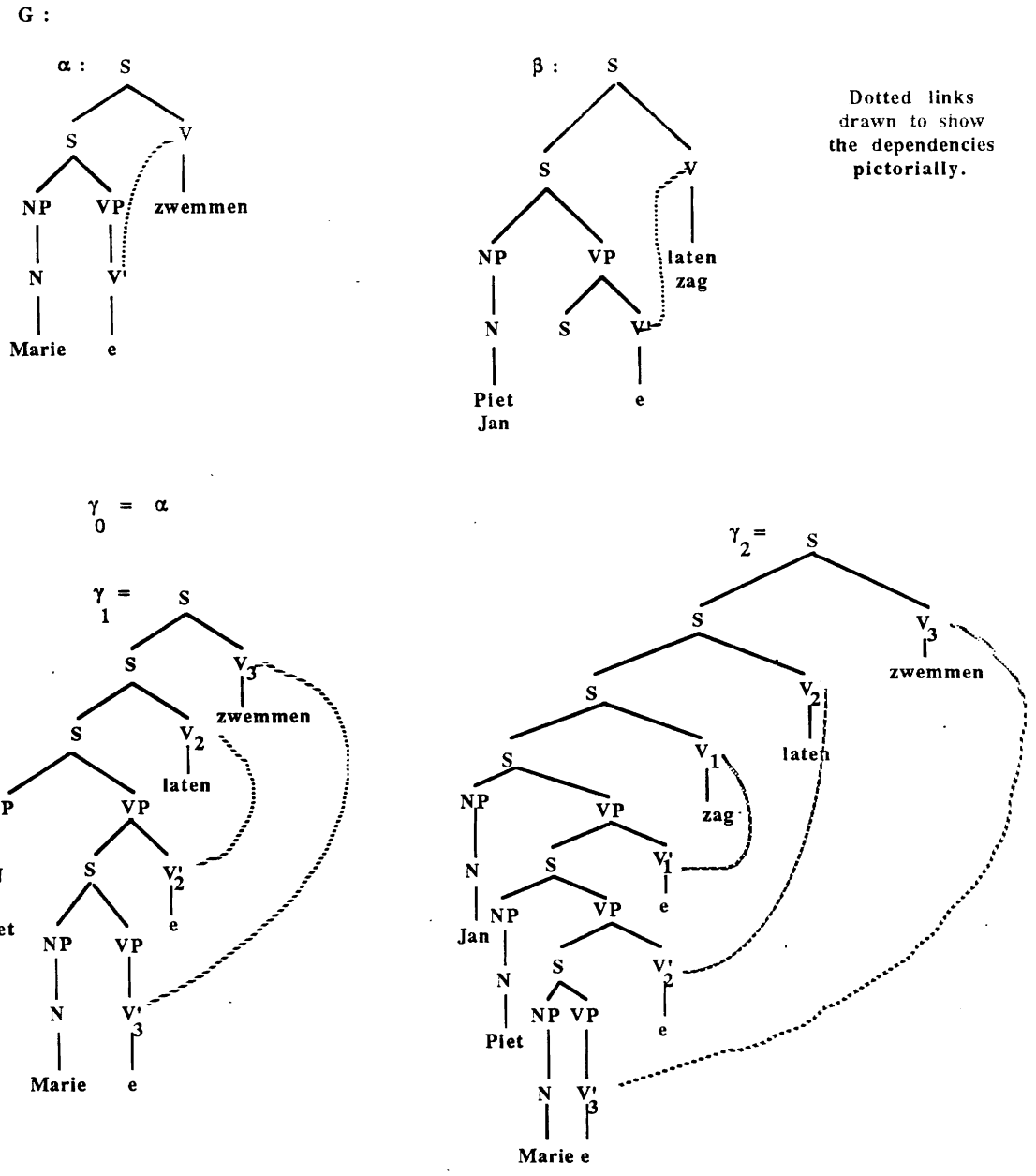


Fig. 4

(See Joshi 83 and Kroch and Santorini 87 or further details. We have slightly simplified the grammar given by Kroch and Santorini, without sacrificing the essential characteristics of the grammar).

For nested dependencies of German, Kroch and Santorini give the following TAG, G' (Fig. 5). Note that here we do not have verb "raising". The derivation of (2) in Section 1 then consists of adjoining β to the root α, deriving a tree γ and then adjoining β to the root of γ, deriving a tree γ',

resulting in the desired structure. We have not shown this derivation in Fig. 5. PDAs are special cases of EPDAs. Thus an EPDA, essentially following the discipline of a PDA, can process G', however, this EPDA will not be in accordance with the principle of partial interpretation (PPI). In Section 4, Fig. 2 we have presented an EPDA, M_g which processes nested dependencies of German, in accordance with PPI. The TAG, G' does not directly map onto M_g. However, since for every EPDA there is an equivalent TAG, there is a TAG which is equivalent to M_g, say G''. (See Fig. 5 for G' and Fig. 6 for G''). The derivation in G'' consists of adjoining β to the interior S node α, marked by an arrow (and not to the root node of α as in the case of G'), deriving a tree γ and then adjoining β to γ as before deriving γ', resulting in the derived structure. We have not shown this derivation in Fig. 6.

Fig. 5

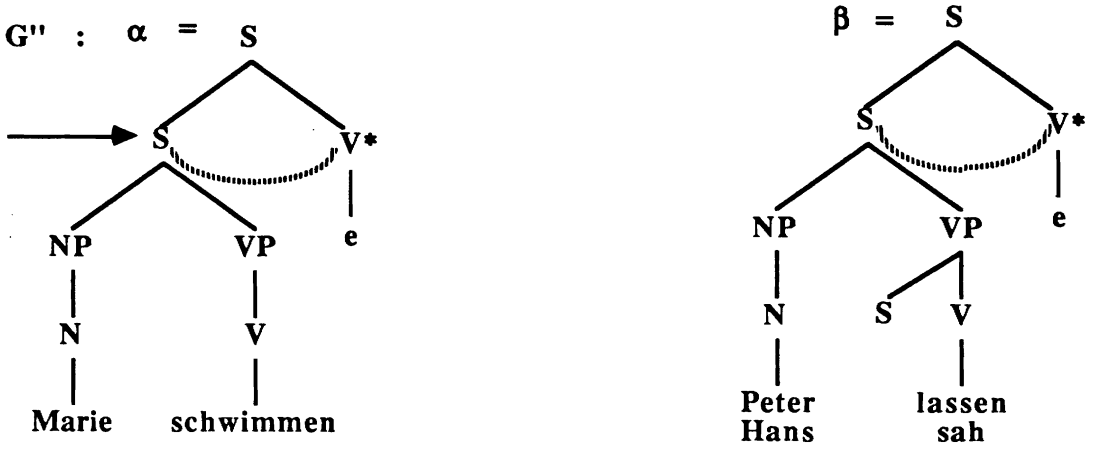


Fig. 6

G'' is clearly a TAG and it is a TAG for the nested dependecies. This grammar[2] directly maps into M_g in the sense that it encodes, in a way, the behavior of M_g, which corresponds to witholding the $NP\ VP$s until the top level structure is reached and then discharging them in the reverse order. G'' differs from G' only in this respect, Clearly, G' is a kind of grammar a linguist would write (based on the usual distributional considerations). G'' is like G' except that the structure represented by the right daughter of the root node and the associated link (co-indexing) with the middle S node is an encoding (in the grammar) of that part of the bahavior of M_g just mentioned above. G'' is not the kind of grammar a linguist would write (based on distributional considerations), however, it is closely related to G'.

For the Dutch case, TAG, G maps more directly onto the EPDA, M_d as compared to the mapping between the TAG, G' for German and the EPDA, M_g. The TAG G'' for German maps more directly onto M_g. Thus, in some sense, the TAG, G for Dutch reflects more directly the principle of partial interpretation (PPI) than the TAG, G' for German. We need to construct G'' for German if we want a more direct encoding of PPI in the grammar itself. Another way of saying this is that the 'natural' grammar for the crossed dependencies of Dutch reflects PPI more directly than the 'natural' grammar for the nested dependencies of German. A reflex of this disparity is then the relative processing difficulty of nested dependencies.

7 Conclusion

Motivated by the results of Bach, Brown, and Marslen-Wilson (1986) and their discussion of these results concerning processing of crossed and nested dependencies, we have shown that embedded push-down automaton (EPDA) permits processing of crossed and nested dependencies consistent with the principle of partial interpretation. We have shown that there are appropriate complexity measures according to which the processing of crossed dependencies is easier than the processing of nested dependencies. This EPDA characterization is significant because the EPDAs are *exactly* equivalent to Tree Adjoining Grammars, which are capable of providing a linguistically motivated analysis for the crossed dependencies. The significance of EPDA characterization is further enhanced because two other formalisms (Head Grammars and Combinatory Categorial Grammars), based on principles completely different from those embodied in TAGs, which are also capable of providing analysis for crossed dependencies, are known to be equivalent to TAGs. We have also briefly discussed some issues concerning the degree to which grammars directly encode the processing by automata, in accordance with the principle of partial interpretation.

[2]By a grammar we mean the set of elementary trees and the constraints that specify what auxiliary trees are adjoinable at what nodes in each elementary tree. These constraints are not shown explicitly in G, G', and G''

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