

## **Search Strategies in Syntactic Reanalysis**

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*We first consider the nature of syntactic reanalysis, paying particular attention to questions about whether and how it differs from the construction of an initial analysis, such as whether it is encapsulated or whether alternatives are considered in parallel or not. We then outline different strategies that the processor may use in reanalysis, and review the relevant evidence. We show that our experimental evidence is compatible with an encapsulated serial search strategy.*

### **INITIAL ANALYSIS AND REANALYSIS**

Most sentence-processing work since Kimball (1973) has focused on the question of how the processor constructs an initial analysis: what information sources can be used immediately, whether different analyses be considered at the same time, and so on. Reanalysis has been employed largely as a method of testing initial analysis, essentially as a diagnostic test for misattachment (e.g., Rayner, Carlson, & Frazier, 1983). Exceptions to this generalization are of two broad types: theoretical and computational models that focus on reanalysis difficulty (Fodor & Inoue, 1994; Gorrell, 1995; Lewis, 1998; Pritchett, 1992; Sturt & Crocker, 1996) and experimental studies of the factors that affect recovery (Ferreira & Henderson, 1991; Pickering & Traxler, 1998; Warner & Glass, 1987). However, accounts of reanalysis have paid little attention to the central questions that have driven research on initial analysis.

We begin this paper by outlining these general questions in relation to reanalysis. Perhaps the central concern for theories of initial attachment is whether the processor is greatly restricted in the sources of information that can be employed initially or not. Unencapsulated theories argue that there

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is no restriction about when particular sources of information can be used (e.g., MacDonald, Pearlmutter, & Seidenberg, 1994; Trueswell, Tanenhaus, & Garnsey, 1994). Encapsulated theories usually assume that initial decisions are made on the basis of syntax alone, as in the garden-path model (Frazier, 1978, 1987). A great deal of experimental evidence indicates that nonsyntactic factors do affect parsing, such as plausibility (Rayner *et al.*, 1983; Ferreira & Clifton, 1986; Trueswell *et al.*, 1994) and discourse context (Altmann & Steedman, 1988; Britt, 1994; Mitchell, Corley, & Garnham, 1992). Proponents of the garden-path model argued that such effects occur during reanalysis, as in the Thematic Processor proposed by Rayner *et al.*, (1983). Because this processor is able to propose analyses that are felicitous, both in terms of syntax and plausibility, it must be unencapsulated, or at least weakly interactive (cf. Steedman & Altmann, 1989).

Hence, all current models accept that potentially relevant information can be used rapidly. The critical controversy simply concerns whether it is used immediately or not. Thus experimenters attempt to determine what happens during the very earliest stages of processing, using increasingly sensitive techniques such as traditional eye tracking (Frazier & Rayner, 1982), head-mounted eye tracking (Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995), event-related potentials (Garnsey, 1993), and speed-accuracy tradeoff (McElree, 1993). The consequence is that both sides of the initial analysis controversy appear to assume that reanalysis itself is unencapsulated, presumably because they assume that it occurs late enough for nonsyntactic sources of information to have an effect. (A proviso is that many unencapsulated accounts allow for extended parallel processing, with changes in preferences occurring rather than reanalysis.)

We argue that unencapsulated reanalysis is not necessarily the case. In fact, there are four logical possibilities for the relation between initial processing and reanalysis with respect to encapsulation. First, as assumed by some proponents of the garden-path theory (Frazier & Clifton, 1998; Rayner *et al.*, 1983), initial processing might be encapsulated while reanalysis is unencapsulated. Second, both initial processing and reanalysis might be encapsulated—encapsulation might occur, for instance, simply because nonsyntactic information sources take longer in principle to access than syntactic information, and the processor does not delay in processing the word string. Third, initial analysis could be unencapsulated, but reanalysis is encapsulated. This appears to be an odd combination, but it might occur because reanalysis is an inherently more complex operation than initial attachment, as any number of previous choice points could be revisable in any number of alternative ways. Encapsulation in reanalysis would thus be a way of saving computational effort. Finally, both reanalysis and initial attachment might be unencapsulated. This position would be the most natural one for constraint-

based theories (MacDonald *et al.*, 1994; Trueswell *et al.*, 1994), although such models typically have not considered questions of reanalysis (but see the proviso above).

In order to test whether reanalysis is encapsulated, we need to perform experimental investigations that are analogous to investigations of initial processing, but with clear evidence that the processor has previously constructed an analysis and is, therefore, reanalyzing. To our knowledge such studies have not been carried out to date.

Most studies of initial processing employ ambiguity as a tool to determine the mechanisms employed. Similarly, studies of reanalysis could profit from employing sentences that involve an initial analysis and an ambiguity about how to reanalyze. Alternatively, they could employ sentences in which there is ambiguity about whether to reanalyze or whether to continue with the current analysis. In this paper, we will discuss a reanalysis mechanism that is encapsulated. This is the simplest model to test and it is consistent with experimental evidence, which we will outline below.

Before we move on to consider the model, we note that one central architectural question is whether initial processing takes place in serial or parallel. This question can equally well be applied to reanalysis; in other words, if the processor abandons an analysis, does it consider more than one alternative or does it just adopt the first available (re)analysis? Parallel accounts of initial processing divide into those that assume momentary parallelism, as in propose-dispose accounts (e.g., Altmann & Steedman, 1988) and those that allow for parallelism to be extended over longer periods (e.g., Gibson, 1991; Jurafsky, 1996; MacDonald *et al.*, 1994). If momentary parallelism holds, then the processor would entertain one analysis before it decides to reanalyze; if reanalysis works similarly, it would then momentarily consider different possible alternative analyses and choose one (cf. Hirose & Inoue, 1998). If extended parallelism holds, reanalysis will only occur if the current input item is incompatible with all current analyses. The model described in this paper only considers a single analysis at the point of reanalysis.

## ENCAPSULATED SEARCH MODELS

Reanalysis involves a search for an alternative to the current analysis. Encapsulated search models, such as the one which we outline below, claim that this search is based on restricted information. In this section, we will look in detail at the principle of minimal revisions (Frazier, 1990), which has informed a number of theories of reanalysis (often implicitly). This principle applies to purely structural representations and is, therefore, a good principle on which to base a description of encapsulated search models.

## Minimal Revisions and Experimental Evidence

Minimal revisions accounts assume that revising structure is costly and that some revisions are harder than others. Intuitive evidence suggests that reanalyses can differ greatly in difficulty (Pritchett, 1992; Gorrell, 1995) and experimental evidence for this was provided by Sturt, Pickering, and Crocker (1999b), who considered sentences like the following:

- (1) The Australian woman saw the famous doctor had been drinking quite a lot.
- (2) Before the woman visited the famous doctor had been drinking quite a lot.

A great deal of research suggests that people initially attach *the famous doctor* as the direct object of the immediately preceding verb in both (1) and (2), at least as long as this verb is biased toward this reading (Clifton, 1993; Ferreira & Henderson, 1991; Pickering & Traxler, 1998; Rayner & Frazier, 1987; Trueswell, Tanenhaus, & Kello, 1993). Therefore in both of these sentences, reanalysis will be necessary in the region *had been drinking*. However, intuitively, the reanalysis in (2) is more difficult than that in (1) and many theories claim that this is because the reanalysis in (1) is less destructive than in (2) (Gorrell, 1995; Pritchett, 1988; Sturt & Crocker, 1996; Weinberg, 1995). This difference in difficulty was confirmed by Sturt *et al.* (1999b); self-paced reading studies revealed that the disambiguating region *had been drinking* was read more quickly in (1) than the equivalent region in (2), in relation to appropriate unambiguous control sentences. Importantly, the studies in Sturt *et al.* (1999b) held other potentially relevant factors constant between (1) and (2), for example, plausibility and verb bias. Note that these results are compatible with an encapsulated model of reanalysis.

Minimal revisions accounts of reanalysis simply claim that people adopt the analysis that is least destructive to the representation. If all other factors are held constant, as Sturt *et al.* (1999b) attempted, then the reanalysis that involves the least destruction should also be the easiest reanalysis. Hence, it should, in principle, be possible to determine the minimal revisions analysis experimentally by finding the revision that causes the least processing difficulty. One problem is that it is often difficult to distinguish between the difficulty of making a revision, on the one hand and the difficulty of diagnosing the initial misanalysis, on the other (Fodor & Inoue, 1994, 1998). Another problem is that deciding which reanalysis involves the least destruction may be dependent on assumptions about linguistic theory [just as is the case for a principle like minimal attachment (Frazier, 1978), which is affected, for example, by whether binary branching is assumed.]

It is not immediately clear how to quantify destructiveness. Perhaps the most obvious possibility is to assume that each break in the tree structure counts as a single revision and that the (re)analysis, which minimizes the number of such revisions, is the minimal revisions analysis. However, there are also theories that claim that the destructiveness of the reanalysis depends on the *type* of representation being broken (see Sturt & Crocker, 1998, for discussion).

Above, we outlined an empirical method by which one may determine which of two revisions is minimal, by experimentally testing which of two revisions is the easier. In the following, we will discuss how one can test whether the minimal revisions analysis is also the preferred revision in ambiguous situations, where more than one (re)analysis is possible. One way to test this hypothesis is to find a situation in which two different reanalyses are possible and one of these is predicted to be more destructive than the other. The processor should adopt the less destructive analysis and processing difficulty should be found later if the sentence is disambiguated toward the more destructive reanalysis. Note that this method of testing minimal revisions relies on the details of how a particular model defines destructiveness.

However, there is a simpler way of testing minimal revisions, which only requires some very limited and uncontroversial assumptions about linguistic representation. Minimal revisions predicts that reanalysis is the last resort (Fodor & Frazier, 1980); given that reanalysis, by definition, involves the destruction of some form of representation at some level, any theory based on minimal revisions would predict that the processor avoids reanalysis when an alternative is possible. In Sturt, Pickering, and Crocker (1999a), we tested this prediction in a series of self-paced reading experiments, we will outline the results in the following paragraphs as a case study in how minimal revisions can be empirically tested. Compare (3) and (4) below:

- (3) The troops found the enemy spy had shot himself.
- (4) The troops who found the enemy spy had shot themselves/himself (and) were later mentioned in the report.

The sentence in (3) is similar to (1) above. Since *found* is an NP-biased verb, it is uncontroversial that reanalysis will be necessary when the verb *had* is read. However, in (4), there is an alternative attachment of *had*, which does not involve reanalysis; this word could be attached as the head of the main clause, thus avoiding the reanalysis, which would involve the reattachment of *the enemy spy*. This main clause analysis of *had* is predicted by minimal revisions to be the preferred continuation, because it does not involve any destruction of linguistic relations. The continuation predicted by minimal revisions is consistent with the “*themselves*” continuation (with

the conjunction *and*). Note that this is a good test of minimal revision because if the processor does not follow the strategy of minimal revisions, then it is reasonable to expect that the reanalysis option will be taken. Not only does this option involve attaching the word *had* to the more recent of the two possible sites (thus satisfying a well-known structural preference in first-pass parsing (e.g., Altmann, van Nice, Garnham, & Henstra, 1998; Kimball, 1973), but also, the reanalysis involved in doing so is comparatively easy (Sturt *et al.*, 1999b). This latter option (cf. Fodor & Inoue, in press) is compatible with the “*himself*” continuation. Sturt *et al.* (1999a) tested 32 subjects in a self-paced reading experiment with 24 sentences similar to (4). The results were compatible with the minimal revisions hypothesis; reading times on the critical reflexive pronoun were reliably longer for *himself* than for *themselves* (see also Schneider & Phillips, 1999). In a further experiment, with 28 further subjects, we tested 24 sentences like (5) and (6):

- (5) The troops who found the enemy spy had used up all the supplies were later mentioned in the press report.
- (6) The troops who found that the enemy spy had used up all the supplies were later mentioned in the press report.

In this experiment, we included unambiguous control sentences like (6), using the complementizer *that*. The inclusion of this condition allowed us to test the points in the sentence at which reanalysis was taking place. The presence of a complementizer in (6) forces *the enemy spy* to be initially attached as the subject of a complement clause. Therefore, there will be no reanalysis at the region *had used up* in (6). The minimal revisions hypothesis predicts that no reanalysis will take place in this region even when complementizer is not present, as in (5). Therefore, we expect reading times to be similar in this region regardless of whether there was a complementizer in the prior context or not, and this is what we found. However, minimal revisions does predict that there should be reanalysis at the later region beginning *were later mentioned*, in (5), so reading times should be longer in (5) than in (6) in this region, or soon after. This is because, if the minimal revisions hypothesis is correct, the parser will attach *had* as the main verb of the sentence in (5). However, in (6), this attachment will be impossible, forcing attachment of *had* as the head verb of a complement clause. This means that, in (6), the word *were* will be easily attached into its correct position as the main verb of the sentence. However, in (5), where no complementizer was present in the prior context, reanalysis must take place, as the sentence already has a main verb. We found very clear evidence for reanalysis at this region; reading times were significantly longer for *were later mentioned* in (5) than in (6). This led to an reliable interaction of region and ambiguity, between the regions *had used up* and *were later mentioned*.

Note that these results are compatible with an encapsulated search process in which the (syntactically defined) minimal revisions analysis is initially adopted and, therefore, reanalysis is avoided. We will describe such a process below. An alternative, unencapsulated model might make the decision of whether or not to reanalyze based on other, nonstructural information, such as the bias of the ambiguous verb *found*, or plausibility. Although we cannot rule out such an unencapsulated account, the results of Sturt *et al.* (1999a) show no signs that verb bias, which we manipulated in both experiments, had any effect on this decision [although see Hirose and Inoue (1998) for evidence that semantic factors can affect the resolution of reanalysis ambiguities in which the processor has to choose the point in the tree at which a reanalysis operation is applied.]

## Serial Search Strategies

In the previous section, we discussed the minimal revisions strategy in representational terms, but we said little about how such a strategy could be implemented. We will now discuss a serial search strategy which implements a version of minimal revisions without the need to explicitly compare alternative analyses. Importantly, this is done in terms of a purely structural (and thus encapsulated) search. The parser works by applying structurally defined parsing operations to the input. Within the restricted search space of the parser, minimal-revisions behavior is obtained by ordering less-destructive parsing operations before more destructive operations.

### *A Search Procedure Based on Linguistic Prominence*

One of the subtasks of reanalysis is the identification of a previous choice point, to allow an alternative analysis can be found. In this section, we will consider a search model in which previous choice points are considered in an order determined by their prominence within the linguistic structure. This contrasts with more naive search strategies, such as chronological backtracking, in which previous choice points are simply considered in the reverse of the chronological in which they were created [see Lewis (1998) for a summary of the weaknesses of chronological backtracking for psycholinguistic modeling]. The model which we discuss here (based on Sturt & Crocker, 1996) defines structural prominence in terms of the *right frontier* of the phrase structure tree (see below), but other models have defined structural prominence differently, for example, in terms of paths of grammatical dependencies (Fodor & Inoue, 1998), or X-bar projections within the phrase structure tree (Lewis, 1998).

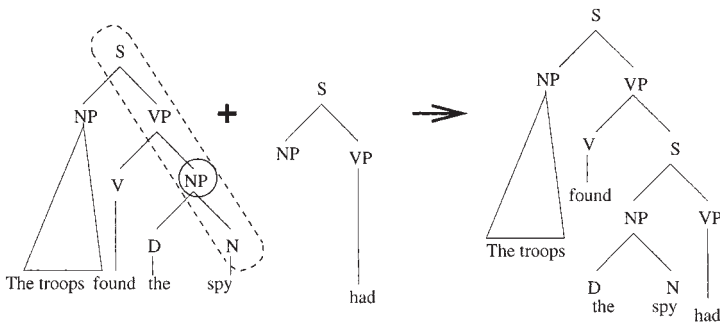
The strategy proposed in Sturt and Crocker (1996) is encapsulated: The order in which alternatives are considered is based on the geometry of the

phrase structure tree and is not influenced by nonsyntactic factors, such as verb bias or plausibility. It is also serial: Potential attachment sites are considered one at a time and alternatives are not considered once an acceptable analysis has been found.

The model assumes that processing is incremental (i.e., each word is analyzed into a fully connected tree as soon as it is encountered). Therefore, with respect to initial attachment, the set of potential attachment sites for a new word is defined by the right frontier of the current partial phrase marker (CPPM). The right frontier corresponds to the set of nodes that do not precede any other node, or alternatively, the path of nodes from the root of the CPPM to the bottom-right corner of the CPPM (see Fig. 1). Any attachment to a node, which is not on the right frontier, results in an incoherent tree with crossing branches and, therefore, would not be grammatically permissible on standard syntactic assumptions.

In reanalysis, the situation is slightly different, in that the choice points that need to be revised may not actually correspond to nodes on the right frontier. However, given that initial parsing has to obey the right frontier restriction, it is also natural to assume that the right frontier defines a notion of accessibility for previous choice points in reanalysis search. This assumption is made explicitly in both Sturt and Crocker (1996) and Stevenson (1998).

The search strategy presented in Sturt and Crocker (1996), is based on the use of three attachment operations, which apply to the right frontier of the tree. The first two of these, left and right attachment, are used for simple attachment and involve combining the projection of the current input word (new projection) with the CPPM in a nondestructive way, either by attaching the root of the CPPM to the left frontier of the new projection (left attachment), or by attaching the root of the new projection to the right frontier of the CPPM (right attachment).



**Fig. 1.** Illustration of a reanalysis operation taking place on the right frontier. The dotted loop indicates the right frontier. Abbreviations: S, "Sentence;" NP = "Noun Phrase;" VP = "Verb Phrase;" D = "Determiner;" N = "Noun."

The third operation, *tree lowering*, involves inserting the new projection into an intermediate position in the right frontier of the CPPM. This operation can be used for reanalysis, because it does not preserve sisterhood relations between nodes in the CPPM. As an example, consider Fig. 1, which illustrates the input of the word *had* with the CPPM shown.

In Fig. 1, the word *had* projects to a sentential node, which requires a noun phrase on its left. The tree-lowering operation allows a node on the right frontier of the CPPM (shown by the dotted loop in Fig. 1) to be detached from its current position, and reattached (via left attachment) to the projection of the new word. This projection is then attached (via right attachment) into the position vacated by the detached node. In Fig. 1, this operation can apply to the circled NP node on the right frontier of the CPPM. The result will be a new CPPM shown on the right of the figure.

There are several points to notice about this operation. First, the relevant choice points at which the operation can be applied are searched according to a structurally defined notion of accessibility (i.e., the right frontier). Second, the operation does not require the destruction and reconstruction of previously built structure; the noun phrase *the enemy spy* is simply detached as a chunk and reattached as the subject of *had*. Third, the error signal itself can act as a guide to the search; the fact that *had* requires a noun phrase on its left allows the parser to search actively for such a category on the right frontier of the CPPM (see Frazier & Rayner, 1982; Fodor & Inoue, 1994, for discussion of the role of error signals in reanalysis).

In Fig. 1, only one parsing operation can apply, but this is not the case generally. In Sturt and Crocker (1996) it was assumed that the processor first attempts to attach the current word using left or right attachment and only subsequently attempts to apply the tree-lowering operation if these two operations fail. It can be seen that this results in minimal revisions behavior in the parser. As tree lowering, but not left or right attachment, can result in reanalysis, postponing the application of this operation guarantees that all possibilities for first pass parsing operations are exhausted before reanalysis takes place. Note that this minimal revisions behavior emerges as a consequence of a serial search strategy, rather than as a consequence of the parser finding all solutions and subsequently choosing the least destructive option. We can demonstrate that this ordering of attachment operations correctly predicts the on-line processing behavior found in the experiments discussed above. Recall (5) above. At the point where the word *had* is encountered, the CPPM will be as follows:

(7) [<sub>NP1</sub> The troops who found [<sub>NP2</sub> the enemy spy]]

The grammar of English requires *had* to have a subject to its left. Theoretically, there are two parsing operations that could apply here. First,

left attachment could apply, in which case, the noun phrase NP1, consisting of the root of the whole CPPM, could be attached as the subject of *had*. This would involve no reanalysis. Second, tree lowering could apply, as in Fig. 1, with the noun phrase NP2 being reattached as the subject of *had*. In this case, there would be reanalysis. As the search strategy is serial, this second possibility, which involves reanalysis, is never considered. Therefore, no properties of the ambiguous verb (such as verb bias) are predicted to have an effect on the decision of whether or not to reanalyze. Instead, the left attachment operation is applied and reanalysis is avoided, consistent with the results found in Sturt *et al.* (1999a).

## CONCLUSIONS

In this paper, we have considered the question of encapsulation in reanalysis and pointed out that the commonly held assumption that reanalysis is unencapsulated is not necessary. We have discussed an encapsulated, serial model of reanalysis search, and demonstrated that it is consistent with minimal revisions effects that we have found in experimental investigations.

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