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Against Repair-Based Reanalysis in Sentence Comprehension

Daniel Grodner,[1,4] Edward Gibson,[1] Vered Argaman,[2] and Maria Babyonyshev[3]

Structural reanalysis is generally assumed to be representation-preserving, whereby the initial analysis is manipulated or repaired to arrive at a new structure. This paper contends that the theoretical and empirical basis for such approaches is weak. A conceptually simpler alternative is that the processor reprocesses (some portion of) the input using just those structure-building operations available in first-pass parsing. This reprocessing is a necessary component of any realistic processing model. By contrast, the structural revisions required for second-pass repair are more powerful than warranted by the abilities of the first-pass parser. This paper also reviews experimental evidence for repair presented by Sturt, Pickering, and Crocker (1999). We demonstrate that the Sturt et al. *findings are consistent with a reprocessing account and present a self-paced reading experiment intended to tease apart the repair and reprocessing accounts. The results support a reprocessing interpretation of Sturt* et al.'s *data, rendering a repair-based explanation superfluous.*

KEY WORDS: parsing; sentence comprehension; syntactic ambiguity; reanalysis; prosodic phrasing; repair.

INTRODUCTION

The human sentence processing mechanism often misinterprets ambiguous input. For instance, the sentences in (1a) and (2a) are initially compatible with multiple interpretations. The italicized region in each sentence forces a

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[1] Massachusetts Institute of Technology, Cambridge, Massachusetts.
[2] Northeastern University, Boston, Massachusetts.
[3] Yale University, New Haven, Connecticut.
[4] To whom all correspondence should be addressed: Department of Brain and Cognitive Sciences, NE20-437, MIT, Cambridge, MA 02139. email: dgrodner@tedlab.mit.edu

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particular structural analysis. Individuals experience measurable difficulty over this region relative to unambiguous control sentences (1b) and (2b). This suggests that in each case the incorrect reading has been activated sufficiently to disrupt the processing of the ultimately correct interpretation.

(1) a. The boat floated down the river *sank.*
    b. The boat which was floated down the river sank. (Bever, 1970).
(2) a. The Australian woman saw the famous doctor *had been drinking quite a lot.*
    b. The Australian woman saw that the famous doctor had been drinking quite a lot (Sturt, Pickering, & Crocker, 1999)

Structural ambiguity is pervasive, and the processor often pursues an incorrect alternative. Yet language comprehension usually proceeds, albeit sometimes with difficulty. There thus must be reanalysis mechanisms that permit recovery of the correct structure. These mechanisms cause some parsing missteps to be remedied more easily than others. For instance, (2a) is substantially easier to comprehend than (1a). Patterns of differential misanalysis difficulty such as this have provided the primary source of insight onto the processes of reanalysis.

Most investigators assume structural reanalysis is representation-preserving, whereby an initially built structure is manipulated or repaired to arrive at a new structure. According to these theories, the NP subcategorization structure for the initial parse of "the Australian woman saw the famous doctor" in (2a) is altered when the disambiguating verb "had" is encountered, as shown in Fig. 1. This repair involves inserting between the verb "saw" and the NP "the famous doctor" the phrase structure for the null complementizer (Comp in Fig. 1) and the embedded sentence S node and its projections. In this way, aspects of the initial analysis can be preserved in the second analysis. The representation that successive structures share varies from proposal to proposal. It has been suggested that the processor preserves syntactic relations (Gorrell, 1995; Pritchett, 1992; Sturt & Crocker, 1996; Suh, 1994; Weinberg, 1995), thematic relations, (Pritchett, 1988; Sturt & Crocker, 1997), or aspects of prosodic structure (Bader, 1998). What all these proposals have in common is the prediction that reanalysis is more difficult when the target analysis requires amending the preserved representation.

The primary motivation for preservation is that it minimizes the need for redundant structure-building operations in the second analysis (Lewis, 1998); preserved structures only need to be built once and can then be stored for a second analysis. It is therefore implicitly assumed that building a new structure is more resource-intensive than storing and repairing the initial structure. There is no evidence, however, that structure building is

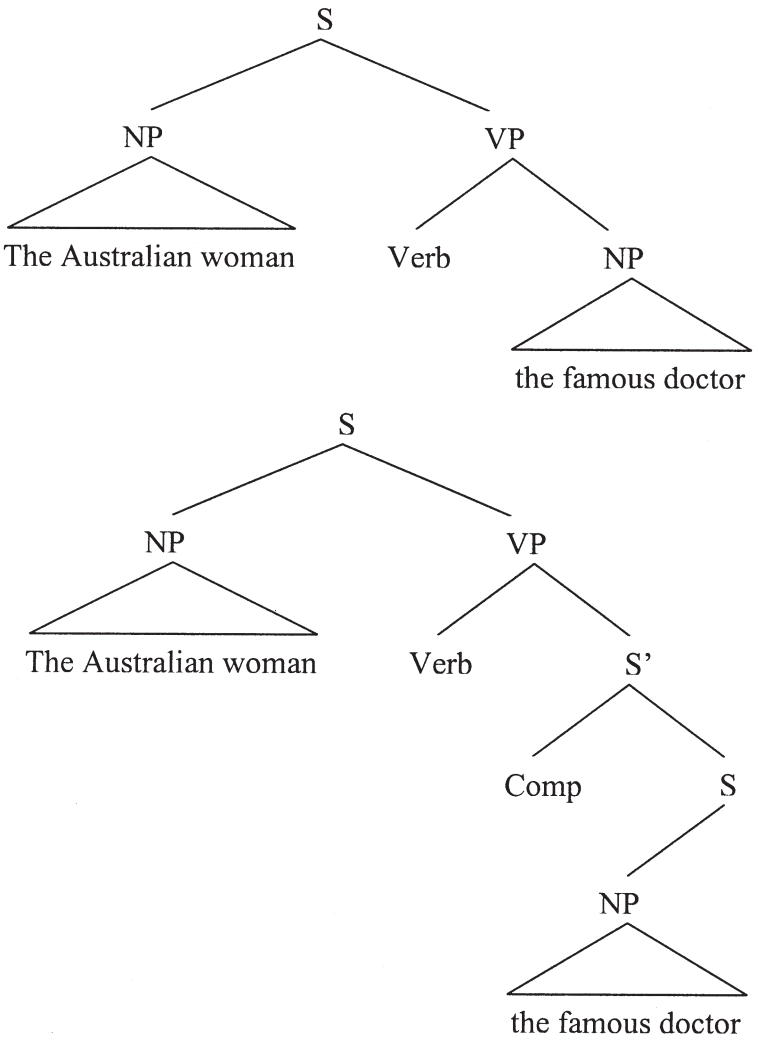

Fig. 1. The structural alternatives for the NP/S ambiguity. Recovery from the ambiguity in (2a) involves reanalyzing the NP "the famous doctor" from the object of the verb "saw" to the subject of the sentential complement of "saw." This alters the dependency between the verb "saw" and the NP.

especially resource-intensive. After all, the parser must assign a structure to every input string. As a result, structure-building operations are likely to be highly automated. Nevertheless, most investigators implicitly or explicitly assume that reanalysis proceeds by repair (Bader, 1998; Ferreira & Henderson, 1991; Fodor & Inoue, 1994, 1998; Frazier & Clifton, 1998;

Frazier & Rayner, 1982; Koneiczny, Hemforth, & Scheepers, 1997; Lewis, 1993, 1998; Pritchett, 1988, 1992; Stevenson, 1994, 1998; Sturt *et al.,* 1999; but cf. Gibson, 1991, 1998; Jurafsky, 1996).

Note that repair requires a more powerful set of structure-manipulating operations than does first-pass parsing. On first pass, all that is necessary is to find an attachment site within the current structure for the current word. Reanalysis is invoked when an input word cannot be incorporated into the current phrase marker. In this situation, a repair mechanism would have to (a) find an existing relationship to revise, (b) find new attachments for each element detached as a result of the revision, and (c) find an attachment site within the current structure for the original input word just as in first-pass parsing. Thus the operations involved in repair are a proper superset of those involved in the first pass. Steps (a) and (b) of this process are the most open-ended and require specifying a number of free parameters. For instance, how do second-pass mechanisms decide which structural relations to revise? There are, in general, more potential sites for revision than for the attachment of a new element (Sturt & Crocker, 1998). What are the intermediate products of destructive operations, how are they stored, and how are they to be recombined? These are complex issues that need to be worked out in detail for any specific representation-preserving proposal.

Despite the popularity of repair-based approaches, the present paper contends that the conceptual and empirical grounds for repair-based reanalysis are weak. A potentially simpler alternative that has not received much attention is that reanalysis proceeds by reprocessing (some portion of) the input using just those grammatical operations available to first-pass parsing. The only additional operations required for reanalysis concern the control structure of the parsing algorithm. For instance, it will be necessary to schedule potential sites to initiate reanalysis. However, such control mechanisms are essential to any theory of reanalysis. The reprocessing approach crucially differs from repair because it avoids positing specialized structure-manipulating operations in the second pass.

The issue of whether reanalysis proceeds by repair versus reprocessing has been obscured somewhat by the question of how many representations the sentence comprehension mechanism retains as new words are processed. Whether or not the human parser can follow more than one representation in parallel has not yet received a convincing resolution. The existing evidence is consistent with either a probabilistic serial model or a probabilistic ranked parallel model (Gibson & Pearlmutter, 2000; Lewis, 2000). In either model, potential structures are ranked according to a number of constraints. See Pearlmutter and Mendelsohn (1999) and Gibson and Pearlmutter (2000) for evidence and arguments for a ranked parallel approach; see Frazier and

Clifton (1996), Lewis (2000), Traxler, Pickering, and Clifton (1998) and Van Gompel, Pickering, and Traxler (2001) for evidence and arguments for a serial approach. Advocates of a serial architecture often support repair-based reanalysis, but there is no logical dependency between these positions. The question of repair versus reprocessing is orthogonal to whether the processing mechanism pursues one structural alternative at a time or maintains several alternatives in parallel. In particular, repair is not a necessary component of either a serial or parallel framework: Reanalysis can be implemented by reprocessing rather than repair in either architecture.

Reprocessing in a serial framework has been called *backtracking* (Winograd, 1983) because the processor must retreat to an earlier parse state and reparse the ambiguous material. There are a number of ways to implement backtracking (cf. Lewis, 1998). Perhaps the most feasible is to adopt a selective backtracking scheme (Frazier & Rayner, 1982) such that the processor keeps a marker of the onset of each structural ambiguity, up to resource constraints. If the current analysis is no longer tenable, the parser can then backtrack to one of these markers and reprocess the input from that point (cf. also the ranked flagged serial model of Inoue & Fodor, 1995). Because the number of compatible structures for an input can grow exponentially with the length of a sentence, it may not be feasible to retain a marker for every alternative that is encountered. Plausibly, the markers to be maintained are the most highly ranked alternatives, according to the same constraints that were used to rank the structures initially. If the processor needs to arrive at a structure that was not marked in initial parsing, reprocessing will be necessary to allow its reconsideration. The error signal that is provided at disambiguation adds a constraint that permits a reevaluation of the structures to be considered and discourages the parser from retreading the initial path.

In a ranked parallel architecture there are two means of recovering the target structure. If the desired alternative is among the subordinate structures being maintained, then it can be promoted above the current structure. If the correct structure is not available, then the input can be reparsed just as in a serial architecture. Both of these types of reanalysis (reparsing and reranking) will be referred to as *reprocessing* below to distinguish them from repair.

In contrast to repair, reprocessing is a necessary part of any plausible model of reanalysis. For example, intuition suggests that extreme garden paths such as in (3) are reparsed (often repeatedly) to try and figure out what was meant.

(3) a. The horse raced past the barn fell. (Bever, 1970)
    b. Tom told the children the story scared a riddle. (Frazier, 1978)

For other cases there is no alternative but to reprocess the input. For instance, representation-preservation is not useful when the candidate

readings of an ambiguity have little or no structural or semantic overlap. This is the case with syntactic category ambiguities such as the noun/verb ambiguity in (4) (Frazier & Rayner, 1987; MacDonald, 1993).

(4) a. The warehouse fires cause a lot of damage.
b. The warehouse fires many employees each spring.

The word "fires" is ambiguous between a noun, resulting in a noun-noun compound analysis of "the warehouse fires" as in (4a), and a verb, resulting in an NP-verb analysis of "the warehouse fires" as in (4b). In this reanalysis situation, it seems implausible that one analysis might be repaired to arrive at the other, because there is little (if any) structure or meaning of the initial structure for "fires" that can be used in the target structure (but cf. Pritchett, 1992). The sequence of sounds and letters is the same for the two lexical entries, but little else overlaps. The second analysis is most likely derived by reparsing the input or reranking a subordinate structure at disambiguation.

Given that reprocessing appears to be a necessary component of sentence comprehension, it is worth evaluating whether additional mechanisms like repair are also needed in first-pass parsing. For instance, certain revision operations are needed in first-pass parsing in order to process left-recursive structures incrementally. Such revision operations might extend to some instances of repair, such as the sentential complement ambiguity in (2a) (Sturt, p.c.). If so, then positing repair operations to reanalyze these constructions would not require extending the abilities of the parser. Consider the left-branching NP in (5):

(5) I like John's mother's friend's brother's grandfather.

The structure that is built initially for the input "I like John's" is provided on the left in Fig. 2.[5] When the possessive-case marked noun "mother's" is encountered, an additional possessive NP ("NP-poss" in the figure) is adjoined inside the predicted accusative object NP ("NP-acc"). This requires destroying the connection between the NP headed by "John's" and the predicted NP-acc, whose head has not yet been confirmed in the input. The resulting structure is shown on the right in Fig. 2. There is no way to predict in advance how many left-recursive steps there will be when processing a left-recursive structure such as this one. The incremental nature of sentence comprehension suggests that the processor builds and maintains fully connected structures at each parse step (Stabler, 1994; Steedman, 1989;

[5] The specific phrase structure analysis of possessive structures assumed here is not critical to the argument presented. The relevant feature of English possessive structures is that they are left-recursive: an NP is a specifier (subject, pre-head dependent) of a further noun.

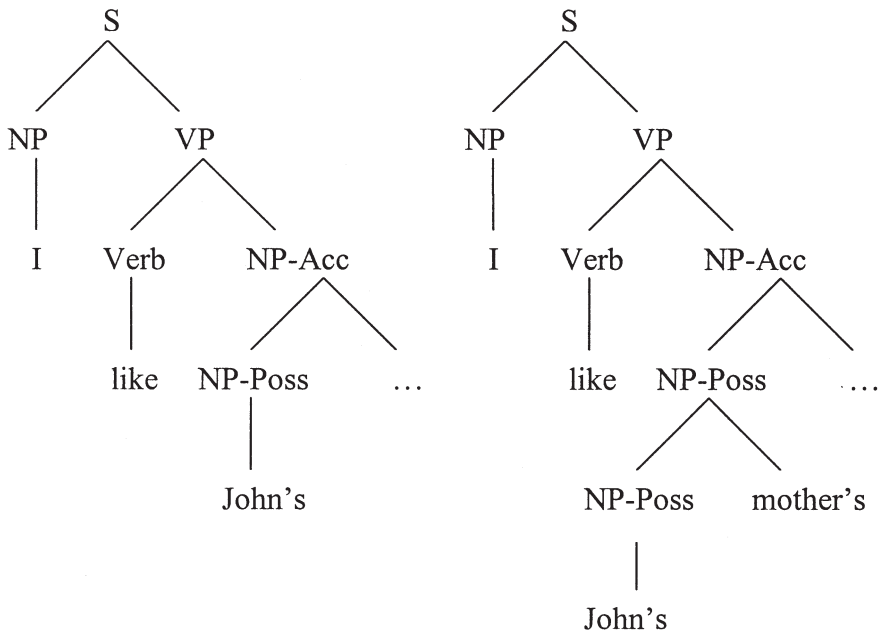

Fig. 2. Adjunction of the NP headed by "mother's" in the structure for the input string "I like John's mother's . . ." in (5).

Sturt & Crocker, 1996). Thus the link between the highest NP-poss and NP-nom must be broken as each possessive NP in (5) is introduced.

In general, any psychologically plausible model of sentence comprehension must be able to make adjunctions to the current structure in order to accommodate incoming material that necessitates left-recursive structures.[6] The question of relevance to this paper is whether this process is sufficient for any situations in which reanalysis is required. The answer appears to be "no." Consider again the ambiguity in (2a). Reanalysis for this sentence involves going from the preferred reading, where the NP "the famous doctor" is a direct object of the verb "saw," to the ultimately correct reading where this NP is the subject of a sentential complement to "saw," as depicted in Fig. 1. This reanalysis deletes the argument relation between the verb and the NP. More generally, reanalysis always involves changing the *type* of syntactic dependency—a head-argument, a head-specifier, or a head-modifier relationship—in which a confirmed element participates. In this case, the

[6] Tree Adjoining Grammars provide one formalization amenable to implementing this type of adjunction in an online parser (Joshi, Levy & Takahashi, 1975; Joshi, 1985).

confirmed element whose dependency relation is changed is the verb "saw." The head-argument relation between this head and the NP "the famous doctor" is altered by reanalysis. There is no adjunction in this operation.

Conversely, no dependency relations associated with confirmed elements in the input are deleted when making adjunctions. For instance, the adjunction step in (5) breaks the connection between the predicted object NP and the possessive NP headed by "John," but it does not change any dependency relations associated with confirmed elements. In particular, the possessive NP headed by "John" is in a specifier-dependency relation with a predicted NP in the initial structure. This dependency relation remains in the new structure, even though the identity of the predicted NP has been changed by the adjunction from a nominative NP to a possessive NP. Likewise, the argument relation between the verb "like" and the predicted object NP remains unaffected by the adjunction. Before and after the adjunction, an unheaded NP acts as the object of "like." Modifier adjunction, such as in PP-attachment, also does not alter the type of dependency for any confirmed element and so is not powerful enough to serve in reanalysis.

Although the process of adjunction involves changing a structure that was built in an earlier parse state, this process appears to be distinct from repair. Whereas reprocessing is a necessary component of sentence comprehension, there does not appear to be any logical argument that structure-manipulating operations as powerful as those invoked for repair are required in sentence processing.

Empirical Considerations

Insight into reanalysis processes comes primarily from work examining how difficult it is to recover from an initial misanalysis. The repair and reprocessing accounts make distinct claims about the influences that can affect the difficulty of this process. The reprocessing account claims that misanalysis difficulty will be related to two factors:

(6) a. The relative commitments to the alternative analyses
b. The type of disambiguating error cue

Repair-based accounts also allow that these factors affect misanalysis difficulty, but characteristically include an additional factor:[7]

[7] It should be noted that not all representation-preserving models attribute differences in misanalysis difficulty to differential repair processes. For instance, Fodor and Inoue (1998) and Frazier and Clifton (1998) claim that structural repairs have no inherent processing costs. The empirical arguments given below are not relevant to these theories. However, the theoretical arguments given above are especially relevant because the empirical consequences of repair in these models are hard to directly evaluate.

(6) c. The type of structural modification needed to recover the correct analysis.

We now review the empirical basis for each factor.

First, the ability to recover a correct structure is a function of how committed the processor is to the alternative analyses of the ambiguity (6a). This factor is required to explain why two sentences that contain the same structural ambiguity can differ in terms of misanalysis difficulty. For instance, (7a) and (7b) are structurally and lexically identical except for the ambiguous verb. Yet it is more difficult to recover the ultimately correct reduced relative structure after initially misinterpreting the ambiguous verb as part of a main clause in (7a) than in (7b) (adapted from Trueswell, 1996).

(7) a. The gourmet picked by the judges did not deserve to win.
b. The gourmet selected by the judges did not deserve to win.

Both sentences cause more difficulty than an unreduced control over the disambiguating by-phrase. This suggests that the main clause reading is actively interfering with the processing of the reduced relative reading. Note that the candidate readings of these two sentences have identical structures. Thus the same types of semantic and syntactic revisions are required in each, so (6c) cannot be responsible for the disparity. Factor (6b) is also ruled out because both sentences are disambiguated with the same by-phrase. The critical factor here is the relative activation strengths of the alternatives (6a). When the ambiguous verb appears frequently as a past participle as does *selected* in (7b), reanalysis to the reduced relative clause reading is reliably easier than when it has a low participle frequency as does *picked* in (7b) (Trueswell, 1996). Higher participle frequency makes the reduced relative reading more available. As a result, it is easier to jettison the main clause structure and recover the correct relative clause structure.

Different parsing architectures capture such degree of commitment effects differently. In a deterministic serial model in which one structural analysis is uniformly chosen and pursued until it is no longer consistent with the syntax of the sentence (cf. Frazier & Clifton, 1996), the relative commitments primarily affect how easy it will be to construct the ultimately correct interpretation after misanalysis.[8] In a probabilistic serial model the relative commitment to each structure determines how likely it is that the wrong reading will initially be adopted. Within a ranked parallel model, degree of commitment affects how difficult it will be to promote a subordinate structure above the initially favored structure. Though the precise

[8] For the Garden Path Model (Frazier, 1987) this is primarily a function of the thematic processor (Clifton & Ferreira, 1989).

mechanism varies between parsing architectures, all of these parsing models are capable of explaining why the relative commitments to the candidate readings affect misanalysis difficulty. Critically, the relative strengths of the structural candidates will affect reading times under either a reprocessing or a repair account of reanalysis.

Second, reanalysis difficulty is a function of the disambiguating material (Fodor & Inoue, 1994). For example, Fodor and Inoue cite the following example:

(8) a. Have the soldiers marched to the barracks tomorrow.
b. Have the soldiers marched to the barracks, would you.

Each of these written sentences is initially misinterpreted as an interrogative. Intuitions suggest that it is easier to reanalyze to the correct imperative reading of the sentence in (8b). This is likely because attempting to incorporate the tag question "would you" into the interrogative structure (8b) leads to a structural anomaly. This provides a more conspicuous error signal than the adverb "tomorrow" in (8a), which is structurally compatible with the interrogative, but pragmatically odd. Just as with the factor (6a), effects of disambiguating material on misanalysis difficulty (6b) are equally compatible with either a reprocessing strategy or a repair strategy.

Repair-based accounts critically differ from reprocessing accounts in predicting that the type of structural modification needed to yield the correct analysis will also influence misanalysis difficulty (6c). Indeed, this is what characterizes most representation-preserving accounts of reanalysis. Thus, to motivate repair, evidence must be provided that different structural revisions affect the ease of recovering the correct structure independent of the other two factors.

Most empirical evidence that has been provided as support for repair-based reanalysis mechanisms has come from intuitions (e.g., Fodor & Inoue, 1994, 1998; Lewis, 1993, 1998; Pritchett, 1988, 1992; Sturt & Crocker, 1996) or metalinguistic tasks (Ferreira & Henderson, 1991, 1998). One recent exception is a reading time study performed by Sturt *et al.,* (1999) (SPC) examining two types of structural ambiguity (9). One of these contained a verb that took a sentential complement (S) but was also compatible with a transitive argument structure (NP) (9a). The other sentence type contained an intransitive (or zero complement) verb (Z), but was also temporarily compatible with an NP analysis (9b).

(9) a. S: The employees understood the contract would be changed very soon.
b. Z: Because the employees negotiated the contract would be changed very soon.

All verbs were frequency biased toward the NP reading to ensure a misanalysis effect. SPC found that temporarily ambiguous Z sentences elicited greater misanalysis difficulty than S sentences (a larger slow down for ambiguous sentences over the disambiguating region relative to an unambiguous control). They attributed this effect to distinct repair processes which they claim are necessary to arrive at the correct structure after misanalysis. Specifically, recovering the Z reading requires altering existing dominance relations. The initial VP dominates the ambiguous NP in the NP interpretation, but not in the Z interpretation. In contrast the initial VP dominates the NP in both analyses of the NP/S. Revising dominance relations is theorized to be costly (cf. Gorrell, 1995; Pritchett, 1988, 1992). The ability to preserve this dominance relation makes repair easier in the NP/S, but not the NP/Z. SPC made an effort to control for other factors that affect misanalysis difficulty. Each NP/S verb was matched with an NP/Z verb that was equally likely to take an NP object. Plausibility differences were also matched across the two ambiguities. These controls served to equate lexical and semantic support for the favored NP reading. Additionally, the disambiguating material was identical across the two conditions, so it is unlikely that factor (6b) contributed to the differential misanalysis difficulty between S and Z sentences.

Despite controlling the plausibility and frequency of the NP reading, the increased difficulty with temporarily ambiguous Z sentences relative to S sentences is not necessarily a consequence of disparate structural repairs as described in (6c). It is possible that differential difficulty arises because the relative activation levels of the structural candidates are not balanced across the two ambiguities. If so, the results would follow from factor (6a), and would be compatible with a reprocessing account. There are at least two ways in which the NP/S and NP/Z ambiguities differ that may cause the Z reading to be less available than the S reading. Either of these could lead to more difficulty resolving Zs than Ss.

First, the S and Z readings each involve attaching an ambiguous NP [“the contract” in (9)] as the subject of a new clause. These analyses differ in how recently the attachment site for this clause has been encountered. There is an increasing body of evidence that the cost associated with integrating a new word into the current parse is related to the amount of lexical material intervening between the new word and its attachment site (Gibson, 1998). One effect of this can be observed in modifier attachment ambiguities where a constituent can be attached in more than one way. There is a graded preference for the more local attachment (Altmann, van Nice, Garnham, & Henstra, 1998; Pearlmutter & Gibson, 2001; also cf. Frazier, 1978). This predicts a locality bias in the NP/Z toward the favored NP reading, but not in the NP/S. To see why, note that in the sub-

ordinate S reading of (9b), the NP is the subject of a clause that is linked with the immediately preceding verb ("understood"). In contrast, for the subordinate Z reading of (9a) the new clause must be linked semantically and syntactically with the clausal connective ("because")—a nonlocal integration that spans an entire clause. If the parser is building fully connected structures at each parse state, then this integration occurs immediately upon seeing the postverbal (subject) NP. The favored transitive NP reading of (9a) and (9b) requires only a local integration to the preceding verb. There should thus be a locality bias favoring the NP in the NP/Z ambiguity, but no such bias in the NP/S ambiguity.

A second nonrepair explanation for the SPC result relates to prosodic aspects of the structural alternatives. Recently, Fodor has proposed that readers project a prosodic contour onto linguistic input during silent reading (Fodor, 1998; 2000). This implicit prosody is thought to influence ambiguity resolution. That is, other things being equal, the parser favors the syntactic analysis associated with the most natural (default) prosodic contour for an ambiguous input. To illustrate, consider the relative clause (RC) attachment ambiguity in (10) (Fernández & Bradley, 1999).

(10) a. My friend met the aide of the detective [that was investigating the case].
b. My friend met the aide of the detective [that was fired].

The bracketed RC could potentially modify the local nominal head *detective* (low attachment) or the more distant nominal head *aide* (high attachment). Interestingly, the preferred attachment is affected by the length of the RC. Shorter RCs such as (10b) increase the likelihood of low attachment relative to longer RCs as in (10a). This has been verified in English for both off-line interpretations of globally ambiguous sentences like (10), and in patterns of on-line reading difficulty when the RC is forced to the high or low site (Fernández & Bradley, 1999). The RC-length has also been observed in a number of other languages (see Fodor, 2000 for a review). This effect has been plausibly attributed to a prosodic phrasing bias. At the end of an RC there is a high probability of a prosodic phrase boundary (Gee & Grosjean, 1983, Watson, 2002). Further, when the RC attaches high, producers are more likely to insert a prosodic boundary before the RC (Cooper & Paccia-Cooper, 1980). Thus, high attachment generally implies that the RC stands on its own in a prosodic phrase. In contrast, low attachment usually causes the RC to be prosodically grouped with the preceding NP. Fodor proposes that the parser prefers prosodic structures in which sister constituents are balanced in terms of prosodic weight (the *balanced sister hypothesis,* Fodor, 1998). This hypothesis claims that short RCs prefer to attach low in sentences like (10) because they lack the prosodic weight to stand on their own

as a prosodic phrase. Long RCs, on the other hand, have sufficient weight to be their own prosodic constituents so that high attachment is licensed.

Analogously, the balanced-sister hypothesis could result in a prosodic bias toward the NP reading for ambiguous Z sentences. Note that the candidates for the NP/Z ambiguity have radically different prosodic phrasings [depicted by the bracketing in (11)].

(11) Because NP Verb NP
  a. Z: [Because NP Verb] [NP . . .]
  b. NP: [Because NP Verb NP] [. . .]

Under either reading, the major prosodic break occurs between the subordinate and main clauses. This carves the sentence into two intonational phrases. For the Z reading, the first intonational phrase consists of just three prosodic words, the connective "because," the simple subject NP, and the verb. For the NP analysis the subsequent NP is incorporated into the phrase. The Z reading might give rise to an intonational contour that lacks sufficient prosodic weight to stand alone. Given that the second intonational phrase incorporates the entire main clause under the default prosodic contour, it will on average be greater than three prosodic words in length. If the parser takes the prosodic weight of predicted constituents into account, the balanced-sister hypothesis predicts a preference to chunk the postverbal NP with the subordinate clause and thereby lengthen the initial intonational phrase. Thus there may be a prosodic bias promoting the NP analysis relative to the Z analysis. In contrast, the default prosodic contours for the NP and S analyses are similar through the ambiguous region (9a).[9] Thus there is no reason to select one or the other structure on the basis of any prosodic constraint.

Experiment

We have reviewed the repair, locality, and implicit prosody explanations for why Z sentences are more difficult to resolve than S sentences. A self-paced reading study was conducted to distinguish these three accounts. S and Z sentences such as in (12) were prepared, where the presence of an RC modifier on the initial subject was manipulated.

[9] Nagel, Shapiro, Tuller, and Nawy (1996) showed that a boundary after the verb pushes individuals toward an S over an NP reading; however, they did not demonstrate that the default prosody for the S analysis involves a prosodic break after the verb. We know of no experimental or intuitive support for a prosodic break between the verb and the NP in the S-complement reading. More importantly, even if there is an occasional preference for a low-level prosodic boundary here, it is far less prominent than the analogous break required after the verb in the Z analysis. The prosodic differences between the Z and NP readings are far more pronounced than any that might exist between the S and NP analyses.

(12) a. S: The employees (who initiated the strike) understood the contract would be changed very soon.
b. Z: Because the employees (who initiated the strike) negotiated the contract would be changed very soon.

The modifier has the effect of altering the attachment and prosodic properties of the ambiguities without affecting the qualitative structural repairs necessary to recover the correct structure. The locality and implicit prosody accounts predict that modification should alter misanalysis difficulty. In contrast, the repair account predicts no effect of modification.

Modification increases the locality bias toward the NP reading for ambiguous Z sentences, but not for the S sentences. Specifically, the modifier increases the integration distance between the ambiguous NP and the connective in the Z reading of (12b), but it does not affect integration distance in (12a). The locality-based account therefore predicts that the misanalysis effect will be larger for modified versions of the Z (12b) than for unmodified versions, but modification should not affect misanalysis difficulty in (12a).

In addition to increasing the length of the subordinate clause, modifying the initial subject lends prosodic weight to the first intonational contour in the Z analysis. If the initial bias toward the NP analysis stems from a bias toward balanced prosodic constituents, there should be less cause to adopt the NP analysis as the subordinate clause is made heavier. Under an implicit prosody account, there should be a decrease in misanalysis difficulty for modified Z sentences.[10] Just as for the unmodified conditions, the candidates of the modified NP/S are prosodically similar throughout the ambiguous region. Prosodic considerations do not distinguish the NP and S readings, and there is no reason to expect any effect of modifying the subject.

In contrast to the locality and implicit prosody accounts, the repair account predicts that modification should not differentially influence misanalysis difficulty for the S or Z sentences. This is because the necessary structural repairs are unaffected by the inclusion of a modifier.

To summarize, the locality account predicts an interaction between modification and sentence type such that modified ambiguous Z sentences

[10] As noted in the text, speakers often pause at the right edge of an RC. If this were true for the RCs in the Z items, then a new prosodic phrase would start at the verb. The Z analysis would then isolate the verb in a phrase by itself, which might lead to a bias to incorporate the postverbal NP into this constituent. We feel that this is unlikely, however. Intuitively, unambiguous Z sentences produced with a pause after the RC sound much worse than without it. Further, when five naive individuals were asked to rehearse and read single unambiguous Z sentences aloud, there were no detectable pauses after the RC. It is possible that the large prosodic break between the subordinate and matrix clauses diminishes prosodic variations within each clause.

precipitate more misanalysis difficulty than unmodified Z sentences. The implicit prosody account also predicts an interaction of modification and sentence type, but predicts that ambiguous modified Z sentences should be easier to resolve than the unmodified Z sentences. The repair account predicts no interaction of sentence type and modification.

METHODS

Participants

Fifty-three introductory psychology students from Northeastern University received course credit for participating in the present study.

Materials

Forty stimulus items were constructed according to a $2 \times 2 \times 2$ design crossing the factors Sentence Type (NP/S vs. NP/Z), Modification (present or absent), and Ambiguity (unambiguous vs. temporarily ambiguous). Sentence Type was a between-items factor, with 20 items containing verbs that were compatible with an NP or an S, and 20 containing verbs that were compatible with an NP or Z analysis. A sample NP/S item is given in (13a) and a sample NP/Z item is given in (13b).

(13) a. NP/S: The employees (who initiated the strike) understood (that) the contract would be changed very soon to accommodate all parties.
b. NP/Z: Even though the girl (who forgot her watch) phoned(,) the instructor was very upset with her for missing a lesson.

For the modified conditions a subject-extracted relative clause was attached to the initial subject NP in the sentence. This clause was always four words in length. Z items were made unambiguous by inserting a comma immediately after the verb. This forced a prosodic break at this point. S items were made unambiguous by inserting the overt complementizer "that" after the verb. For all unambiguous conditions the NP object attachment was not possible upon encountering the postverbal subject. In both the S and Z ambiguous conditions, the NP reading was possible through the postverbal NP. After this point a verbal predicate appeared, indicating the existence of a second clause.

All items contained verbs that were biased toward an NP subcategorization, in order to ensure that the ambiguous conditions would induce a misanalysis effect. Verb bias was established by compiling structural frequencies from the two-million-word parsed Penn Treebank corpus

(Marcus, Santorini, & Marcinkiewicz, 1993). Subcategorization frequencies were tabulated by extracting all occurrences, including inflected variants, of each ambiguous verb. If a verb appeared immediately before an NP complement, the usage was counted as an NP. If the verb appeared with a clausal complement, it was classified as an S. If the verb appeared with no overt complement it was classified as a Z. Following SPC, NP-bias for the NP/S verbs was calculated as the ratio of NP usages to the sum of NP and S usages. NP-bias for the NP/Z verbs was calculated as the ratio of NP usages to the sum of NP and Z usages. The average NP-bias for the S verbs was 75.9% ($SD = 13.3$). The average NP-bias for Z verbs was 60.7% ($SD = 24.8$). NP-bias was reliably greater for the S items [$t(37) = 5.8$, $MSe = 398$, $p < .05$]. This was expected to promote the NP analysis in the S conditions, making it harder to recover the correct reading relative to the Z conditions. As a result, if ambiguous Z sentences elicited more difficulty than ambiguous S sentences, it could not be attributed to a lexical frequency bias. Appendix A lists the experimental stimuli used along with NP-bias statistics.

Apparatus and Procedure

Sentences were presented using a noncumulative, self-paced, word-by-word display on a computer monitor. Each trial began with dashes standing in for the characters in a passage. Participants pressed the spacebar to reveal each new word of the sentence. As each new word appeared, the preceding word disappeared. A yes/no comprehension question followed each sentence. For target items this question queried the thematic relationships between the subject and predicate contained in the second clause. For instance, the question after (13b) was, "Was the instructor pleased with the girl?" Successfully answering the questions required correctly interpreting the ambiguous NP as a subject of the predicate. Participants were instructed to read at a normal rate in a manner that would enable them to answer the comprehension questions accurately. The computer recorded the time between button presses to the nearest millisecond. Line breaks occurred between words after 100 characters. The disambiguating region always occurred before a line break. Experimental stimuli were pseudorandomly intermixed with 80 fillers. Twenty of these were NP sentences that were temporarily compatible with a Z analysis. Half of these contained commas after the ambiguous NP. At least another 20 were NP sentences that were temporarily compatible with an S reading.

RESULTS

In this section we report question-answering accuracy data and reading time data for target stimuli.

Comprehension Questions

Participants responded correctly to 90.6% of comprehension questions after experimental items. A 2 × 2 × 2 ANOVA crossing Sentence Type, Modification, and Ambiguity revealed that responses after Z sentences were more accurate (93.5% correct responses) than after S sentences (87.7%) [$t_1(52) = 23.6$, $MSe = .02$, $p < .001$; $t_2(38) = 2.9$, $MSe = .04$, $p < .10$]. There was also an interaction of Sentence Type and Modification [$F_1(1,52) = 4.5$, $MSe = .02$, $p < .05$; $F_2(1,38) = 4.2$, $MSe = .01$, $p < .05$]. Namely, modified subjects led to slightly higher rates of correct responses for Z sentences (94.5% for modified vs. 92.1% for unmodified), and to slightly lower accuracy rates for S sentences (86.7% vs. 88.8%). No subjects were excluded on the basis of response accuracy on target or filler items.

Reading Times

To adjust for differences in word length across conditions, as well as overall differences in participants' reading rates, a regression equation predicting reading time from word length was derived for each participant, using all filler and experimental items (Ferreira & Clifton, 1986; see Trueswell, Tanenhaus, & Garnsey, 1994, for discussion). At each word position, the reading time predicted by the participant's regression equation was subtracted from the actual measured reading time to obtain a residual reading time. Residual reading times beyond 3.5 *SD* from the mean for a given condition and position were excluded from analyses. This adjustment affected 1.6% of the data. Raw reading times exhibited the same numerical patterns as trimmed residual reading times. Appendix B reports raw and trimmed residual reading times. Because question-answering accuracy was relatively high, and because the present study was intended to explore the processes underlying successful reanalysis, only reading times from trials for which the comprehension question was answered correctly were entered into analyses. When data from all trials regardless of response accuracy were analyzed, the same qualitative patterns emerged as those reported below.

Misanalysis difficulty was measured as the effect of Ambiguity over the first three words of the disambiguating verbal predicate (Region 5 in Appendix B). Difference scores were calculated for each subject and item by subtracting the mean residual reading times for the unambiguous conditions from the corresponding mean for the ambiguous conditions over this region. The resulting difference scores are plotted in Fig. 3. Note that difference score averages were reliably positive for both the S conditions [$t_1(52) = 2.56$, $SE = 8.6$, $p < .05$; $t_2(19) = 2.80$, $SE = 7.92$, $p < .05$] and the Z conditions [$t_1(52) = 5.19$, $SE = 9.4$, $p < .001$; $t_2(19) = 9.32$, $SE = 5.33$, $p < .001$]. This verifies that the ambiguous S and Z conditions engendered a garden

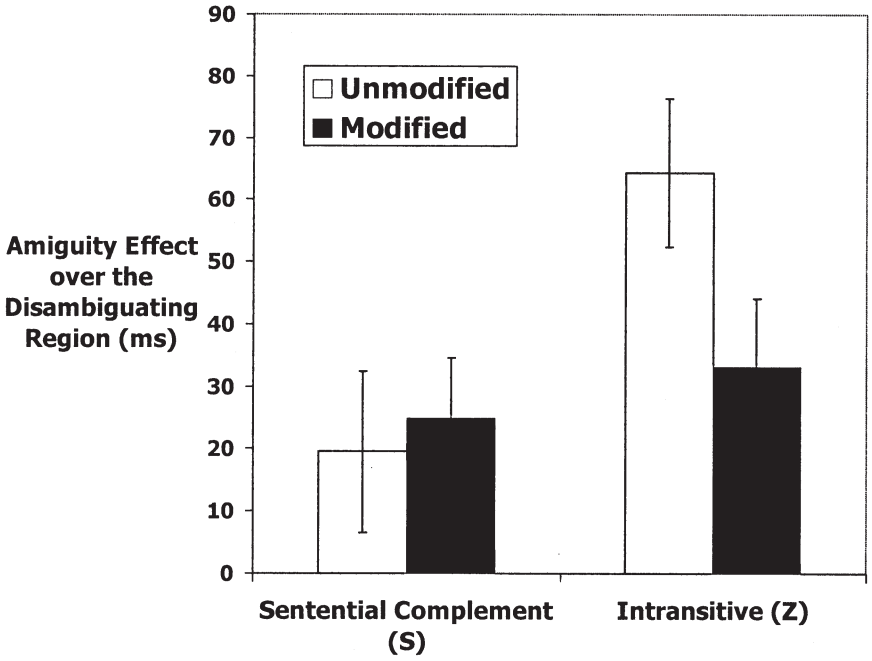

Fig. 3. Misanalysis difficulty as a function of ambiguity and subject modification (N = 53). Standard errors in parentheses.

path effect. A 2 × 2 ANOVA crossing Sentence Type and Modification was conducted. This yielded a main effect of Sentence Type—Z sentences were more difficult to recover than S sentences overall [$F_1(1,52) = 5.27$, $MSe = 7060$, $p < .05$; $F_2(1,38) = 8.31$, $MSe = 1820$, $p < .01$], replicating the SPC findings. There was also a marginal interaction between Sentence Type and Modification [$F(1,52) = 3.85$, $MSe = 4600$, $p = .055$; $F_2(1,38) = 2.91$, $MSe = 1790$, $p = .096$]. Ambiguous Z sentences elicited significantly more difficulty than S sentences in the unmodified conditions [$t_1(52) = 5.3$, $MSe = 4900$, $p = .05$; $t_2(1,38) = 8.41$, $MSe = 2260$, $p < .01$]. In the critical modified conditions, this disparity vanished ($Fs < 1$). Thus, modification eliminated the differential difficulty between the Z and S sentences.

DISCUSSION

Of the three accounts presented, the results are most consistent with the implicit prosody account. Modifying the subject of the first clause reduced

the misanalysis effect in for Z sentences, but left difficulty with the S sentences unaffected. This manipulation did not alter the structural changes necessary to reanalyze either ambiguity. Thus, differential misanalysis difficulty was eliminated without affecting repair processes. This vitiates a repair-based account of SPC's finding that Z sentences are more difficult than S sentences. The present results are also not explained by the locality account. The locality account claimed that the Z analysis was less available than the S analysis because the former requires a more distant attachment than the competing NP analysis. If this were true, then lengthening the pivotal attachment for the Z analysis should have increased the discrepancy in misanalysis difficulty. This was not attested; modifying the subject NP of the subordinate clause had the reverse effect. Unlike the locality and repair accounts, the implicit prosody account is capable of explaining both the SPC result and the present results by appealing solely to factor (6a), the relative activation strengths of the alternative structures. Structures that satisfy more prosodic constraints are promoted relative to structures that do not. In this case, modifying the initial subject imparted sufficient prosodic weight to the first intonational phrase of the Z analysis so that it was more accessible relative to the NP analysis.

It should be stressed that this evidence only indirectly supports an implicit prosody account. We have demonstrated that manipulating the length of subordinate clause alters the relative commitments to the NP and Z structures. Changing the length of the embedded clause also affects the length of the prosodic contour for the first intonational phrase so it is plausible to apply a prosodic explanation. However, there are other aspects of the NP/Z sentences that may have been altered by modifying the initial subject. For instance, modified subjects have distinct semantic and pragmatic properties relative to simple subjects. Manipulating these properties may have altered the relative merits of the competing analyses. Regardless of what factors make the NP more available in the Z conditions relative to the S conditions, the present results disconfirm the predictions of repair-based reanalysis. The repair account claims that the Z analysis should be fundamentally harder to recover after misanalysis relative to an S analysis. The present study found that the addition of a modifier actually eliminated the difference between the S and Z analyses. This makes it unlikely that reanalyzing a Z sentence is intrinsically more difficult than reanalyzing an S sentence.

SUMMARY

We have argued that theoretical and empirical considerations militate for an account of reanalysis that does not include repair. Instead we suggest

that reanalysis proceeds by reprocessing the input. This reprocessing seems to be a necessary part of any realistic model. In contrast, the structural manipulations involved in repair are not manifestly part of the processing mechanism. Some investigators have claimed that repair is necessary to explain patterns of misanalysis difficulty. The strongest support for this claim comes from the SPC finding that ambiguous Z sentences are more difficult to recover than S sentences after initial misanalysis. SPC interpreted their results as evidence for differential structural repairs in resolving S and Z sentences. We have adduced evidence that these results are equally compatible with a reprocessing account in which the candidate readings of each ambiguity are more or less available. The repair account is therefore unnecessary to explain the data. Our evidence, of course, does not rule out representation-preserving mechanisms across all cases of reanalysis, but it does highlight the difficulty of providing evidence for a repair-based account. To show direct and unambiguous evidence for repair, one must demonstrate that a discrepancy in the misanalysis difficulty between two ambiguities is due to differences in the structural changes required to recover the correct structures (6c). This requires controlling the relative accessibility of the structural alternatives (6a). This is a tall order. Different structural ambiguities are likely to have distinct nonstructural properties. It is therefore difficult to unambiguously attribute differential misanalysis effects to structural factors. One way to establish the influence of factor (6a) is to perform an elicited production norm for the ambiguities of interest, using, for example, a sentence completion task. In this way one could assess the relative accessibility of the alternative readings in the absence of any reanalysis effects. If one candidate is more highly activated in comprehension, then it should appear more often as a proportion of completions for an ambiguous sentence onset (modulo any task demands specific to production).

A second, less direct, prediction of the repair account is that it may be possible to construct a locally ambiguous sentence that is easier to process than its unambiguous counterpart (Gibson, Babyonyshev, & Kaan, 1998). This is because repair-based ambiguity resolution can invoke structure-manipulating operations that are not available in the first pass. This permits a repair-based parser to circumvent parse states that a first-pass parser must traverse (cf. Lewis, 1998). Consider a case in which the unambiguous sentence structure is complex. In such a case, the parser might be able to bypass the high-processing-cost parse states by first pursuing a less costly analysis, which is made available by the temporary ambiguity, and then altering this structure to arrive at the target interpretation. In contrast, the reprocessing alternative predicts that this kind of situation should not be possible because there is only one way to build structures (i.e., using first-pass structuring mechanisms). Additional reranking or reparsing can only increase complexity.

In any case, the available evidence is consistent with either an account based on repair plus reprocessing or reprocessing alone. Given that repair requires a powerful and, as of yet, unspecified set of structure-manipulating operations, an account based solely on reprocessing seems preferable.

APPENDIX A: EXPERIMENTAL ITEMS

The unambiguous modified forms of each item are given below. Items 1 to 20 were S sentences. Items 21 to 40 represent the Z conditions. The proportion of instances in which the critical verb appeared with an NP direct object is in parentheses after each item. Underscores indicate pairs of words that were displayed and analyzed as a single word.

1. The employees who initiated the strike understood that the contract would be changed very soon to accommodate all parties. (.736)
2. The mechanic who repaired dented vehicles accepted that the car looked in worse shape than before he worked on it. (.97)
3. The old_man who fractured his skull recalled that the nurse had complained to the doctor that the patient never took his medication. (.635)
4. The traveler who stayed_at the hotel heard that the clock had woken everybody up in the youth hostel. (.919)
5. The journalist who read the bulletin confirmed that the story would be published on the front page the next day. (.615)
6. The worker who hurt his back maintained that the walls fell down in a heap before he arrived. (.778)
7. The apprentice who wanted fresh air forgot that the bicycle was standing in the garage next to the car. (.727)
8. The committee which selected the location mentioned that the issue would cause a problem at the meeting. (.848)
9. The army which invaded the country found that the supplies saved many lives during the long conflict. (.784)
10. The umpire who officiated the double-header warned that the spectators would probably get too rowdy if beer was served. (.462)
11. The coach who scouted new talent discovered that the player tried to show off all the time. (.578)
12. The woman who proofread the ads noticed that the flyer had the wrong address listed on the front. (.741)
13. The tourists who visited the kingdom saw that the palace was being restored to its original condition. (.851)
14. The scientist who designed large trucks proved that the theory could help build cars with better mileage. (.598)

15. The soldiers who witnessed the battle remembered that the town had been flattened in the bombing raid. (.753)
16. The priest who performed the ceremony recognized that two guests were necessary for the marriage to be legal. (.866)
17. The reporter who worked_for the Globe revealed that the politician received some payments from the unscrupulous millionaire. (.784)
18. The owners who purchased the estate insured that the house would never get flooded again when it rained. (.789)
19. The lawyer who questioned the witness established that the alibi was not sufficient to free the defendant from blame. (.984)
20. The store which sold used appliances guaranteed that the television would last for ten years without failing. (.762)
21. Even_though the band which played funk music left, the party went on for at least another two hours. (.713)
22. In_case the executive who lost the organizer forgot, the assistant would remind him of his daily meetings and appointments. (.588)
23. Although the maid who wore a uniform cleaned, the house was still in a state of total chaos. (.897)
24. Because the class that memorized the constitution failed, the exam was rewritten by the teacher so it was much easier. (.017)
25. Once the child who rehearsed the sonata played, the piano was moved to the corner of the room. (.68)
26. As the couple who loved ballroom music danced, the tango began to be played by a live orchestra. (.172)
27. After the kids who stole the test cheated, the teacher had them sit at separate desks and think about what they had done. (.429)
28. After the mugger who wielded a club attacked, the jogger was rubbing his sore leg, but it didn't help. (.796)
29. Even_though the girl who forgot her watch phoned, the instructor was very upset with her for missing a lesson. (.769)
30. Even_though the janitor who cleaned the office vacuumed, the carpet was covered with dust and crumbs from the office party. (1)
31. Although the candidates who bought many votes debated, the issues were overlooked by most of the media who covered the campaign. (.833)
32. Because the train which spewed dark smoke stopped, the traffic was rerouted through side streets for several hours. (.407)
33. In_case the team which fired their coach lost, the tie-breaker was scheduled for the following week at the local park. (.818)
34. After the librarian who supervised the staff called, the intern began returning books to the shelves. (.445)

35. Even_though the army which guarded the border surrendered, the territory was filled with land mines that still had to be cleared. (.5)
36. While the narrator who caught a cold read, the story was dramatized by the troop of skilled actors. (.734)
37. Before the tribe which pierced their lips worshipped, the idol was placed on a large platform. (.571)
38. In_case the manager who won several awards quit, the company began training new staff in several departments. (.382)
39. As the customer who hated the meal paid, the waitress could see how large the tip was. (.819)
40. While the artist who decorated the house painted, the furniture was covered with white cloths to shield it from dust. (.571)

APPENDIX B: RESIDUAL (AND RAW) READING TIMES IN MS BY CONDITION AND REGION

		Z Conditions							
		Unmodified				Modified			
	Region	Ambiguous		Unambiguous		Ambiguous		Unambiguous	
1	Although the girl	−23	(452)	−26	(400)	2	(433)	−20	(405)
2	who forgot her watch					−16	(407)	−18	(400)
3	phoned(,)	−30	(402)	−10	(452)	11	(464)	30	(494)
4	the instructor	−22	(382)	−16	(402)	−9	(415)	29	(448)
5	was very upset	35	(452)	−29	(382)	17	(432)	−17	(395)

		S Conditions							
		Unmodified				Modified			
	Region	Ambiguous		Unambiguous		Ambiguous		Unambiguous	
1	The employees	−26	(397)	−32	(393)	−32	(392)	−24	(398)
2	who initiated the strike					−14	(415)	−17	(413)
3	understood	−7	(467)	−16	(460)	−23	(449)	−1	(471)
4	that			23	(431)			−15	(393)
5	the contract	−4	(412)	−21	(396)	−17	(401)	−29	(388)
6	would be changed	8	(424)	−9	(410)	−2	(419)	−28	(391)

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