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Resolving attachment ambiguities with multiple constraints

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Abstract

Different theories of syntactic ambiguity resolution argue for different sources of information determining initial parsing decisions (e.g., structurally defined parsing principles, lexically specific biases, or referential pragmatics). However, a "constraint-based" approach to syntactic ambiguity resolution proposes that *both* lexically specific biases and referential pragmatics are used in parallel by the comprehender. Analyses of text corpora, sentence fragment completions, and self-paced reading experiments were conducted to demonstrate that both local information (lexically specific biases) and contextual information (referential presupposition) contribute to the on-line resolution of prepositional phrase attachment ambiguities. There does not appear to be a role for purely structurally defined parsing principles (i.e., minimal attachment). Present and previous evidence is consistent with a developing framework in which multiple constraints (bottom-up *and* top-down) interact immediately to determine initial syntactic commitments.

1. Introduction

Ambiguous constructions have been central in sentence processing research because of what they can reveal about the mechanisms that are responsible for building a parse and for recovering from an initially incorrect interpretation. Among the numerous types of ambiguous constructions, sentences containing ambiguously attached prepositional phrases have

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figured prominently in the sentence processing literature. An example of this ambiguity type is given below in sentence (1):

(1) The Arapahoe Indian shot the cowboy with the leather vest.

This sentence is syntactically ambiguous because the prepositional phrase (PP) could either be attached to the verb phrase (VP) "shot..." or to the noun phrase (NP) "the cowboy...". If the reader parses this phrase as attached to the NP, then "with the leather vest" is interpreted as modifying (or further specifying) the NP "the cowboy...". In this case, the NP within the PP expresses an *attribute* of the head noun. However, if the PP is parsed as attached to the VP, then it is interpreted as further specifying the VP "shot...". Here, the NP within the PP plays the thematic role of *instrument*. Reading time studies have shown that, for sentences presented in isolation, people show a general preference for attaching an ambiguous PP to the VP rather than to the NP. In sentence (1), for instance, as a leather vest does not make a plausible instrument for shooting someone, the sentence becomes difficult to read at the prepositional phrase, where it becomes apparent that the preferred VP-attachment analysis is pragmatically deviant. There is substantial evidence for increased processing time for sentences with the syntactic structure of (1) and *not* for sentences with the syntactic structure of (2), where attaching the PP at the level of the VP does not result in incongruity (Altmann, 1986; Frazier, 1978; Rayner, Carlson, & Frazier, 1983; Rayner, Garrod, & Perfetti, 1992; but see also Taraban & McClelland, 1988):

(2) The Arapahoe Indian shot the cowboy with the bow and arrow.

This result is interpreted as an indication that readers tend to initially parse an ambiguously attached PP as attached to the VP, and thus experience a "garden path" effect only when the phrase is more plausibly parsed as an NP-attached phrase. Determining what causes this attachment preference (as well as the parsing preferences in other syntactic ambiguities) has been the goal of a great deal of work in sentence processing.

The purpose of the present paper is to examine the roles of three potential sources of constraint in sentence processing: structurally defined parsing principles, lexically specific biases and referential pragmatics. We provide evidence from corpus analyses, sentence completions, and self-paced reading that *both* referential pragmatics and lexically specific biases have immediate influences in syntactic ambiguity resolution. Moreover, when these two constraints are taken into account, it becomes apparent that the postulation of an additional, structure-based, principle is unnecessary. The results favor a constraint-based model of sentence processing in which the bottom-up input computes, in parallel, the possible syntactic alternatives

at the point of ambiguity, and contextual constraints provide immediate support for one or another of those alternatives.

We will begin by directly evaluating the claims made by three different classes of accounts of parsing preferences for ambiguously attached PPs: (1) an account based on syntactically stated parsing principles; (2) explanations based on lexically specific information; and (3) theories of ambiguity resolution that hinge on discourse-based interpretation. The first account, articulated by Frazier (1978, 1987), assumes a two-stage processing system in which the initial construction of a parse is based on a highly restricted body of information, essentially limited to information regarding the syntactic category membership of incoming lexical items, and information that licenses the building of phrase structures. The parser also includes a set of parsing-specific principles that allow for a choice to be made in the event that phrase-structure constraints and categorial information are insufficient to produce a single parse. In the case of ambiguous PP attachment, for instance, the Minimal Attachment principle ensures that the least complex structure will initially be computed by the parser, where structural complexity is defined in terms of the number of syntactic nodes that are required to construct a syntactic tree-structure representation of the sentence. It has been argued that for sentences with ambiguously attached PPs, the NP-attached versions involve more syntactic nodes and deeper branching of the constituent structure.[1] In this two-stage account, contextual information as well as lexical information, other than categorial membership, is assumed not to play a role in determining the initial parse. Pragmatic and lexically specific information can be used only to confirm or reject the output of the initial stage.

A number of quite different proposals can be grouped together in the second class of accounts, which focuses on the role of lexically specific information in ambiguity resolution. One subclass within this group deals with the importance of argument structure, and emphasizes the availability of possible or preferred subcategorization frames in determining an initial parse (e.g., Abney, 1989; Britt, 1994; Britt, Perfetti, Garrod, & Rayner, 1992; Ford, Bresnan, & Kaplan, 1982). However, we will be primarily concerned with accounts that rely on lexical information of a more fine-grained nature, and are not limited to structural aspects of lexical entries such as subcategorization frames. For instance, Taraban and McClelland (1988, 1990) have argued that the semantic content of each constituent is taken into consideration and evaluated with respect to the role it plays in the event being described. They pointed out that attachment differences co-vary

[1] For PP attachment ambiguities, this difference in the number of non-terminal syntactic nodes only holds following certain assumptions concerning constraints on phrase structure building that are spelled out in Frazier (1990). Frazier argues in this paper that the constraints on phrase structure building that are relevant to the parser are not necessarily isomorphic with grammatical constraints on phrase structure.

with differences in the semantic role of the PP, and proposed that semantic role expectations associated with verb + noun + preposition combinations may determine what structural attachment is initially preferred in the reading of a PP attachment ambiguity. To support this view, they had subjects perform sentence completion and rating tasks to find the predictable semantic roles for the object of the preposition, and found that for some verb + proposition pairs expected semantic roles ruled out one or the other syntactic attachment. A word-by-word self-paced reading task corroborated these findings by showing that stimuli in which the expected semantic roles were inconsistent with a VP attachment had faster reading times when the PP was attached to the NP, and vice versa.

An account that makes similar empirical predictions to the semantic expectations story, but is considerably different in spirit, is one that attributes PP attachment preferences to the frequency of co-occurrence of specific lexical items. Hindle and Rooth (1993) analyzed a large corpus of text and found that out of 880 sentences in which the main verb was followed by an NP and then a PP, 67% of them were NP-attached constructions. A result such as this, which runs counter to the general preference for VP attachment observed in human sentence processing, could be interpreted as strong evidence for a specialized parsing rule that operates without recourse to information about distribution patterns (i.e., Frazier, 1987). However, an analysis of attachment preferences based on specific lexical items revealed a more complex pattern: a calculation of co-occurrences between individual nouns, verbs and prepositions determined the preferred attachment for each sentence with close correspondence to judgments made by humans (Hindle & Rooth, 1993). Whether due to semantic role expectations or frequency of co-occurrence, the common thread between these latter two accounts is that they predict lexically specific biases that will manifest themselves as different attachment preferences in different sentences.

In contrast with these local influences on parsing (either structural or lexical) operating essentially independently of the discourse context, a referential account of PP attachment ambiguity places the responsibility for initial attachment preferences largely in the hands of knowledge representations relating to the discourse context (Altmann, 1986, 1987; Altmann & Steedman, 1988; Crain & Steedman, 1985; Ni and Crain, 1990; Steedman & Altmann, 1989). According to Referential Theory, the attachment preference for ambiguously attached PPs is largely determined by the way in which the parser attempts to establish referential links with a mental discourse model. Proponents of this approach have stressed that even when no explicit discourse context is presented, some form of a discourse model will have been developed from the information that precedes the point of syntactic ambiguity. Thus, a non-biasing context may be categorically impossible to construct, as even the absence of a context biases the reader toward a particular alternative of the syntactic ambiguity (Altmann &

Steedman, 1988; Crain & Steedman, 1985). The referential account for evidence of a garden path effect in sentences containing NP-attached prepositional phrases is based upon the discourse properties of definite NPs. On this view, the structural indeterminacy hinges upon the temporary ambiguity of interpreting a definite NP (i.e., "the knife") as a complete simple NP (sentence 3a) or as an incomplete complex NP (sentence 3b):

(3) a. I bought [the knife]$_{NP}$ from the pawn broker.
b. I bought [the knife from World War II]$_{NP}$.

It is assumed that a definite NP must refer to a unique referent already established in the discourse model. In the absence of preceding context, or if the context does not contain a previously established referent, the reader must accommodate the definite NP's reference by creating a referent in the discourse model (Heim, 1982). Furthermore, Steedman and colleagues (e.g. Altmann & Steedman, 1988; Crain & Steedman, 1985; Steedman & Altmann, 1989) claim that simple and complex definite NPs carry different referential presuppositions. A *simple* definite NP presupposes the existence of a single referent in context corresponding to the entity described by the head noun. For example, in (3a), it is presupposed that there is a single referent which has the label *knife*. In contrast, a *complex* definite NP presupposes the existence of multiple possible referents bearing the label associated with the head noun (e.g., *knife*), from which a unique one is being distinguished via the attribute expressed by the modifier (*from World War II*). This presuppositional difference between simple and complex NPs hinges on the fact that definites presuppose the existence of a uniquely identifiable discourse entity. In the case of the simple NP, the head noun itself is sufficient to pick out a unique referent, whereas in the case of the complex NP, a restrictive modifier is used to restrict over a set of entities in order to identify a unique referent (Kamp & Reyle, 1993; Steedman & Altmann, 1989). Referential Theory assumes that these two alternative NP analyses (simple and complex) are proposed in parallel by the human language processing system. Upon determining the contextual appropriateness of each of the two mutually exclusive pragmatic presuppositions (of a single NP referent or of multiple NP referents), the system opts for the NP analysis whose presupposition is satisfied by the discourse model. In the absence of any explicit linguistic context, the preferred analysis will be the one that results in fewer accommodations of unsatisfied presuppositions to the discourse model. Given that the simple NP analysis is associated with fewer presuppositions than the complex analysis, the simple analysis will be preferred by the parser, resulting in a preference for VP attachment for sentences presented in isolation.

Each of the accounts described above focuses on some particular information source as bearing the responsibility for the general preference for VP attachment in parsing attachment ambiguities. However, there is a recent

and growing body of research that provides evidence for the simultaneous interaction of a number of different sources of constraint (Britt, 1994; Burgess, 1991; MacDonald, 1994; Pearlmutter & MacDonald, 1992; Spivey-Knowlton, Trueswell, & Tanenhaus, 1993; Spivey-Knowlton & Tanenhaus, 1994b; Trueswell, Tanenhaus, & Garnsey, 1994). These studies suggest that what is needed is a framework for describing the mechanisms whereby different constraints exert influence upon parsing. Models formulated within a constraint-based approach provide such a framework (see, for instance, Bates & MacWhinney, 1989; MacDonald, Pearlmutter, & Seidenberg, in press; Spivey-Knowlton et al., 1993; Taraban & McClelland, 1988, 1990). Current constraint-based models remain largely underspecified, and differ with respect to the particular constraints that are emphasized, but share the following assumptions: Multiple alternatives of an ambiguous string are made available on the basis of "bottom-up" input, and constraining evidence from a number of different contextual domains is integrated immediately to resolve the ambiguity in favor of a single analysis. The degree to which an analysis is preferred is directly related to both the relative importance (or weight) that the system assigns to the constraints favoring that analysis, and the strength of the evidence provided by those constraints in that particular sentence. The specific predictions generated by constraint-based models depend upon the exact specification of the constraints and their relative weights, just as the specific predictions generated by a two-stage model such as Frazier's depend upon the precise formulation of parsing principles. However, what is common to all constraint-based models is the notion of simultaneous multiple constraints exerting graded effects depending upon the strength of those constraints.

The purpose of the present study is to examine the on-line effects of three separate domains of information: structurally based parsing principles, lexically specific biases, and referential pragmatics. Our results indicate that none of the specific mechanisms described above can single-handedly explain the data obtained for PP attachment preferences. In the first section, we present evidence from a corpus analysis motivating a referentially based explanation for the VP attachment preference found in experimental work. We then report data from two reading time experiments indicating that, while referential factors appear to have a weakly modulating effect upon on-line attachment preferences, there is a residual VP attachment preference that cannot be accounted for by referential factors. In the second section, we investigate the interaction of referential factors with lexically based information related to the semantic classes of verbs. We present evidence from a corpus analysis and sentence completions suggesting that the residual VP attachment preference in the reading time experiments can be attributed to a strong lexically specific bias toward VP attachment of the ambiguous PP. The results point to a different class of verbs (i.e., psych/perception verbs) which has a slight lexical bias toward *NP attachment* of an ambiguous *with*-phrase. A reading time study using these verbs shows that

referential factors contribute strongly toward on-line attachment expectations when lexically specific information is less constraining. Furthermore, once these two factors are taken into consideration, there is no evidence for an independent, structurally defined principle, such as Minimal Attachment. Given this pattern of data, we argue in the final section that a constraint-based framework is needed to account for this interaction between lexically specific biases and referential pragmatics, and we discuss what a particular model within this framework might look like.

2. The role of referential pragmatics

The most compelling evidence for the influence of referential factors in on-line processing comes from the effect of establishing a discourse context in which modification of a definite NP is referentially supported (e.g. Altmann, Garnham, & Dennis, 1992; Altmann, Garnham, & Henstra, 1994; Altmann & Steedman, 1988; Britt, 1994; Britt et al., 1992; Crain & Steedman, 1985; Spivey-Knowlton et al., 1993; Spivey-Knowlton & Tanenhaus, 1994b; but see Ferreira & Clifton, 1986; Mitchell, Corley, & Garnham, 1992; Murray & Liversedge, 1994; Rayner, Garrod, and Perfetti, 1992). Example (4) below, taken from Altmann and Steedman (1988), demonstrates the use of context with the PP attachment ambiguity:

(4) A fireman was running to the scene of a fire carrying a heavy axe. He had to smash down a door. When he got to the scene of the fire, he found a door which had a rusty lock and a door which was nailed shut.

Target: The fireman smashed down the door with the rusty lock/heavy axe but smoke overcame him.

In this example, the context introduces two NP referents in discourse (i.e., two doors) prior to the target sentence. It has been shown in the studies cited above that this produces a preference for a complex NP analysis of the crucial definite NP, thus reversing the parsing preference observed when the context contains only one NP referent (or in the absence of context). This result poses problems for theories that claim initial syntactic parsing takes place independently of context.

However, the specific mechanism that drives this contextual influence may or may not be attributable solely to referential presuppositions. A context that contains two NP referents, only one of which will become important for subsequent discourse, necessarily poses a minimal pair of more or less mutually exclusive entities among which the reader may expect discrimination via NP modification. In the passage in (4), for instance, we have been told in advance that the fireman will smash down a door; when we encounter the two NPs, both referring to doors, we are unsure as to which is

the relevant one in this event. This indeterminacy may create a strong expectation, before the target sentence is even encountered, that subsequent discourse will provide information to choose between these two doors. The context effect, then, may not be an effect of accommodating referential presuppositions so much as an effect of developing expectations as to the informational content that is likely to be relevant for subsequent discourse. While similar to Referential Theory in spirit, this influence of informational (or conceptual) expectation would not require the satisfaction of referential presuppositions, nor hinge on the definiteness of the crucial NP.[2] For example, Spivey-Knowlton (1992) produced an *increase* in VP attachment bias when two similar possible *events* preceded the target sentence as compared to when the two possible events were dissimilar (the two possible events are italicized in example 5). This context effect may well be mediated by presuppositions related to discourse structure, but it is not clear that a purely referentially based mechanism could easily account for it. (At the very least, such a theory would have to incorporate a notion of reference to events and their related presuppositions.)

(5) **Context with two similar events:** One day on the subway, a kind got on carrying a weapon in each hand. He almost *hit* someone by swinging a whip and pretended to *hit* someone else using a baseball bat...
Context with two dissimilar events: One day on the subway, a kid got on carrying a weapon in each hand. He almost *hit* someone by swinging a whip and pretended to *threaten* someone else using a baseball bat...
VP-attached target sentence: That kid hit the girl with a whip before he got off the subway.
NP-attached target sentence: That kid hit the girl with a wart before he got off the subway.

Because these two factors (referential presuppositions and informational expectations) are often conflated in experiments with referential NP contexts, we sought to test the predictions made by Referential Theory without relying on the manipulations that have been typically used in which referential presuppositions are either satisfied or not by the preceding context. Rather than looking at sentences that require the satisfaction of certain referential presuppositions, and comparing them across contexts, our strategy was to compare sentences that carry such presuppositions with ones

[2] A precursor of the referential theory, namely Altmann's (1987) principle of referential failure, accounts for the effect of context without appealing to the specific presuppositions associated with modifiers of definite NPs. This principle says that when a unique referent is required (i.e., the NP is definite), there will be a bias toward treating incoming material as a modifier in order to help identify the referent in case the content of the head noun does not by itself pick out a unique referent. However, this principle does rely on the uniqueness presupposition associated with definite NPs, whereas an informational expectations view does not.

that do not. We accomplished this by exploiting the presuppositional differences associated with definite versus indefinite descriptions, and manipulated the definiteness of the NP immediately preceding the ambiguously attached PP.

Crain and Steedman (1985) argue that the presuppositions that must be satisfied for modified definite NPs do not carry over to indefinite descriptions. For example, the definite phrase "the horse which was raced past the barn" presupposes (minimally) a set of horses in the discourse model, as well as a single horse that is uniquely identifiable by the content of the relative clause. The corresponding indefinite phrase, "a horse which was raced past the barn" can be used "if no particular set of horses has been mentioned, whether or not the question of racing has been raised and [with] no implication that there is one individual who fits the description" (Crain & Steedman, 1985; pp. 335–336). These observations have been supported by recent work focusing on the semantic properties of definite and indefinite descriptions. In particular, it is agreed that definites, but not indefinites, are used to convey the uniqueness of the discourse object that they describe, though there is disagreement with respect to the status of the uniqueness effect for definite NPs (see, for example, Kadmon, 1990; Heim, 1982, 1990). This distinction is the crucial difference between definite and indefinite NPs with respect to the predictions made by the referential theory. Given the lack of uniqueness presuppositions for indefinites, modifiers serve the purpose of simply providing additional information about the referent, rather than selecting a single member from a set.[3]

[3] In addition, Heim (1982) argues that an important difference between definites and indefinites is that only definites presuppose their descriptive content. That is, definite descriptions are anaphoric, with their descriptive content serving to identify their antecedent in the discourse. By contrast, indefinite descriptions do not need to be linked with existing (or presupposed) discourse referents, therefore the descriptive content of indefinite phrases serves merely to provide additional information about the discourse entity being introduced. This generalization is complicated somewhat by the existence of so-called *specific* indefinites, which have certain anaphoric properties similar to definite descriptions. For instance, Enc (1991) has argued that, whereas definites are anaphoric by virtue of having to correspond to a previously introduced object, specific indefinites are also anaphoric in that they require the specific NP to be a member of a previously introduced set. Therefore, modifiers associated with specific indefinites may be presuppositionally loaded. Consider, for instance, the following example from a reviewer of this paper: "In the end, Sue decided to buy a car with power steering." This seems to presuppose that some set of cars with power steering is under discussion, perhaps in contrast with a set of cars having some other property. However, while referential presuppositions may be involved in some uses of indefinites, there remain some crucial differences between definite and indefinite NPs. First, the anaphoric use is optional for indefinites, but not for definites. For instance, the above example could easily be uttered in a context that does not include a presupposed set of cars with power steering (e.g., in a context where a salesman is trying to sell Sue a car with air-conditioning, but she ignores his advice and buys a car with power steering instead). A definite NP, however, could not be used in the same context to refer to an entity that is novel in the discourse. Furthermore, we assume, following the semantics literature (e.g., Enc, 1991; Heim, 1982), that indefinites are most natural in a non-specific

The work presented in this paper examines the consequences for parsing preferences in sentences like (6), where the NP preceding the point of syntactic ambiguity is *indefinite*:

(6) The Arapahoe Indian shot a cowboy with a leather vest.

If parsing preferences for ambiguously attached PPs are determined entirely by referential factors, sentence (6) should not exhibit a preference for VP attachment, as the simple indefinite NP is presuppositionally equivalent to a complex indefinite NP interpretation. Alternatively, a theory which attributes the preference for VP attachments in ambiguous sentences solely to local parsing mechanisms, such as the Minimal Attachment principle (Frazier & Rayner, 1982), the semantic expectations account (Taraban & McClelland, 1988, 1990) or the lexical association model (Hindel & Rooth, 1993), predicts an initial VP attachment preference in sentence (6) that is equally strong as in sentences containing *definite* NPs, such as sentence (1). As recent work emphasizes a tight coupling between corpus data and on-line parsing preferences (Juliano & Tanenhaus, 1993), we begin by presenting the results of a corpus analysis. The results provide evidence of the asymmetrical function of PPs modifying definite versus indefinite NPs and motivate the investigation of on-line effects of NP definiteness.

3. Corpus analysis

Proponents of Referential Theory claim that the VP attachment preference that has been observed in the psycholinguistic literature is due to difficulty with accommodating referential presuppositions for complex NPs in non-supporting contexts. On this view, the function (or a main function) of PP modifiers of definite NPs is to pick out a unique member from a presupposed set. We have argued that, due to the lack of a uniqueness presupposition for indefinite NPs, modifiers occurring with indefinite NPs do

interpretation, and require special supporting context to get the specific reading. This assumption has received independent support from the case-marking systems of a number of languages in which Accusative case is assigned to indefinite objects if they are specific, with no case marking occurring if the indefinite is non-specific (Enc, 1991). This suggests that the non-specific reading corresponds to the unmarked, default interpretation of an indefinite NP. However, most crucial for our purposes is the fact that, even when indefinites are specific, and therefore anaphoric in nature, they do not presuppose the uniqueness of their referent. This can be seen in the example about Sue's car purchase above. This sentence is felicitous whether or not the car she chose to buy was uniquely identifiable in the discourse context by virtue of having power steering. Clearly, this is not the case for modified definites. Therefore, although there may be instances where the use of an indefinite involves referential presuppositions, the presuppositional complexity will always be greater for definites than indefinites.

not have this function; rather modifiers of indefinite NPs serve simply to provide extra information about the discourse entity. Therefore, while the modification of a definite increases its presuppositional complexity, the modification of an indefinite does not.

If the complexity of referential presuppositions is implicated in attachment preferences, as is claimed by Referential Theory, we might expect to find an interaction between definiteness of the object NP and the relative frequencies of NP and VP attachments. In order to determine whether definiteness is in fact an effective predictor of attachment in naturally occurring language, we conducted an analysis of the Brown corpus (Kucera & Francis, 1967). Because we intended our experiments to focus on target sentences where the ambiguous PP was introduced by the preposition *with*, we extracted from a computerized version of the Brown corpus a set of 231 sentences with features similar to those of the experimental stimuli (i.e., *with* was temporarily ambiguous in its attachment to the NP or to the VP). To test for definiteness contingencies on PP attachment in this set of sentences, we separated them into two groups: those with definite object NPs and those with indefinite object NPs.

For an unrestricted set of relevant corpus items, we extracted all sentences that contained a verb (any tense), followed by a determiner, followed by a noun, followed by "with". Intervening words and constituents were allowed in this set of 231 sentences. Thus, passive constructions were included, as were V-det-N-PP-"with" constructions as well as adjectivally modified nouns. A smaller restricted set (of 147 sentences) was also analyzed in which only adjectives were allowed to intervene between the critical words. Such sentences more closely mirror those which we intended to use in the experiments.

In the unrestricted set, 10.4% of the sentences either remained ambiguous with respect to whether "with" attached to the VP or to the NP, or "with" appeared to begin an adjunct attaching at the sentential level. These sentences were excluded from the statistical analysis. A chi-square goodness-of-fit test was computed for the attachment of "with" (to the NP or to the VP) cross-indexed with definiteness of the NP in the remaining 207 sentences. No main effect of definiteness was observed, but VP attachments (62%) significantly outnumbered NP attachments (38%); $\chi^2(1) = 11.13$, $p < .001$. Moreover, a strong interaction between attachment and definiteness showed that definite NPs followed by "with" were highly biased toward VP attachment (85.7% vs. 14.3%) and indefinite NPs followed by "with" were biased toward NP attachment (66.3% vs. 33.7%); $\chi^2(1) = 56.78$, $p < .0001$. Frequency counts are given in Table 1.

Similar results were obtained with the restricted set of sentences. Of the 147 sentences in this set, 12.2% were excluded because they remained ambiguous or because "with" attached high in the tree-structure. A chi-square goodness-of-fit test, like the one above, revealed no main effect of definiteness, but a main effect of attachment (VP attachment: 60.5%, NP

Table 1
Frequency counts of sentences from the Brown corpus

	NP-attached	VP-attached	Totals
Unrestricted set			
Definite NP	16	96	112
Indefinite NP	63	32	95
Totals	79	128	207
Restricted set			
Definite NP	6	58	64
Indefinite NP	45	20	65
Totals	51	78	129

attachment: 39.5%) was observed; $\chi^2(1) = 5.24$, $p < .025$. The interaction between definiteness and attachment was again robust; $\chi^2(1) = 45.86$, $p < .0001$. Definite NPs followed by "with" were highly biased toward VP attachment (90.6% vs. 9.4%), and indefinite NPs followed by "with" were biased toward NP attachment (69.2% vs. 31.8%).

Table 1 shows that definiteness clearly affects the attachment frequencies for ambiguous sentences in the Brown corpus. PP attachment ambiguities containing *definite* object NPs are 6–10 times more likely to be VP-attached than NP-attached.[4] Conversely, PP attachment ambiguities containing *indefinite* object NPs are twice as likely to be NP-attached as VP-attached. This asymmetry in attachment sites of PPs occurring with definite and indefinite NPs is most plausibly accounted for by a referential component. No other account of attachment preferences in parsing draws a distinction between definite and indefinite NPs preceding the ambiguous phrase. However, given our assumption that modified indefinites are presuppositionally equivalent to simple indefinites, the NP attachment bias in the indefinite condition cannot be explained by referential factors alone. It appears that other factors are necessary to explain the distribution of PP attachment with indefinite NPs. The predominance of NP-attached phrases in the indefinite condition could in principle be accounted for by lexically specific biases if it could be demonstrated that the majority of the lexical items occurring in the corpus with indefinite NPs exhibited a bias towards NP attachment. Minimal Attachment clearly cannot account for the preference for NP attachment following indefinite NPs, nor would we expect it to, as it is explicitly formulated as a principle specific to *parsing*, while the corpus data reflect patterns pertaining to *production*.

[4] On the surface, these results appear incompatible with Hindle and Rooth's (1993) results where NP attachments predominated. However, they used a wide range of prepositions. Our corpus analysis was limited to ambiguously attached "with"-phrases, which may be statistically biased toward Instrumental VP attachment.

EXPERIMENT 1

The results of the corpus analysis provide a rough baseline for the effect of definiteness upon attachment. We have established that definite NPs are much less likely to be modified by a following PP than are indefinite NPs. This asymmetry is consistent with the claims made by Referential Theory with respect to the presuppositional asymmetry between definites and indefinites.

In order to determine how prominently definiteness would figure in on-line parsing, we conducted a self-paced reading experiment. This experiment was designed to closely mirror the experimental circumstances present in Altmann and Steedman's (1988) study, which found evidence for contextual referential effects. Our experiment manipulated the definiteness of the object NP (and, in tandem, the definiteness of the NP within the PP)[5] and the attachment of the PP.

The parsing theories we have discussed so far make different predictions with respect to the expected parsing preference for this set of materials. Minimal Attachment (along with maximally exclusive versions of any structurally based parsing preference theory) predicts that readers will exhibit equal processing difficulty (slowed reading times) for an NP-attached PP in both definite NP and indefinite NP conditions. In contrast, an exclusively referentially driven theory predicts that readers will be "garden-pathed" by an NP attachment *only* in the definite NP condition. A general frequency-driven model might also predict, based on the corpus data, that definite NP conditions will result in a VP attachment preference; however, it makes the additional prediction that indefinite NP conditions will result in an NP attachment preference. This pattern of data could also be consistent with a semantic expectations account, if we make the added assumption that the distributional patterns found in the corpus data reflect biases of a semantic/conceptual nature.

4. Method

4.1. Subjects

Thirty-two undergraduates from the University of Rochester participated in this experiment for course credit. All were native English speakers and were naive to the experimental manipulations.

[5] These sentences also change the definiteness of the NP *within the PP*. Such a change is unavoidable as modifying an indefinite NP with a definite NP (i.e., "The Arapahoe Indian shot a cowboy with the leather vest") is felicitous only in the most artificial of contexts.

4.2. Materials and design

This experiment had a 2 × 2 design with Definiteness (definite NP/indefinite NP) and Attachment (NP attachment/VP attachment) as the independent variables. Altmann and Steedman's (1988) 32 target sentences were used as a basis for our sentences, with minor changes made to accommodate lexical differences between American and British English, and to accommodate an 80-column screen presentation width. Sample target sentences are shown below:

(7) a. The fireman/ smashed down/ the door/ with the rusty lock/ but smoke/ overcame him.
b. The fireman/ smashed down/ the door/ with the heavy axe/ but smoke/ overcame him.
c. The fireman/ smashed down/ a door/ with a rusty lock/ but smoke/ overcame him.
d. The fireman/ smashed down/ a door/ with a heavy axe/ but smoke/ overcame him.

Sentences (7a–d) are all four versions of one of the stimuli. Sentences (7a) and (7b) are the NP-attached and VP-attached versions, respectively, of the definite NP condition. Sentences (7c) and (7d) are the NP-attached and VP-attached versions, respectively, of the indefinite NP condition. Slashes separate presentation windows in the self-paced reading task.

Eight of the 32 target sentences were assigned to each of the four experimental cells, which rotated to create four versions of each stimulus. Each subject was exposed to only one of the four stimulus lists, and therefore to only one version of any one target sentence. The 32 target sentences (experimental trials) were randomly embedded within 48 filler sentences (distractor trials), with at least one distractor trial intervening every two experimental trials. All of the experimental trials and half of the distractor trials were followed by yes/no questions that (for the target sentences) probed what syntactic attachment the subject had finally made. Subjects pressed the "yes" or "no" buttons to give their answers.

4.3. Procedure

Stimuli were presented on an IBM clone with a Digitry board and button box installed. Subjects pressed one button to begin a trial, at which time a row of dashes appeared on the screen. (A dash replaced each character in the sentence; while spaces and the period remained unchanged.) Subjects then pressed a different button to present each phrase of the sentence in a non-cumulative fashion (Just, Carpenter, & Woolley, 1982). All sentences were under 80 characters long.

The phrasal unit of presentation, see (7), was used for two reasons. First,

it is possible that effects get washed out in a single-word presentation moving-window paradigm because the subject may tend to put his/her finger on "automatic pilot", thus delaying the noticeability of any garden path. Second, we wanted this experiment to be directly comparable to Altmann and Steedman's (1988) Experiment 2, which employed phrasal reading times with the same segmentation of the same sentences, but with definite NP versions only. However, we chose not to use a cumulative window display (as in Altmann & Steedman, 1988) because results obtained with a cumulative window display tend to correlate poorly with gaze duration in eye-tracking studies (Just *et al.*, 1982).

Subjects were instructed to read the sentences at a comfortable pace that closely approximated their normal reading speed, and to read them carefully enough to correctly answer the questions that followed many of the sentences. Including a practice session of 10 trials, the entire experiment lasted approximately 25 min.

5. Results and discussion

All subjects scored 80% or above on the comprehension questions. Table 2 displays the reading times for the four conditions at each phrase position. An analysis of variance of the reading times at the PP revealed that PPs following indefinite NPs were read faster than PPs following definite NPs; $F1(1, 28) = 15.32$, $MS_e = 13\,739$, $p < .002$; $F2(1, 31) = 3.84$, $MS_e = 54\,801$, $p > .1$. Also, VP-attached PPs were read faster than NP-attached PPs; $F1(1, 28) = 11.5$, $MS_e = 16\,499$, $p < .005$; $F2(1, 31) = 7.57$, $MS_e = 25\,061$, $p < .02$. The interaction of Definiteness × Attachment was marginally significant by subjects only; $F1(1, 28) = 3.97$, $MS_e = 6994$, $p = .056$; $F2 < 1$, with a stronger preference for VP attachment occurring in sentences that had definite object NPs than sentences with indefinite object NPs. A Tukey's post hoc contrast indicated that, within the definite NP condition, the VP-attached PP was read much faster than the NP-attached PP; $p < .001$.

Table 2
Experiment 1: reading time (ms) by sentence region

	NP region	Verb region	NP region	PP region	Next region
Definite NP					
NP-attached	559	549	533	835	704
VP-attached	532	541	532	728	661
Difference	27	8	1	107	43
Indefinite NP					
NP-attached	545	548	518	724	698
VP-attached	545	558	516	677	638
Difference	0	−10	2	47	60

The same statistic applied to the indefinite NP condition revealed that the difference between reading times for the VP-attached PP versus the NP-attached PP was reliable, but much less robust: $p < .05$. Thus, while referential factors cannot be said to determine attachment preferences on their own, there was a suggestion in the data that definiteness of the NP had an effect on the magnitude of the VP attachment preference.

An analysis of variance on the reading times at the phrase following the PP again revealed that when the PP was attached to the VP, reading times were shorter than when the PP was NP-attached; $F1(1, 28) = 9.38$, $MS_e = 9047$, $p < .01$; $F2(1, 31) = 4.58$, $MS_e = 18\,526$, $p < .05$. However, the main effect of Definiteness and the interaction between Definiteness and Attachment were completely absent at this phrase position. Statistical analyses of other phrase positions revealed no reliable differences.

The main effect of Definiteness is explainable simply by string length: the definite condition has two characters more than the indefinite condition condition. Adjusting reading times for string length resulted in an elimination of the main effect of Definiteness ($F1 < 1$; $F2 < 1$). The most striking result from this reading time experiment is the demonstration of a reliable VP attachment preference for both the definite and indefinite NP conditions. The existence of a VP attachment preference for the indefinite condition is not predicted by Referential Theory (although the *increase* in VP attachment preference seen in the definite condition *is*). Clearly, something other than a referentially based mechanism is necessary to account for the VP attachment preference, at least in the indefinite condition.

The presence of a VP attachment preference across definiteness conditions is compatible with the Minimal Attachment account. In fact, the existence of a parsing preference that flies in the face of corpus-based distributional patterns could constitute some of the strongest evidence for Minimal Attachment. However, this study also yields a suggestive result that is potentially problematic for a Minimal Attachment account: namely, the marginal significance of the interaction between Definiteness and Attachment. Although the VP attachment preference is present and reliable for both definiteness conditions, it is modulated somewhat by definiteness, indicating that referential factors may in fact play a role in the resolution of PP attachment ambiguities.

The persistent VP attachment preference may also be attributable to lexically specific factors. If most of the verbs used in the experimental stimuli tend to have a strong frequency- based (or semantically based) bias toward VP attachment, this would explain both the pervasive VP attachment preference and the relatively weak effect of referential factors. We will return to this issue later in the paper.

Clearly, these results warrant further investigation. In order to replicate these effects and rule out a possible artifact, we conducted a second reading time experiment on the same experimental items.

EXPERIMENT 2

Recall that in the previous experiment, manipulation of the definiteness of the direct object NP also entailed changing the definiteness of the NP internal to the ambiguous PP, which we considered theoretically irrelevant. The following experiment was aimed at replicating the results of Experiment 1 and eliminating a possible objection to the interpretation of those results: namely, that the definiteness of the NP *within* the PP (not of the NP preceding the PP) could be responsible for the interaction between definiteness and attachment observed in the results of Experiment 1. No present theory of sentence processing would predict such a circumstance. Nonetheless, it was a factor identically manipulated with the factor in question in Experiment 1, and therefore this alternative interpretation must be ruled out before we can confidently attribute the effects to the definiteness of the direct object NP.

6. Method

6.1. Subjects

Thirty-six undergraduates for the University of Rochester participated in this experiment for course credit. All were native English speakers and were naive to the experimental manipulations.

6.2. Materials and design

This experiment used 30 of the experimental sentences and the 48 filler sentences from Experiment 1. However, an additional definiteness condition was added: one in which the crucial NP was definite, but the NP within the PP was indefinite (see examples 8e and 8f). Sentences (8a–d) were identical to those in Experiment 1. A 3×2 design manipulated Definiteness of the NPs (both definite/both indefinite/definite NP and indefinite in PP) and Attachment (NP attachment/VP attachment). Each of the six stimulus lists contained one version of each of the stimuli. Slashes in (8) separate presentation windows in the self-paced reading task.

(8) a. The fireman/ smashed down/ the door/ with the rusty lock/ but smoke/ overcame him.
(both definite, NP-attached, same as in Experiment 1)

b. The fireman/ smashed down/ the door/ with the heavy axe/ but smoke/ overcame him.
(both definite, VP-attached, same as in Experiment 1)

c. The fireman/ smashed down/ a door/ with a rusty lock/ but smoke/ overcame him.
(both indefinite, NP-attached, same as in Experiment 1)

d. The fireman/ smashed down/ a door/ with a heavy axe/ but smoke/ overcame him.
(both indefinite, VP-attached, same as in Experiment 1)
e. The fireman/ smashed down/ the door/ with a rusty lock/ but smoke/ overcame him.
(definite–indefinite, NP-attached, control condition)
f. The fireman/ smashed down/ the door/ with a heavy axe/ but smoke/ overcame him.
(definite–indefinite, VP-attached, control condition)

6.3. Procedure

Stimuli were presented and data were collected in the same manner as in Experiment 1.

7. Results and discussion

All subjects answered at least 80% of the comprehension questions correctly. Table 3 shows reading times for individual regions as a function of definiteness condition and PP attachment.

We break up the analysis into three tests for the interaction between definiteness and attachment, first comparing the both-definite with the both-indefinite conditions, then the both-definite with the definite–indefinite conditions, and finally the both-indefinite with the definite–indefinite conditions. In the comparison of the both-definite and both-indefinite conditions (which were included in the previous experiment), a main effect of

Table 3
Experiment 2: reading time (ms) by sentence region

	NP region	Verb region	NP region	PP region	Next region
Definite NP, Definite NP within PP (as in Experiment 1)					
NP-attached	595	624	605	1002	863
VP-attached	559	624	614	877	747
Difference	36	0	−9	125	116
Definite NP, Indefinite NP within PP					
NP-attached	580	610	599	855	861
VP-attached	574	594	586	766	733
Difference	0	16	13	89	128
Indefinite NP, Indefinite NP within PP (as in Experiment 1)					
NP-attached	569	609	565	844	839
VP-attached	569	605	588	830	713
Difference	0	4	−23	14	126

Definiteness was observed; $F1(1, 30) = 22.79$, $MS_e = 16\,724$, $p < .001$; $F2(1, 29) = 8.79$, $MS_e = 36\,120$, $p < .01$. A marginal effect of Attachment was also observed; $F1(1, 30) = 7.13$, $MS_e = 24\,555$, $p < .02$; $F2(1, 29) = 1.4$, $MS_e = 104\,179$, $p < .2$. Most importantly, the interaction between the two, in which the definite condition shows a 125 ms VP attachment preference and the indefinite condition shows only a 14 ms VP attachment preference, was significant by subjects; $F1(1, 30) = 6.53$, $MS_e = 17\,244$, $p < .02$; $F2(1, 29)$, $MS_e = 37\,653$, $p = .12$. A Tukey's post hoc contrast was applied separately to the two definiteness conditions, and revealed a reliable VP attachment preference in the definite condition ($p < .001$) and no reliable attachment preference in the indefinite condition ($p > .3$).

A comparison between the both-indefinite condition and the definite–indefinite (control) condition revealed no effect of definiteness; $F1 < 1$; $F2 < 1$; and a weak effect of attachment; $F1(1, 30) = 5.59$, $MS_e = 17\,256$, $p < .05$; $F2(1, 29) = 1.16$, $MS_e = 69\,441$, $p < .2$. The predicted interaction between these two factors approached significance in the subjects analysis only; $F1(1, 30) = 3.23$, $MS_e = 16\,020$, $p = .08$; $F2 < 1$. A Tukey's post hoc contrast conducted on the definite–indefinite condition revealed, like the both-definite condition, a reliable VP attachment preference ($p < .01$).

Finally, a comparison between the both-definite condition and the definite–indefinite condition revealed both main effects but no hint of an interaction. PPs containing a definite NP were read slower than PPs containing an indefinite NP; $F1(1, 30) = 30.3$, $MS_e = 19\,766$, $p < .001$; $F2(1, 29) = 12.49$, $MS_e = 39\,961$, $p < .001$. NP-attached PPs were read slower than VP-attached PPs; $F1(1, 30) = 12.7$, $MS_e = 32\,859$, $p < .001$; $F2(1, 29) = 3.57$, $MS_e = 97\,435$, $p < .07$. The interaction between Definiteness (within the PP) and Attachment did not approach significance; $F1 < 1$; $F2 < 1$.

Analysis of the region following the PP revealed a reliable VP attachment preference across all definiteness conditions; $F1(1, 30) = 40.85$, $MS_e = 20\,022$, $p < .001$; $F2(1, 29) = 18.7$, $MS_e = 36\,448$, $p < .001$. No effect of Definiteness was apparent, nor was there any interaction. Tukey's post hoc contrasts showed strong VP-attachment preferences for the both-definite condition ($p < .001$), the both-indefinite condition ($p < .001$), and the definite–indefinite condition ($p < .001$).

Results of this experiment generally replicate the effects seen in Experiment 1. A hint of an interaction between definiteness of the object NP and attachment of the PP was observed. Nonetheless, as in Experiment 1, a preference for VP attachment is still reliably present when the object NP is indefinite (seen on the region *after* the PP, in this experiment). Thus, both experiments show a persistent VP attachment preference beyond the point at which definiteness has an effect. This suggests that to the extent that referential factors do play a role in resolving the ambiguity, they are not used merely to evaluate an initial parse and guide reanalysis. If this were the case, we should see the effect of definiteness occurring at the end of the

garden path, rather than at the beginning.[6] The results of this experiment also rule out the possibility that definiteness *within the PP* was responsible for the suggestion of an interaction in Experiment 1. Manipulating the definiteness within the PP (both-definite vs. definite–indefinite) did not affect VP attachment preference.

THE INTERACTION OF LEXICAL AND REFERENTIAL FACTORS

The presence of a pervasive VP attachment preference in Experiments 1 and 2, despite the greater corpus frequency of NP attachments in sentences containing indefinite NPs, is intriguing. As we mentioned earlier, this discrepancy between reading time data and frequency patterns may constitute strong support for an independent parsing principle such as Minimal Attachment. However, the mismatch does not necessarily reflect a true difference between on-line parsing preferences and distributional patterns in naturally occurring language. It is possible that the materials used in the on-line study actually consisted of a restricted subset of the sentences that contain PP attachment ambiguities in the corpus.

In fact, a closer look at the materials used in the reading time study reveals that the verbs in these sentences were all characterizable as action verbs, with the subject bearing an Agent role, and the direct object bearing a Theme role. The corpus, on the other hand, included a wider range of verb types: in addition to action verbs, there were many instances of verbs of perception, psychological predicates, as well as numerous sentences containing the verbs *have* and *be*. It is possible that action verbs, as a class, exhibit a parsing bias for ambiguously attached PPs that is not present with other classes of verbs.

EXPERIMENT 3

To collect normative data on human subjects' parsing preferences for the class of verbs that was used in the reading time experiments, we collected *off-line* parsing preferences based on the stimuli from these experiments. We had subjects complete sentence fragments which contained an ambiguously attached preposition, and scored their completions as NP attachments or VP

[6] Note that we, like others in the literature, infer the presence of a garden path from a comparison of relative difficulty between two resolutions of the ambiguity. However, it should be noted that the PP attachment ambiguity does not provide a syntactically unambiguous baseline. In contrast, the reduced relative ambiguity (i.e., "The actress selected by the director quit") can be compared to a syntactically unambiguous baseline (i.e., "The actress chosen by the director quit") to test for the effects of the *presence* of a syntactic ambiguity, rather than its ultimate resolution. Therefore, attributing reading time differences to initial processing versus reanalysis may be less direct in the case of PP attachment ambiguities.

attachments. As in the reading time experiments, we manipulated the definiteness of the direct object NP in order to determine the effect of NP definiteness on attachment preferences for sentences containing action verbs.

8. Method

8.1. Subjects

Twenty undergraduates from the University of Rochester participated in this experiment for course credit. All were native English speakers and were naive to the experimental manipulations.

8.2. Materials and design

This experiment manipulated only Definiteness of the object NP. Only the initial fragments of the sentences were presented, up to and including the preposition. Sentences (9a and b) are the two versions of one of the stimuli. Sentence (9a) is the definite NP version, and (9b) is the indefinite NP version. All experimental sentences were taken from Altmann and Steedman's (1988) stimuli.

(9) a. The burglar blew open the safe with _____ .
b. The burglar blew open a safe with _____ .

Sixteen of the 32 target sentences were assigned to each of the two experimental cells, which alternated to create two versions of each stimulus. Each subject was exposed to only one of the two stimulus lists, and therefore to only one version of any one experimental sentence fragment. The 32 target items were randomly embedded within 48 filler items, with at least one filler item intervening between every two experimental items.

8.3. Procedure

Stimuli were presented on paper and subjects were instructed to write the first sensible and grammatical completion of each sentence that came to mind, without editing or re-thinking their initial response. The entire experiment lasted approximately 20 min.

9. Results and discussion

Of the entire data set, 4% of the responses were attachments that remained ambiguous, attachments at a level higher than the VP, or skipped

items. These data were excluded from the analysis. All remaining responses were coded as NP attachments or VP attachments. There was a numerically overwhelming preference for VP attachment over NP attachment for both the definite and indefinite conditions, although the bias was somewhat stronger for sentences in the definite condition. Fragments with definite NPs were completed as VP attachments 96% of the time, whereas those with indefinite NPs were completed as VP attachments 90% of the time. Given this quite small effect of definiteness in the off-line sentence completions, it is not surprising that there was merely a hint of an interaction between definiteness and attachment in the reading times of Experiment 1 and 2. An analysis of variance was computed on the attachment preference as a function of NP definiteness. The effect of Definiteness, though numerically small, was statistically robust: $F1(1, 18) = 9.20$, $MS_e = .0029$, $p = .01$; $F2(1, 31) = 8.33$, $MS_e = .0053$, $p < .01$.

Results indicate that definiteness of the NP preceding the preposition has a small, yet reliable, effect on the off-line attachment preference in PP attachment ambiguities. Thus, a referential mechanism appears to gain some validation from this experiment. This is in line with the results of the corpus study which indicate a reliable effect of Definiteness on Attachment. However, the completion data and corpus data diverge with respect to attachment preferences for sentences containing indefinite NPs. Recall that the corpus analysis revealed a preference for NP attachment following indefinite NPs, whereas the present completion study indicates a robust VP attachment preference. Note that neither of these results can be accounted for entirely by referential factors, as the presuppositional equivalence of simple and complex indefinite NPs would lead us to expect roughly equal numbers of NP and VP attachments.

The differences between our corpus analysis and completion results are particularly striking given that the study by Hindle and Rooth (1993) demonstrated a close correspondence between distributional frequencies in naturally occurring language and human attachment preferences for combinations of specific nouns, verbs and prepositions. In order to pursue further the hypothesis that the action verbs typical of the reading time study have stronger VP attachment biases than some other classes of verbs, we conducted a more fine-grained analysis of our corpus data by separately comparing the attachment preferences for verbs belonging to the class of action verbs, and a class consisting of psychological predicates and verbs of perception. This latter group differs semantically from the former in two respects: the subject bears the role of Experiencer, rather than Agent; and a VP-attached PP typically bears the role of Manner, rather than Instrument. Given the semantic and conceptual differences between the two classes of verbs, it would not be surprising to find that they behave differently with respect to attachment preferences.

The matrix verbs in the restricted set of corpus sentences (i.e., those 129 sentences in which the direct object NP was immediately followed by an

ambiguously attached preposition) were identified as either *action* verbs (involving an agentive subject and an affected theme as direct object) or *psych* and *perception* verbs (referring to mental states or perception). After excluding sentences whose verbs did not fall clearly into either class, 66 sentences remained. A chi-square analysis was then conducted on the frequencies of these two verb classes having NP- or VP-attached PPs. See the "Totals" rows in Table 4. There was a greater number of action verbs (72.7%) than psych and perception verbs (27.3%); $\chi^2(1) = 12.74$, $p < .001$. There was also an overall greater number of VP attachments (66.7%) than NP attachments (33.3%); $\chi^2(1) = 6.68$, $p < .01$. Finally, there was a clear interaction where action verbs favored VP attachment (83.3%) over NP attachment (16.7%) and psych and perception verbs favored NP attachment (77.8%) over VP attachment (22.2%); $\chi^2(1) = 19.34$, $p < .0001$.

Two additional analyses were performed on the corpus items to determine the effect of definiteness on attachment frequencies *within each verb class*. Table 4 shows how action verbs were more frequently followed by definite NPs (64.6%) than indefinite NPs (35.4%); $\chi^2(1) = 3.52$, $p = .06$. Action verbs also showed a bias toward VP attachment over NP attachment (see percentages above); $\chi^2(1) = 20.02$, $p < .0001$. The interaction between definiteness and attachment for these action verbs revealed that sentences with definite object NPs strongly favored VP attachments (100%) over NP attachments while those with indefinite object NPs showed no preference for VP attachment (52.9%) over NP attachment (47.1%); $\chi^2(1) = 14.28$, $p < .001$.

In contrast, the psych and perception verbs exhibited almost the opposite results, but having so few items impeded statistical significance. They showed no bias for definiteness, but a reliable preference for NP attachment over VP attachment was present (see percentages above); $\chi^2(1) = 4.5$, $p < .05$. Finally, the interaction between definiteness and attachment suggested that psych and perception verbs with definite object NPs showed little or no attachment bias (57.1% vs. 42.9%), but when they appeared with indefinite object NPs there was a strong bias for NP attachment (90.9%)

Table 4
Frequency counts of sentences from the restricted set

	NP-attached	VP-attached	Totals
Action verbs			
Definite NP	0	31	31
Indefinite NP	8	9	17
Totals	8	40	48
Psych and Perception verbs			
Definite NP	4	3	7
Indefinite NP	10	1	11
Totals	14	4	18

over VP attachment (9.1%); although the chi-square did not approach significance.

The results of this more detailed corpus analysis suggest that the relatively weak effects of definiteness on attachment preference in Experiments 1–3 were due to the experimental items (all of which contained prototypical action verbs) being strongly biased toward VP attachment. If a given sentence has a very strong verb-based preference for Instrumental VP attachment, then any additional bias toward that attachment due to referential factors is likely to appear small because of a ceiling effect. This can easily be seen in the sentence completions of Experiment 3. In the indefinite condition, the VP attachment preference was 90%. So, already, the effect of definiteness was limited to a maximum of 10% influence. Thus, the effect of definiteness may have been underestimated in Experiments 1–3 due to a verb-based preference for VP attachment. (Note, however, that the context manipulations in Altmann and Steedman's (1988) study, using almost identical experimental items, was sufficiently powerful to reverse this bias in contexts supporting NP attachment.) In order to evaluate the effect of definiteness for less biasing materials, the next logical step was to test the same effect of definiteness on experimental items that do not show this verb-based preference for VP attachment.

EXPERIMENT 4

A new set of stimulus items was developed in which the matrix verbs were exclusively psych verbs and perception verbs (see Appendix for materials). For the purposes of comparing parsing preference data with corpus data, it would be ideal to conduct sentence completions based on the actual verbs found in the corpus study. However, this was impossible for two reasons: (1) the high occurrence of *have* and *be* verbs in the corpus would require their taking up almost a quarter of the experimental items, and (2) the constraint that every verb be equally natural occurring with the same direct object and followed by the preposition *with* in both attachment conditions could not be met by relying exclusively on the verbs in the corpus study. There was, however, considerable overlap between the verbs falling in the psych and perception category in the corpus study, and the verbs used in the new experimental items.

The first determination of attachment preference with these items was based on sentence completions. If these classes of verbs generally disfavor VP attachment, then the indefinite condition should show an NP attachment preference in sentence completions. Moreover, this should allow a VP attachment bias in the definite condition due to referential factors to be especially visible, as there will be no ceiling effect.

10. Method

10.1. Subjects

Twenty undergraduates from the University of Rochester participated in this experiment for course credit. All were native English speakers and were naive to the experimental manipulations.

10.2 Materials and design

This experiment manipulated only Definiteness of the object NP. Only the initial fragments of the sentences were presented, up to and including the preposition. Sentences (10a and b) are the two versions of one of the stimuli. Sentence (10a) is the definite NP version, and (10b) is the indefinite NP version.

(10) a. The woman expected the bus with _____ .
b. The woman expected a bus with _____ .

Eight of the 16 target sentences were assigned to each of the two experimental cells, which alternated to create two versions of each stimulus. Each subject was exposed to only one of the two stimulus lists, and therefore to only one version of any one experimental sentence fragment. The 16 target items were randomly embedded within 32 filler items, with at least one filler item intervening between every two experimental items.

10.3. Procedure

Stimuli were presented and data were collected in the same manner as in Experiment 3.

11. Results and discussion

Of the entire data set, 14% of the responses were ambiguous attachments, adjuncts attached high in the sentence, or skipped items. These data were excluded from the analysis. All remaining responses were coded as NP attachments or VP attachments. An analysis of variance was computed on the attachment preference as a function of NP definiteness. A robust effect of Definiteness was observed. Fragments with definite NPs were completed as VP attachments 54% of the time, while those with indefinite NPs were complete as VP attachments only 24% of the time; $F1(1, 18) = 27.53$, $MS_e = .0317$, $p = .001$; $F2(1, 15) = 30.66$, $MS_e = .0334$, $p < .001$.

The pattern of sentence completions indicates that these stimulus items are generally biased toward attaching the PP to the NP. As a result the

effect of definiteness is not impeded by a ceiling effect, and exerts a 30% increase in VP attachment completions. This increase is much greater than that observed in Experiment 3, where a ceiling effect is likely to have underestimated the effect of definiteness. That ceiling effect on the influence of definiteness may also have been reflected in the weak influence of definiteness observed in the reading time experiments (Experiments 1 and 2). Thus, judging by the correspondence between sentence completions and on-line reading times in the previous experiments, one might expect that reading times for these new stimulus items will show an NP attachment preference in the indefinite NP condition and an elimination of that preference in the definite NP condition.

EXPERIMENT 5

After collecting sentence completion data on these items, this experiment was designed to measure on-line reading times for them. As in Experiment 1, this experiment manipulated the definiteness of the object NP and the attachment of the PP (see Appendix for stimulus items).

The predictions made by the Minimal Attachment hypothesis and the Referential Theory for this experiment are identical to the predictions of these two accounts for the first on-line experiment. As with Experiment 1, Minimal Attachment (as well as maximally exclusive versions of any structure-based parsing preference theory) predicts that readers will exhibit equal processing difficulty (slowed reading times) for sentences in the definite NP and indefinite NP conditions. In contrast, Referential Theory predicts that readers will be garden-pathed by an NP attachment *only* in the definite NP condition. However, predictions made by lexically based accounts are different from those made for the first experiment. Accounts crucially involving lexically specific biases, based on the more detailed corpus data (Table 4) and the sentence completion data (Experiment 4), would predict a moderate general preference for NP attachment in these stimuli.

Given the effect of definiteness on attachment observed in the corpus data, completion study, and the first on-line experiment, we might expect to see an interaction of referential factors with lexically specific factors, yielding a parsing preference even in the indefinite condition, but with different reading time patterns for definite and indefinite sentences. Such a result would suggest the need for a parsing model which allows for the interaction of multiple constraints. The constraint-based approach that we outlined briefly in the introduction would be compatible with an interaction between referential and lexical factors. More specifically, a constraint-based approach makes certain predictions with respect to the nature of the interaction. Recall that constraint-based models predict graded effects, where the strength of the preference for one analysis over another depends

upon the strength of the evidence provided by a particular constraint. The sentence completions and corpus data revealed that the NP attachment preference for psych and perception verbs was not as robust as the VP attachment preference for action verbs. Therefore, we expect to see a weaker effect of the non-referential lexically specific bias in this experiment than in Experiments 1 and 2.

12. Methods

12.1. Subjects

Thirty-six undergraduates from the University of Rochester participated in this experiment for course credit. All were native English speakers and were naive to the experimental manipulations.

12.2. Materials and design

This experiment had a 2×2 design with Definiteness (definite NP/indefinite NP) and Attachment (NP attachment/VP attachment) as the independent variables. Sample target sentences are shown below:

(11) a. The salesman/ glanced at/ the customer/ with ripped jeans/ and then/ walked away.
b. The salesman/ glanced at/ the customer/ with suspicion/ and then/ walked away.
c. The salesman/ glanced at/ a customer/ with ripped jeans/ and then/ walked away.
d. The salesman/ glanced at/ a customer/ with suspicion/ and then/ walked away.

Sentences (11a–d) are all four versions of one of the stimuli. Sentences (11a) and (11b) are the NP-attached and VP-attached versions, respectively, of the definite NP condition. Sentences (11c) and (11d) are the NP-attached and VP-attached versions, respectively, of the indefinite NP condition. Slashes separate presentation windows in the self-paced reading task. The mean string length of the NP-attached PPs was 16.8 characters, and the mean string length of the VP-attached PPs was 16.1 characters.

Four of the 16 target sentences were assigned to each of the four experimental cells, which rotated to create four versions of each stimulus. Each subject was exposed to only one of the four stimulus lists, and therefore to only one version of any one target sentence. The 16 target sentences (experimental trials) were randomly embedded within 32 filler sentences (distractor trials), with at least one distractor trial intervening between every two experimental trials. All of the experimental trials and

half of the distractor trials were followed by yes/no questions that (for the target sentences) probed what syntactic attachment the subject had finally made. Subjects pressed the "yes" or "no" buttons to give their answers.

12.3. Procedure

Stimuli were presented and data were collected in the same manner as in Experiments 1 and 2.

13. Results and discussion

All subjects scored 80% or above on the comprehension questions. Table 5 displays the reading times for the four conditions at each phrase position.

An analysis of variance of the reading times at the PP revealed no main effects of Definiteness or Attachment. However, an interaction between the two was present. When following a definite NP, VP-attached PPs were read faster than NP-attached PPs. In contrast, when following an indefinite NP, NP-attached PPs were read faster than VP-attached PPs. Almost equal and opposite attachment preferences were exhibited in this interaction; $F1(1, 32) = 5.33$, $MS_e = 29\,289$, $p < .05$; $F2(1, 15) = 4.82$, $MS_e = 14\,383$, $p < .05$. Statistical analyses of other phrase positions revealed no reliable differences.

These results indicate a strong and very early influence of referential presupposition in on-line attachment preferences. With verbs that exhibit a general bias toward NP attachment, the effect of definiteness turned this bias around to a preference for VP attachment observable in reading times at the PP. To test whether the role of verb class was based on lexically specific biases, rather than simply a categorical difference between verb classes, we compared the percentage of VP attachment completions (from Experiment 4) for each of the 16 stimulus items in its indefinite condition with mean reading time of the VP-attached PP for its corresponding stimulus item in self-paced reading (Experiment 5). A simple linear regression

Table 5
Experiment 5: reading time (ms) by sentence region

	NP region	Verb region	NP region	PP region	Next region
Definite NP within PP					
NP-attached	536	536	580	770	642
VP-attached	570	545	577	707	677
Difference	−34	−9	3	63	−35
Indefinite NP within PP					
NP-attached	563	533	564	676	660
VP-attached	573	546	596	744	683
Difference	−10	−13	−32	−68	−23

revealed that attachment completion preferences for individual items could account for 24% of the variance in reading times of the VP-attached PP for those items; $r(14) = -.49$, $p = .05$. This result, combined with the comparison of Experiments 1 and 5, indicates that both verb-specific preferences and definiteness are important determinants in the on-line resolution of PP attachment ambiguities.

GENERAL DISCUSSION

We have described previous results and new evidence that are consistent with there being at least two simultaneous constraints on immediate attachment preferences: (1) a data-driven mechanism that opts for the most lexically consistent structure; and (2) a more knowledge-driven mechanism that is aware of context and adheres to the Referential Theory. When the lexically specific biases favor VP attachment (as appears to be the case in the action-like verbs of Experiments 1–3) and the referential constraint does the same (object NP is *definite*), the preference for VP attachment will be quite strong. When the lexically specific biases favor NP attachment (as with psych and perception verbs in Experiments 4 and 5), the referential constraint can induce a VP attachment preference when the PP follows a definite object noun. However, when the referential constraint is irrelevant due to the object NP being *indefinite*, only the lexically specific bias can drive the language processor toward the preferred parse. Thus, with action-like verbs, the indefinite condition reveals a smaller preference for VP attachment (Experiments 1–3); and with psych and perception verbs, the indefinite condition reveals a preference for *NP attachment* (Experiments 4 and 5).

The modulation of attachment preference by definiteness supports the predictions made by a referentially driven theory with respect to the effect of referential presuppositions on syntactic ambiguity resolution in the absence of context. Parsing the PP as a modifier to a *definite* NP has high costs, in that this analysis requires the accommodation not only of a unique referent for the modified NP (a cowboy with a leather vest), but also of a set of potential referents that share with the actual referent the label denoted by the head noun (a set of cowboys). For *indefinite* NPs, however, no such accommodations are called for, therefore an analysis involving a modified NP does not imply increased presuppositional complexity over an unmodified NP.

The difference in attachment preference for action verbs as compared to psych and perception verbs (Experiments 1–3 vs. Experiments 4 and 5) demonstrates that lexically specific information is used in on-line parsing. The interaction between lexical factors and referential factors is consistent with research showing that referential context effects are mediated by the availability of the syntactic alternatives, as determined by lexically specific constraints (Spivey-Knowlton et al., 1993). As recent work by Britt (1994) is

somewhat similar to this approach, we will discuss her proposal in some detail here.

In particular, we will devote more discussion to the nature of the lexical information that is driving these verb-based preferences. It is clear that this information needs to be more fine-grained than the verb-based information that is shown to modulate parsing preferences in Britt (1994). In this work, she distinguishes between verb-argument structures with *obligatory* versus *optional* argument slots, where, for example, "put" *requires* a goal argument, whereas "drop" does not. A VP attachment preference was found to be overridden by referential factors for verbs with an optional location argument slot (e.g., *drop*). However, referential context manipulations appeared to have no effect on the on-line attachment of PPs following verbs with obligatory location argument slots (e.g., *put*). On the basis of these results, Britt postulates a "restricted interactive" model in which all of a verb's obligatory arguments will be automatically filled, without recourse to contextual information. If a verb subcategorizes for an optional argument, however, contextual factors may have an effect on whether an incoming phrase is attached as the verb's argument or not.

This distinction between obligatory and optional arguments, though undoubtedly important for parsing, does not capture the verb-based differences reported in this study. The verbs in both classes studied here have similar subcategorization frames. Furthermore, one can argue that the PPs used here function as adjuncts rather than arguments (cf. Sedivy & Spivey-Knowlton, 1994). Therefore, the optional/obligatory argument distinction cannot account for the difference in attachment preference between action verbs and psych/perception verbs. However, either a frequency-based or a semantically based lexically specific constraint of the sort we have described could account for Britt's (1994) verb-based differences. An important difference between Britt's account of verb-based information and ours is that Britt views the distinction between optional and obligatory arguments as a categorical distinction, whereas we assume that the *strength* of a verb's preference for a location argument will be reflected in the degree of the attachment preference for individual items. Thus, we consider verbs that require location arguments to fall toward one end of a continuum, rather than constituting a separate class from verbs that do not require a location argument. (This continuum of lexically specific biases applies to our distinction between action verbs and psych/perception verbs as well.)

A constraint-based approach to syntactic ambiguity resolution subsumes Britt's (1994) account. Furthermore, it accommodates not only the verb-based effects found in the present study, but also the effects of context and verb-based information on the parsing of reduced relative clauses (MacDonald, 1994; MacDonald, Pearlmutter, & Seidenberg, 1994; MacDonald et al., in press; Ni & Crain, 1990; Pearlmutter & MacDonald, 1992; Spivey-Knowlton et al., 1993; Spivey-Knowlton & Tanenhaus, 1994b; Stowe, 1991; Tabossi, Spivey-Knowlton, McRae, & Tanenhaus, 1994;

Trueswell & Tanenhaus, 1991, 1992; Trueswell et al., 1994). It is not clear whether the restricted interactive model makes any specific predictions for this type of ambiguity (cf. Britt, 1994; Britt, Gabrys, & Perfetti, 1993).

The constraint-based approach makes certain predictions that are distinct from those of the restricted interactive model. Whereas Britt's account predicts that context should never have an effect on the attachment of a phrase following a verb that subcategorizes for obligatory arguments, the constraint-based model predicts that other constraints, if strong enough, will be able to override the expectation that the PP following the verb will be attached as the verb's argument. In fact, in Britt's materials, the argument structure of a verb is collapsed with other possible constraints. Specifically, varying the attachment of the PP resulted in varying the sense of the ambiguous preposition such that for VP-attached items, *on* expressed a location (e.g., *dropped the book on the chair*) whereas for NP-attached items, *on* was used to express a topic (e.g., *dropped the book on World War II*). The verbs in the study that required a location argument tended to be verbs that were more locational in meaning than verbs with optional locational arguments. Thus, the semantic expectations associated with the two groups of verbs may well have interacted with the two possible senses of *on*, resulting in a very strong bias toward VP attachment for the obligatory-location verbs. It is possible that materials in which varying the attachment site does not involve using a different sense of the preposition (i.e., both attachments of "on" involve locations) would yield somewhat weaker effects of the verb's argument structure, and relatively stronger effects of referential context.[7]

Though we have demonstrated that the verb-based information used in these experiments must be finer-grained than information about the verb's argument structure, the experimental results reported here are insufficient to discriminate between a frequency-based and a semantically based account of the lexically specific influences in parsing. On the one hand, the data are compatible with a semantic role expectations account (Taraban & McClelland, 1988, 1990). Under this account, the type of event that is denoted by transitive action verbs typically involves the use of an instrument, a role that gets expressed within a VP-attached PP. Psychological predicates and verbs of perception, however, do not imply the use of an instrument; VP attachment of the PP most naturally expresses a Manner role rather than an Instrument role. It can be argued that specific actions imply prototypical instruments whereas the manner associated with perceptual and psychologi-

[7] An additional constraint that may have been stacked against the NP attachment interpretation of the PPs in these materials may have been frequencies of occurrence associated with the different senses of *on*. Presumably, the dominant meaning of this preposition is the locational one. This may have contributed to the strength of the VP attachment preference such that, in conditions where the verb was particularly strongly biasing toward a VP attachment, referential factors were too weak to have a measurable effect.

cal events is not constrained in a similar way. The expectation for an instrument with an action verb, then, is plausibly stronger than the expectation for a manner adjunct with psych and perception verbs.

On the other hand, the data reported here can fit equally well within a purely frequency-based account (Hindle & Rooth, 1993). Although we assume that semantic and conceptual biases *underlie* the distribution facts in the corpus, it is possible that the parsing mechanism predominantly makes use of statistical frequency information in the process of integrating words into existing structures. Separating the on-line parsing influences of semantic expectations and frequency expectations will be a challenging task, as there is necessarily a high degree of co-occurrence between the two.[8] Distinguishing which of the two is responsible for the local, lexically specific parsing component that we have argued for here is beyond the scope of this paper. Nonetheless, it does seem possible, at least in principle, to construct experiments that will bear on these issues. For instance, one might contextually manipulate the most plausible role for a participant in a pair of events that are described by the same verb. To take a concrete example, imagine the sentence "The truck towed by the van was damaged", embedded within a context describing a broken-down pick-up, which may be an excellent Theme for "towed". Compare this to the same sentence embedded within a context describing a big tow truck, which may be an excellent Agent of the same verb. A semantic expectations account would predict that the conceptual context should have an effect on an initial syntactic analysis that depends upon the assignment of semantic roles to constituents. The frequency-based account, however, predicts no difference between sentences embedded in different biasing contexts, as local co-occurrence statistical patterns remain constant regardless of the context.

The two accounts need not be disjunctive, of course. A particularly interesting possibility is that semantic and statistical factors interact in subtle, but predictable, ways. Thus far, the only effects of frequency we have considered are patterns of co-occurrence among different lexical items. Frequency information associated with the preferred readings of a *single* lexical item is another likely candidate for a local parsing constraint. Particularly relevant for our study is the ambiguity of the preposition *with*. This preposition may introduce at least the following: an attribute, an instrumental phrase, a manner adverbial, and an accompaniment role (e.g., *John went to the store with his sister.*). Given the predominance of VP over NP attachments in our corpus analysis, and the fact that most of the

[8] It is also possible that our effect of definiteness is due solely to the processing system internalizing the relative frequencies of definite versus indefinite NPs being modified by PPs, not to a discourse-based mechanism trying to satisfy presuppositions on-line. However, this seems unlikely in light of evidence that many effects of discourse context found in the literature involve referential definiteness of the crucial NP (Altmann et al., 1992, 1994; Altmann & Steedman, 1988; Crain & Steedman, 1985; Spivey-Knowlton et al., 1993; Spivey-Knowlton & Tanenhaus, 1994b).

sentences containing a VP-attached PP involved an action verb with an instrumental *with*-phrase, it is not implausible to assume that the most frequent lexical instantiation of the preposition *with* is one in which an instrument role is assigned to its object. It is easy to imagine a situation in which the most frequent reading of *with* is matched against the semantic content of the verb to yield exactly the pattern of lexically specific biases that was obtained in the present study: verbs that denote events typically involving instruments will give rise to a very strong expectation of a VP-attached instrumental phrase, as the instrumental reading for *with* is the most prominent. The expectation for a manner phrase attaching to psych and perception verbs will turn out to be relatively mild in part because of the relative infrequency of *with*-phrases as manner adverbials. Clearly, further research is necessary to understand more explicitly the nature of frequency-based information and its relation to other processing constraints. For an insightful discussion of frequency effects in sentence processing, see MacDonald et al. (1994, in press), and for frequency effects combined with competition between syntactic alternatives, see Trueswell and Tanenhaus (1994).

Overall, the experiments presented in this paper indicate that *verb-specific attachment preferences* and *referential properties of NP definiteness* both play important roles in on-line syntactic ambiguity resolution. It is clear from these results that no principle can single-handedly account for on-line parsing phenomena. The locally driven accounts that we have discussed (Minimal Attachment, semantic role expectations and frequency of co-occurrence) do not explicitly allow a role for referential factors, and therefore cannot explain the interaction between Definiteness and Attachment. At the same time, Referential Theory does not explicitly allow a locally driven bias. Such a bias, however, was observed in the indefinite NP condition (though it was modulated by verb-specific preferences), where simple and complex NPs do not carry different referential presuppositions. Thus, a referential constraint appears to influence on-line syntactic ambiguity resolution, but the magnitude of its effect is contingent upon the availability of the syntactic alternatives as determined by "low-level" factors such as graded verb-argument structure preferences (Spivey-Knowlton & Tanenhaus, 1994a).

The predictions to which the overall data pattern best conform are those of a multiple-constraints approach, which proposes *both* lexically specific influences and referential/contextual influences (cf. Sedivy & Spivey-Knowlton, 1993, 1994; Spivey-Knowlton & Tanenhaus, 1994a; Trueswell & Tanenhaus, 1994). In this type of model, multiple alternatives of a syntactic ambiguity are made more or less available by the "bottom-up" input, and evidence from relevant contextual domains is integrated immediately to resolve the ambiguity in favor of the single interpretation with the most evidential support. If a syntactic alternative has very low initial availability, then contextual evidence in support of it will appear to have delayed effects

simply because the more available alternative will initially predominate, not because of architectural restrictions in human sentence processing.

Framing the problem of ambiguity resolution within a constraint-based approach allows for a view of the underlying nature of increases in processing time that is somewhat different from the traditional garden path view. Rather than interpreting elevated reading times as evidence that an initial analysis has been identified as incorrect, and that a new structure is required, our current approach suggests that processing delays are a manifestation of direct competition between opposing alternatives (Spivey-Knowlton, 1994). Near equal activation levels of the two alternatives will result in lengthy competition, hence greatly slowed reading times at the point of ambiguity. Less symmetric activation levels will result in less competition, hence only moderately slowed reading times. Finally, highly asymmetric activation levels will result in little or no competition, and therefore no significant increase in reading times. In this kind of model, the magnitude of influence of a constraint upon the activation level of a syntactic alternative is determined by two factors: the *weight* that the processing system assigns the given source of information, and the *strength of evidence* from that information source in the input under consideration.

To see how this dynamic would generate the data patterns found in the current study, let us simplify the problem and speculate that the following are the precise constraints relevant for resolving the PP attachment ambiguity: (1) semantic information pertaining to the goodness-of-fit between the alternative readings of *with* and the semantic content of the sentence to that point; (2) discourse-based information determining the likelihood of modification of the object NP; and (3) the disambiguating semantic information pertaining to the goodness-of-fit between the content of the *with*-phrase and the available semantic roles.

Let us consider the relative contributions of those constraints in the case of a sentence such as (12):

(12) The burglar blew open a safe with dynamite.

In this example, the semantic expectations associating the event described by the verb with the likelihood of an Instrument role adds most of its activation to the VP attachment alternative; but an Attribute role is still feasible, so some activation goes to the NP attachment alternative. The indefinite object NP, however, adds no activation to any alternative, as a modified NP is presuppositionally equivalent to an unmodified one. The content of the PP, finally, adds activation to the VP attachment alternative. Although all of these constraints activate syntactic alternatives in the same manner, they can do so with varying strengths. It is clear that upon reaching the PP in this example sentence, the latter constraint has greater influence than the others, as this constraint *clearly* resolves the ambiguity in favor of its supported alternative. However, before the ambiguity is resolved, the

two active syntactic alternatives must compete, thereby consuming processing resources until one alternative falls below some threshold. Sentence (12) pits constraints against one another, thus producing competition, as seen in Experiment 2 where relatively slow reading times (830 ms at the PP) were observed for sentences with action-like verbs, indefinite object NPs and a VP-attached PP.

In contrast, when the referential bias supports the VP-attachment alternative, because the object NP is *definite* as in sentence (13), the support for the VP attachment alternative greatly outweighs the support for the NP attachment alternative. This decreases the amount of competition between the syntactic alternatives upon reading the PP.

(13) The burglar blew open the safe with dynamite.

The lessened competition is reflected in faster reading times (766 ms at the PP, in Experiment 2) for sentences such as (13).

It might appear that, with so many factors affecting processing, a constraint-based approach is unfalsifiable. However, when the strength of a constraint is independently determined by norming studies (i.e., corpus analyses and sentence completions), the constraint-based approach directly predicts that processing results will correspond. For example, the corpus data and sentence completions revealed a *strong* VP attachment preference with action verbs, and a *mild* NP attachment preference with psych and perception verbs. If we had found reversed relative strengths for attachment preference in reading times for those two verb classes, it would have been seriously problematic for a constraint-based account.

The ultimate goal of a constraint-based approach is to develop a working quantitative model of sentence processing with fixed intrinsic parameters. Such a model clearly makes strong claims that are falsifiable. In actually building the model, the "strength of evidence" from each of the various constraints for any individual sentence must be independently established via off-line norming (e.g., Tabossi et al., 1994) or corpus analyses (e.g., Juliano & Tanenhaus, 1993). The intrinsic "weights" given to the various constraints can be approximated via regression analyses that match "strength of evidence" of a constraint to its effect in reading time (e.g., Spivey-Knowlton, 1994), or can be acquired by a connectionist model during training (e.g., Juliano & Tanenhaus, in press; Pearlmutter, Daugherty, MacDonald, & Seidenberg, 1994). This allows the intrinsic parameters of the model to remain fixed across all possible inputs. At that point, the model's output for a given sentence is equivalent to the theory's prediction about human processing of that sentence. Indeed, such a model makes more detailed and falsifiable predictions than most other theories of sentence processing.

We have argued for two particular components in the initial parsing of PP attachment ambiguities: referential pragmatics and lexically specific biases.

However, in looking at the literature on several other types of syntactic ambiguity, there appear to be a number of factors that play important roles in syntactic ambiguity resolution. For example, the frequency with which individual lexical items occur in opposing thematic and syntactic relationships determines the initial availability (or activation) of those alternative interpretations (MacDonald, 1994; Tabossi et al., 1994). Other "low-level" factors, such as parafoveal information (Burgess, 1991; Spivey-Knowlton et al., 1993) and verb subcategorization and argument structure (Juliano & Tanenhaus, 1993; Trueswell, Tanenhaus, & Kello, 1993) also modulate this "availability of alternatives". Higher-level information that is directly relevant to the resolution of syntactic ambiguity, such as *semantic/thematic fit* (MacDonald, 1994; Pearlmutter & MacDonald, 1992; Tabossi et al., 1994; Tanenhaus, Carlson & Trueswell, 1989; Taraban & McClelland, 1988, 1990; Trueswell et al., 1994), *referential presupposition* (Altmann et al., 1992; Altmann & Steedman, 1988; Spivey-Knowlton et al., 1993; Spivey-Knowlton & Tanenhaus, 1994b), *temporal coherence* (Trueswell & Tanenhaus, 1991, 1992), and even certain aspects of "*real-world knowledge*" (Farrar & Kawamoto, 1993; Marslen-Wilson & Tyler, 1987; Tyler & Marslen-Wilson, 1977), all provide immediate probabilistic support for one or another of the available alternatives.

While these experimental results have strongly supported this general approach, they have yet to uncover some of the specific details concerning the interaction between frequency- and knowledge-based effects (Spivey-Knowlton et al., 1993; Trueswell et al., 1994). Moreover, preliminary computational models of this framework have so far been encouraging, but are greatly simplified (Juliano & Tanenhaus, in press; Pearlmutter et al., 1994; Spivey-Knowlton, 1994). Further discussion of this general approach to sentence processing can be found in MacDonald et al. (1994, in press), Spivey-Knowlton and Tanenhaus (1994a), Trueswell and Tanenhaus (1994). Future work on the constraint-based approach to sentence processing will have to employ both experimental and computational techniques in order to better understand the relative strengths of the multiple constraints and the nature of their interaction during on-line language comprehension.

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Appendix

The following experimental sentences were used in Experiment 5. The a. versions are NP-attached, while the b. versions are VP-attached. The object NP was either definite ("the") or indefinite ("a"). Five of the stimuli (numbers 3, 7, 10, 15 and 16) had definite or indefinite articles precede the noun *within the PP* to avoid infelicitous sentences.

1. a. The salesman glanced at the/a customer with ripped jeans and then walked away.
   b. The salesman glanced at the/a customer with suspicion and then walked away.
2. a. The contestant hoped for the/a prize with lots of cash but left empty-handed.
   b. The contestant hoped for the/a prize with anticipation but left empty-handed.
3. a. The executive sought the/a promotion with the/a pay raise but was fired instead.
   b. The executive sought the/a promotion with determination but was fired instead.
4. a. The troubled woman looked to the/a priest with experience and he helped her.
   b. The troubled woman looked to the/a priest with hope and he helped her.
5. a. The old man listened to the/an opera with six acts and liked it very much.
   b. The old man listened to the/an opera with a hearing aid and liked it very much.
6. a. The woman expected the/a bus with air conditioning but was at the wrong stop.
   b. The woman expected the/a bus with anticipation but was at the wrong stop.
7. a. The spy saw the/a cop with the/a revolver but the cop didn't see him.
   b. The spy saw the/a cop with binoculars but the cop didn't see him.
8. a. The sailor looked for the/a ship with red sails but saw nothing all day.
   b. The sailor looked for the/a ship with his telescope but saw nothing all day.
9. a. The bank manager knew the/a combination with 12 digits but never used it.
   b. The bank manager knew the/a combination with certainty but never used it.
10. a. The TA despised the/a student with the/a bad attitude but always graded fairly.

b. The TA despised the/a student with obvious hatred but always graded fairly.

11. a. The musician heard the/a performance with 30 violins and loved it all.
    b. The musician heard the/a performance with great pleasure and loved it all.
12. a. The scholar strived for the/an award with great prestige and finally won it.
    b. The scholar strived for the/an award with great effort and finally won it.
13. a. The supervisor demanded the/a report with sales figures so we all worked on it.
    b. The supervisor demanded the/a report with insistence so we all worked on it.
14. a. The child tasted the/a chocolate with almonds and quickly ate it all.
    b. The child tasted the/a chocolate with delight and quickly ate it all.
15. a. The young girl loved the/a man with the/a sense of humor but she feared marriage.
    b. The young girl loved the/a man with all her heart but she feared marriage.
16. a. The designer smelled the/a perfume with the/a sharp scent and pronounced it divine.
    b. The designer smelled the/a perfume with satisfaction and pronounced it divine.

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