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7 Toward a Lexicalist Framework for Constraint-Based Syntactic Ambiguity Resolution

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There is general agreement within the neuroscience and cognitive-science communities that complex multidimensional stimuli are represented and processed in at least partially independent subsystems or "modules." However, real-time processing typically results in local indeterminacy or ambiguity within a module because each subsystem is operating with a limited amount of information. Two general approaches for resolving these indeterminacies have been explored in depth within the cognition and perception literature. One approach is to incorporate domain-specific decision principles into each module. This preserves encapsulation (processing modularity) at the cost of inconsistent solutions across modules that later have to be reconciled. The other approach, which we argue for, is to make use of correlated information from within and across domains, without appealing to domain-specific principles. Although this approach violates the more traditional views of processing encapsulation, consistent solutions across domains can be rapidly coordinated. Within language comprehension, these approaches have been reflected in two-stage parsing models and in interactive or constraint-based models.

Most research on syntactic-ambiguity resolution has been guided by two-stage parsing models, in which an encapsulated syntactic processor within a modular architecture plays a privileged role in structuring the initial input to the language-comprehension system. During the first stage, the system makes an initial commitment to a single structure based on a restricted domain of purely syntactic information. Information that is not used in making initial commitments is then used to evaluate and, if necessary, revise the initial structure (e.g., Clifton, 1993; Clifton, Speer, & Abney, 1991; Ferreira & Clifton, 1986; Ford, 1988; Frazier,

1987, 1989; Frazier & Rayner, 1982; Mitchell, 1987, 1989; Mitchell, Corley, & Garnham, 1992; Pritchett, 1992).

Two-stage models can, of course, differ in what information is used in initial syntactic processing and in what decision principles they propose. The most influential two-stage model is the "garden-path" model originally proposed by Frazier and Rayner (1982) and further developed in more recent work by Frazier, Clifton, Rayner, and Ferreira (e.g., Clifton et al., 1991; Ferreira & Clifton, 1986; Ferreira & Henderson, 1990, 1991; Frazier, 1987, 1989, 1991; Rayner, Carlson, & Frazier, 1983; Rayner, Garrod, & Perfetti, 1992). In this model, the first-stage parser "attaches" each word into the structure it is building by using phrase-structure rules that apply to syntactic categories. At points of ambiguity, attachments follow a few structurally defined parsing principles such as minimal attachment (make the syntactically simplest attachment). These parsing principles are domain specific. They allow the syntactic module to initially structure the input without appealing to lexically specific syntactic information or to potentially relevant constraints from other domains (e.g., semantics and/or discourse context). Processing difficulty due to syntactic misanalysis (i.e., a garden path) is predicted to occur whenever a sentence with a local-syntactic ambiguity turns out to have a syntactic structure different from that predicted by the parsing principles.

In contrast, interactive or constraint-based models have assumed that multiple alternatives are at least partially available, and that ambiguity resolution is accomplished by the use of correlated constraints from other domains (e.g., MacDonald, in press; Marslen-Wilson, 1973; McClelland, St. John, & Taraban, 1989; Spivey-Knowlton, Trueswell, & Tanenhaus, 1993; Trueswell, Tanenhaus, & Garnsey, in press). Within a constraint-based architecture, ambiguity resolution is a continuous, constraint-satisfaction process. The effectiveness of a nonsyntactic constraint at a point of ambiguity will depend on its strength and relevance (e.g., how strongly correlated it is with a syntactic alternative) and the availability of the alternative that it biases at the point of the ambiguity (Spivey-Knowlton et al., 1993). Processing difficulty occurs when there is inconsistent biasing information (e.g., a prior context that supports a less frequent alternative, a subsequent disambiguating phrase that favors an unsupported alternative).

Recent constraint-based models have emphasized the use of rich lexical representations that incorporate information about how a word combines syntactically and semantically with other words in a sentence (e.g., MacDonald, 1993, in press; Trueswell, Tanenhaus, & Kello, 1993; Trueswell et al., in press). Information that is accessed when a word is recognized is used to define a set of syntactic and semantic possibilities (within a circumscribed domain), as well as to provide many of the constraints relevant to evaluating the possibilities. Thus, information accessed during word recognition provides much of the temporary parallelism necessary to make available alternatives over which constraints can apply. The lexicalist approach allows most attachment ambiguities involving verbs to be

treated as lexical/argument-structure ambiguities (see also MacDonald, Pearlmutter, & Seidenberg, chapter 6, this volume). This approach predicts two important similarities between syntactic-ambiguity resolution and word-recognition phenomena. First, the availability of alternative argument structures will be determined, in part, by their frequency. Second, the effectiveness of a contextual constraint will interact with the frequency of the argument structure that it biases.

The syntactic and semantic aspects of verb-argument structure are clear examples of combinatory lexical information. Verb-*subcategorization* information describes the set of syntactic complements, or arguments, that can occur with a particular verb. Verb-*thematic-role* information describes the conceptually defined participants associated with a verb sense, as well as the relationship between these roles and the verb's syntactic complements.

From the perspective of an on-line processing system, thematic information could provide strong constraints on syntactic ambiguity. The semantic fit between a phrase and the thematic role with which it is assigned in different argument structures could serve as a useful constraint for deciding among these structures. The following example illustrates this interdependency:

(1) a. The fossil examined . . . .
    b. The archeologist examined . . . .

The ambiguity in these fragments arises because the form *examined* can be either a past tense or a passive participle. These forms have different argument structures associated with them. In the past-tense form, the fragment is a main clause, with the preceding noun phrase (NP) being the subject of the verb. The entity denoted by the NP plays the role of agent in the event denoted by the verb. In the passive-participle form, the verb is the start of a reduced-relative clause, and the NP is the (logical) object of the verb. In this case, the noun would play the role of theme. Thus, the verb *examined* in (1) is likely to be part of a reduced-relative clause when the preceding NP is a good theme and a poor agent of the verb (e.g., "The fossil examined by the archeologist was . . ."), whereas the same verb is likely to be part of a main clause when the preceding NP is a good agent and a poor theme (e.g., "The archeologist examined the fossil").

The semantic fit between a phrase and a possible thematic role is clearly an example of a correlated (nonsyntactic) constraint. Although constraint-based systems make use of this information during initial ambiguity resolution, two-stage models predict that thematic information should not influence initial syntactic commitments because it does not fall within the proper domain of syntax.

In this chapter, we present evidence that the semantic fit between an NP and a potential argument position has immediate effects on syntactic-ambiguity resolution for sentences with reduced-relative clauses. In addition, we show that data patterns that have been interpreted as evidence for the delayed use of thematic constraints actually provide strong empirical support for constraint-based models

with rich lexicalist representations. We further show that these models provide a better framework for understanding results that have been interpreted as evidence for the delayed use of verb-specific syntactic (subcategorization) constraints.

THEMATIC-ROLE INFORMATION AND THE STRENGTH OF CONSTRAINT

Our discussion of thematic effects on parsing focuses on a set of results from two similar experiments. One experiment is reported in Ferreira and Clifton (1986, Experiment 1), and the other is reported in Trueswell et al. (in press). Both are eye-movement reading experiments that varied the animacy of a noun preceding a reduced-relative clause, as in Sentences 2a and 2b. Unambiguous unreduced relatives (Sentences 2c and 2d) were used as controls.

(2) a. The defendant examined by the lawyer turned out to be unreliable.
b. The evidence examined by the lawyer turned out to be unreliable.
c. The defendant that was examined by the lawyer turned out to be unreliable.
d. The evidence that was examined by the lawyer turned out to be unreliable.

We begin by outlining a constraint-based model of syntactic-ambiguity resolution, focusing on the relative-clause ambiguity (see Trueswell et al., in press). This provides a framework for understanding the various predictions. The model is similar in spirit to recent proposals developed by MacDonald and her colleagues (e.g., MacDonald, in press; MacDonald et al., chapter 6, this volume).

The principles that underlie the approach are simple. Structures are partially activated with the strength of activation dependent on their likelihood given the input. The effects of contextual constraint will depend on its strength and the availability of the alternative structures. To a first approximation, these are the same factors that are important for lexical-ambiguity resolution (MacDonald, in press; Tabossi, Spivey-Knowlton, McRae, & Tanenhaus, in press; Tanenhaus, Dell, & Carlson, 1987). Syntactic- and lexical-ambiguity resolution are viewed as similar and interrelated processes because many syntactic ambiguities depend on lexical ambiguities. Indeed, this becomes particularly clear when one takes into account the alternatives provided by aspects of combinatory lexical information such as argument structure.

Consider the evidence that a lexically based constraint-satisfaction system might use when encountering an ambiguous verb in the context of an NP. We assume that the verb will provide partial evidence/activation for both he past-tense and participial forms, with the strength of the evidence being determined

by relative frequency (Burgess & Hollbach, 1988; Tabossi et al., in press). The question of how to calibrate frequency for lexical-structural ambiguity is just beginning to be explored (Gibson & Pearlmutter, chapter 8, this volume; Hindle & Rooth, 1990; Juliano & Tanenhaus, 1993; MacDonald, 1993; Mitchell & Cuetos, 1991; Trueswell et al., 1993). However, to a first approximation, it appears that frequency is determined by the specific lexical item (i.e., how frequent the past-tense and participial forms are for the particular verb) conditionalized on the frequency with which the forms occur in specific syntactic environments (Juliano & Tanenhaus, 1993). Corpus analyses indicate that, at the beginning of a sentence, a morphologically ambiguous verb that follows an NP is much more likely to be a past-tense verb in a main clause than a passive participial in a reduced-relative clause (Tabossi et al., in press). Thus, at the verb, there will be a clear frequency-based bias in favor of the past-tense/main-clause structure, although the participial/relative-clause structure will also be partially activated. In addition, we assume that verb forms activate the sets of thematic-conceptual roles associated with each form and its corresponding syntactic mappings (Carlson & Tanenhaus, 1988; Cottrell, 1985; McClelland & Kawamoto, 1986; Pearlmutter & MacDonald, 1992; Tanenhaus, Carlson, & Trueswell 1989). The thematic fit of a potential argument is immediately evaluated with respect to the active alternatives.

In thinking about what data patterns to expect and how to interpret them, it is helpful to consider the results of reading studies that have examined other types of lexical ambiguities. Eye-movement research has demonstrated that, for semantically ambiguous words having two equiprobable meanings, reading times are longer to the word when the prior context is neutral or only weakly biasing, compared with when the context strongly biases one meaning. Reading times to an ambiguous word are also longer when the context supports a subordinate, rather than a dominant, meaning (Duffy, Morris, & Rayner, 1988; Rayner, Pacht & Duffy, 1994; see also Rayner & Pollatsek, 1987).

Consider now how this data pattern would be reflected in the relative-clause ambiguity. A good semantic fit between the noun and the agent role ("The defendant examined . . .") is comparable to having a biasing context supporting the dominant meaning of a ambiguous word because a good agent biases the more frequent past-tense alternative. Thus, under these conditions, readers should not have any processing difficulty when reading the ambiguous verb, but should have difficulty with a by-phrase that is inconsistent with the main-clause structure. In contrast, a poor agent and a good patient/theme ("The evidence examined . . .") is comparable to having a biasing context supporting the less frequent alternative because the thematic fit of the noun supports the less active passive participle and runs against the more active past tense. In this case, readers should have increased processing difficulty at the ambiguous verb and less processing difficulty at the by-phrase. The magnitude of the difficulty at the verb should be correlated with the availability of the passive participle and the

strength of the constraint provided by thematic fit. Whether there is any residual difficulty at the by-phrase should also depend on the strength of the semantic constraint and the relative availability of the past-tense and participial forms.

Ferreira and Clifton's (1986) study of reduced-relative clauses found elevated reading times at the verb and the by-phrase for inanimate nouns (nouns that tend to support a relative-clause structure), whereas they only found elevated times at the by-phrase for animate nouns (nouns that tend to support a main-clause structure). This data pattern was used to argue for the delayed use of semantic-thematic information in syntactic processing. Although readers were initially aware of the incongruity of the inanimate noun as the agent, they were still unable to use this information to avoid a main-clause parse, as evidenced by a large "garden-path," or misanalysis, effect at the by-phrase. On this explanation, the Ferreira and Clifton data pattern is the strongest type of evidence that can be marshaled in favor of a modular subsystem that is using domain-specific constraints. A correlated constraint from another domain is available, yet it is not affecting the decisions being made by another module.

However, the Ferreira and Clifton data pattern is also what one would expect when a contextual constraint supports a lower frequency alternative, and/or when the contextual constraints are only weakly biasing. What crucially distinguishes among the two-stage and constraint-based accounts of the data is what happens when the availability of the alternatives and the strength of the constraint is varied. As it turns out, our studies provide the relevant data.

Like Ferreira and Clifton, we (Trueswell et al., in press) monitored eye movements as subjects read reduced- and unreduced-relative clauses preceded by an animate or inanimate NP. Because we believed that many of the Ferreira and Clifton inanimate nouns were not highly biasing, we attempted to develop a new set of inanimate items that did not permit the main-clause alternative (see Trueswell et al., in press). We also included a second set of control conditions with unambiguous reduced-relative clauses, making use of verbs with unique participial forms such as *stolen*.

Shown in Fig. 7.1A are the first-pass (initial) reading times for four different regions of the target sentences: the NP "the defendant," the ambiguous verb *examined,* the disambiguating by-phrase "by the lawyer," and the first two words of the matrix verb phrase "turned out."

As can be seen in the figure, the basic data pattern is quite different from the Ferreira and Clifton results: There are rapid effects of thematic information. First consider the results for the animate nouns (i.e., nouns that were good agents). At the ambiguous verb *examined,* the reduced relative (the filled triangle) is no more difficult than the unreduced (the open triangle). However, at the disambiguating by-phrase, reading times to the reduced relatives are considerably longer than the unreduced relatives (a significant effect), suggesting that readers mistakenly took the preceding verb as part of a main clause. This pattern, no difficulty at the ambiguous verb and difficulty at the by-phrase, is consistent with a prior context

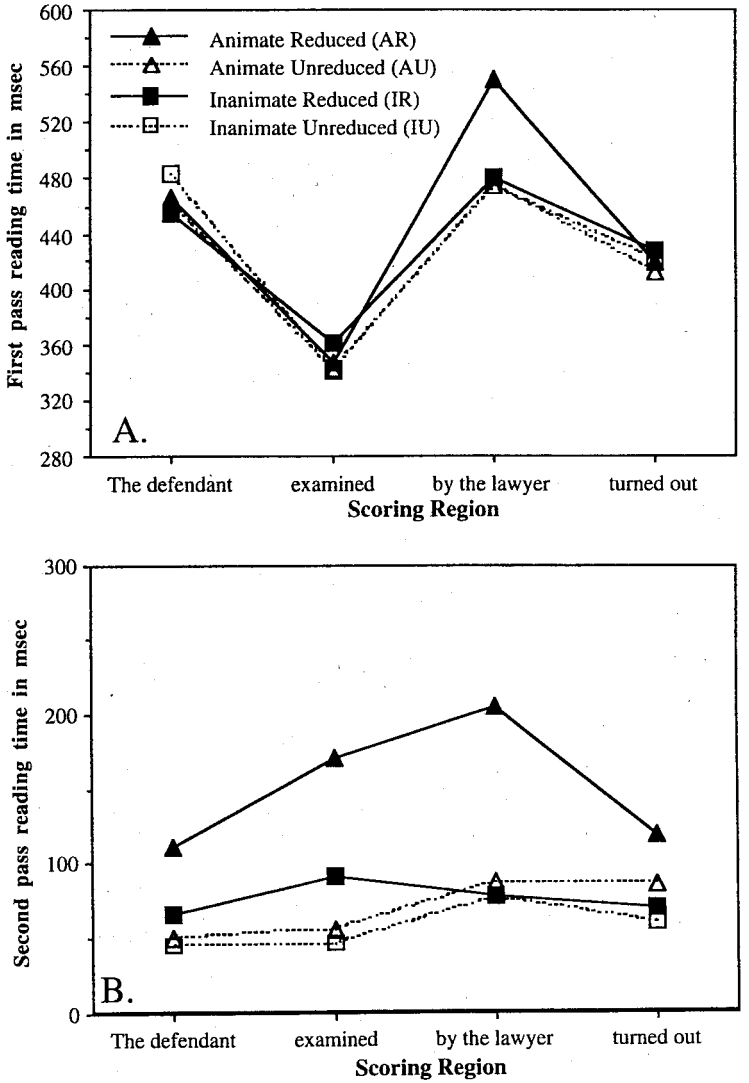

FIG. 7.1. Reading times from Trueswell, Tanenhaus, and Garnsey (in press) for reduced- and unreduced-relative clauses with ambiguous verbs preceded by animate and inanimate nouns. A. First-pass reading times. B. Second-pass reading times.

having supported either an equiprobable or dominant alternative. Now consider the results for the inanimate nouns (i.e., nouns that were poor agents). Even though reduced relatives (the filled squares) were slightly longer than the unreduced (the open squares) at the ambiguous verb, there were no significant differences between these two conditions at any position.[1] Thus, processing difficulty with the inanimate nouns seems to be diminished, if not eliminated. This pattern, slight difficulty at the ambiguous verb and no difficulty at the by-phrase, is consistent either with a biasing context that supports a somewhat subordinate alternative, or with a less biasing context that supports an equiprobable alternative.

Now consider the second-pass reading times (the re-reads), which are plotted in Fig. 7.1B. Reduced-relative clauses with animate NPs were re-read far more often than their unreduced counterparts (this difference was significant at the verb and the by-phrase). Reduced-relative sentences with inanimate nouns were re-read only slightly more often than their unreduced counterparts. Thus, as was the case with the first-pass reading times, there was only minimal processing difficulty with the inanimates.

The results for the reduced and unreduced relatives containing unambiguous verbs (e.g., *stolen*) should tell us whether there is any processing difficulty with reduced-relative clauses that is unrelated to syntactic misanalysis. As can be seen in Fig. 7.2, both first- and second-pass reading times resemble the results we just saw for the inanimate nouns followed by ambiguous verbs: There were only small differences at the verb in both the first- and second-pass readings, all of which were unreliable. Thus, difficulties with unambiguous items pattern onto the ambiguous conditions containing inanimate nouns.

In summary, the data showed rapid effects of thematic information. A breakdown of the items into categories, via a standard analysis of variance (ANOVA), revealed a statistical pattern in which thematic information completely eliminated any processing difficulty with ambiguous reduced relatives. Reduced-relative clauses with animate nouns showed clear signs of a misanalysis, whereas reduced relatives with inanimate nouns showed no reliable elevations in processing difficulty. However, as outlined in the predictions, constraint-based accounts crucially predict graded effects of semantic constraint. One should find some processing difficulty with inanimate nouns, depending on how much the semantic information supports the relative-clause alternative.

As mentioned earlier, the strongest semantic constraints in support of a reduced-relative clause come from nouns that are both poor agents *and* good patients or themes. When selecting inanimate nouns, we made sure the nouns were poor agents of their corresponding verbs. However, we did not worry about

[1]At the by-phrase, the interaction between animacy and the type of relative clause was significant because the animate condition showed an effect of relative-clause type, whereas the inanimate condition showed no such effect.

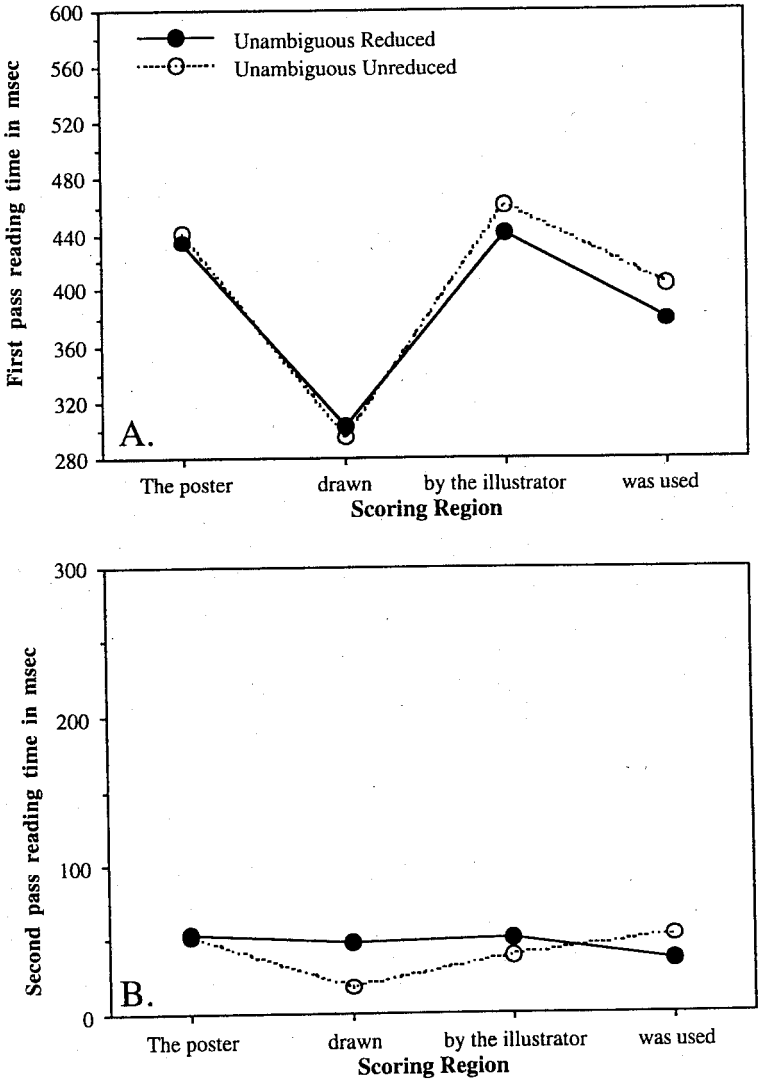

FIG. 7.2. Reading times from Trueswell et al. (in press) for reduced- and unreduced-relative clauses with unambiguous verbs. A. First-pass reading times. B. Second-pass reading times.

TABLE 7.1
Examples of Patient Typicality Ratings

Noun	*Verb*	*Patient/Theme Rating**
The textbook	loved	1.9
The jewelry	identified	4.4
The evidence	examined	6.3

**1 = bad; 7 = good.*

whether they were also good patients or themes. It turned out that the materials do indeed vary along this dimension. As part of a norming project conducted at the University of Southern California by MacDonald and Pearlmutter, in collaboration with Tanenhaus, McRae, and Spivey-Knowlton, a large group of subjects rated the typicality of the patient/theme relationship for each individual verb–noun pair by rating a question like "How typical is it for evidence to be examined by someone?" on a 7-point scale, with 1 as not typical at all and 7 as very typical. As can be seen from the examples in Table 7.1, patient-typicality ratings varied considerably from item to item, ranging from poor patients to good patients. Thus, students do not find textbooks to be very lovable, but evidence is a good thing to examine.

If ambiguity resolution for reduced-relative clauses is related to strength of thematic fit, increases in processing difficulty for individual reduced relatives should depend on the potential fit of the noun as a patient or theme of the verb. That is, the largest increases in processing difficulty with ambiguous reduced-relative clauses should occur for those inanimate items that are poor patients of their verbs. This is exactly what we found. Regression analyses that compared typicality ratings with increases in processing difficulty revealed reliable negative correlations for first-pass reading times at the by-phrase and for second-pass reading times at the first two regions. In addition, there were suggestive negative correlations at other positions (see Table 7.2). These negative correlations are consistent with immediate, but graded, use of semantic constraints. The goodness of fit of an NP as a potential argument predicts how much difficulty readers have with reduced relatives. When the noun is a relatively poor patient or theme, readers have some difficulty. When the noun is a good patient or theme, readers have little or no difficulty.

The conditions with morphologically unambiguous verbs provide an important control. If the correlations with typicality really reflect ambiguity resolution, typicality should not predict reading times for the reduced-relative clauses with morphologically unambiguous verbs. In fact, there were no significant correlations in either the first-pass or second-pass reading times for these conditions.

Before going on, we should mention that a complete replication of the ambiguous-verb conditions has been conducted in a second eye-tracking study

TABLE 7.2
Correlations Between Patient/Theme Typicality and Processing Difficulty

Region	*First Pass*	*Second Pass*
The evidence	—	$R = -.52$*
examined	$R = -.42$	$R = -.56$*
by the lawyer	$R = -.51$*	$R = -.40$
turned out		$R = -.38$

Note. Negative correlations indicate that the better the patient/theme relation, the less the processing difficulty.

*$p < .05$.

using mostly new target sentences (also reported in Trueswell et al., in press). The means and statistical patterns are virtually identical between the two experiments. The ANOVA revealed little or no processing difficulty for reduced relatives with inanimate nouns. Moreover, correlations showed graded semantic effects similar to those reported here.

To illustrate more clearly the graded nature of the constraints, we can compare the inanimate items that had the strongest semantic constraints (i.e., those items with high patient/theme-typicality ratings) with those items that were less constraining. Figure 7.3 plots the reduction effect (reading times to the reduced relative minus the reading times to the unreduced relative) for first-pass reading times at the verb and the by-phrase for both the more constraining inanimate items (filled squares) and the less constraining inanimate items (filled triangles). Reduction effects are reading times to the reduced-relative clauses minus the unreduced. So, positive numbers represent increases in processing difficulty for the reduced. As can be seen in figure, the less constraining items show increases in processing difficulty at both the verb and the by-phrase (+44 ms and +46 ms, respectively), whereas the more constraining items show little or no increases at either position (+7 and −9 ms). In fact, the more constraining items show essentially the same pattern as the morphologically unambiguous verbs (plotted as open squares), which are +7 ms at the verb and −20 ms at the by-phrase. When semantic constraints are strongest, reduced relatives with ambiguous and unambiguous verbs behave similarly.

Finally, Fig. 7.4A replots the less constraining inanimates (filled triangles) and compares them with the animate noun condition (open triangles). At the verb, there is processing difficulty for the inanimates, but not the animates. Then, at the by-phrase, both show some processing difficulty. As you might recall, this is the data pattern reported in Ferreira and Clifton (1986; see Fig. 7.4B). With this result alone, it could be argued that readers are initially aware that the inanimates are poor agents of the verb, but that they still cannot use this

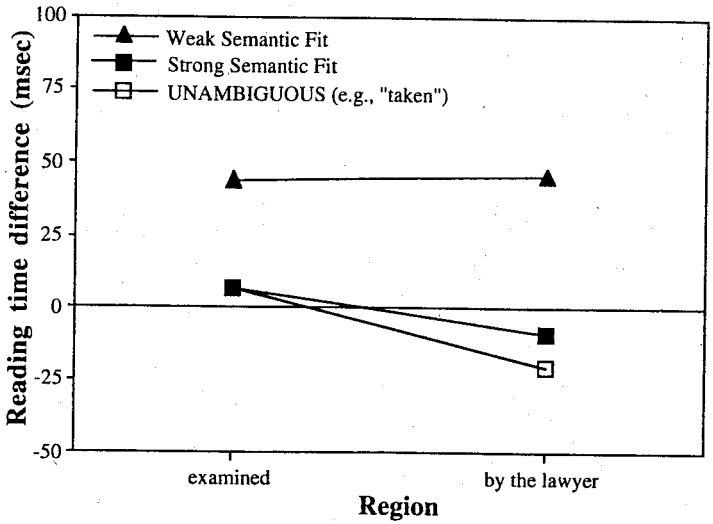

FIG. 7.3. Mean first-pass reduction effects (reduced-relative relatives minus unreduced relatives) for the verb and the by-phrase. Positive numbers indicate increases in processing difficulty for the reduced relative. Inanimate nouns with weak semantic fit and strong semantic fit as compared with unambiguous controls.

information to avoid a syntactic misanalysis. However, in the context of our other results, the Ferreira and Clifton items indicate a data pattern associated with less constraining items.

The data we have presented map nicely onto a constraint-based account of sentence processing, in which syntactic-ambiguity resolution shares many of the properties known to hold for lexical-ambiguity resolution. At first glance, however, there appears to be a problem with this account. As we mentioned earlier, an NP–verb context has a large frequency asymmetry in favor of the past tense/main clause, making the past tense the dominant alternative and the participial the subordinate alternative. Thus, one might expect to see difficulty at the verb when a noun is a poor agent, even when it is also a good theme. (This would be an example of a context biasing a subordinate alternative.) Inconsistent with this prediction, we find that the inanimate items with the strongest semantic constraints behave almost exactly like the unambiguous items.

However, treating the participle as a subordinate alternative does not take into account the effects of parafoveal information on availability. It is well know that short function words (e.g., *by, the, was, that*) are typically skipped in reading because the word can be seen when fixating on the preceding word (Just & Carpenter, 1980; Rayner & McConkie, 1976). In fact, an analysis of fixation

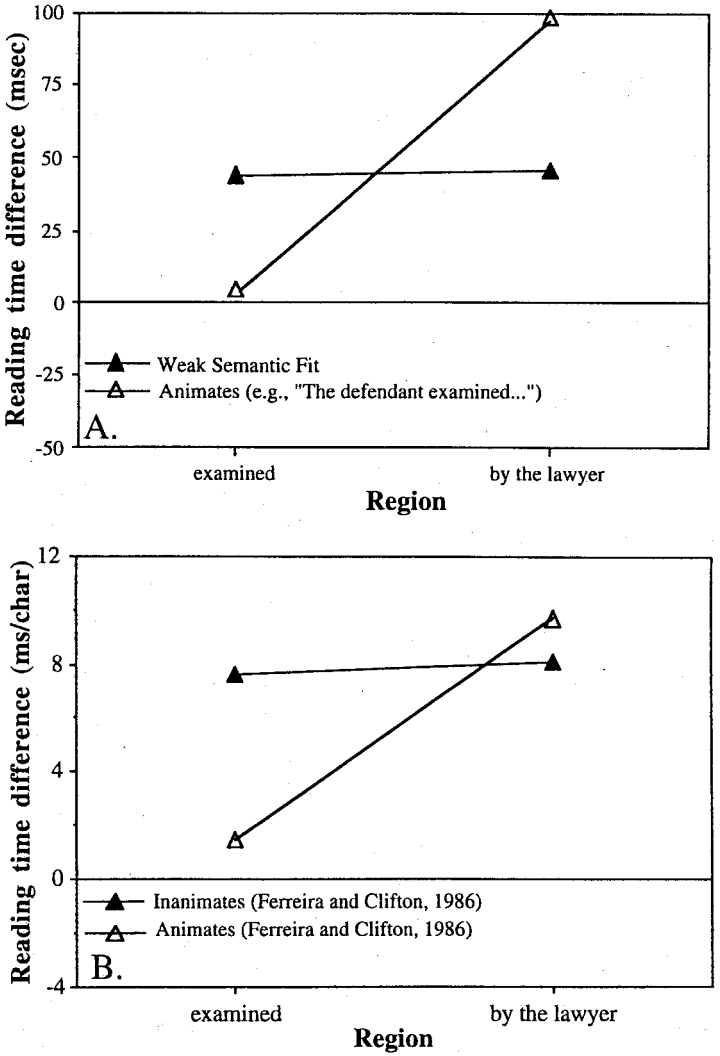

FIG. 7.4. Mean first-pass reduction effects (reduced-relative relatives minus unreduced relatives) for the verb and by-phrase. Positive numbers indicate increases in processing difficulty for the reduced relative. A. Results for the inanimate nouns with weak semantic fit as compared with the animate nouns (Trueswell et al., in press). B. Results for inanimate and animate nouns, as determined from Ferreira and Clifton (1986).

patterns (see Trueswell et al., in press) revealed that readers rarely fixated on the *by,* indicating that it was read parafoveally during fixations on the ambiguous verb. It is likely that this would have increased the availability of the participial/relative-clause structure, making the situation more like that of an ambiguous word with two equally frequent senses. Note that the word *by* is ambiguous and not necessarily inconsistent with a past tense/main clause. Tabossi et al. (in press) showed that *by* following an NP–verb is frequently taken to be a manner or a locative preposition in a main clause when the noun is a good agent, but it is nearly always taken to be an agentive preposition in a relative clause when the noun is a poor agent. Thus, elevations at the verb for weakly biasing inanimates are simply an ambiguity effect related to the nature of the context.

Recent work by Burgess (1991) provides important empirical support for some of our conjectures about the significance of parafoveal support. Burgess conducted two self-paced reading studies using the materials that we modified slightly for Experiment 2. In one study, the sentences were presented one word at a time. In the other study, they were presented two words at a time, with the verb and *by* presented together (e.g.,/The evidence/ examined by/ . . .). Burgess found immediate effects of animacy with two-word presentation, but not with one-word presentation. Thus, strongly biasing nouns had immediate effects only when there was parafoveal support for the less frequent participial form.

SUBCATEGORY INFORMATION AND FREQUENCY

Thus far we have argued that thematic effects on syntactic processing depend on both the strength of the contextual constraint and the availability of the syntactic alternatives. We also suggested that the frequency with which argument structures occur plays an important role in determining availability, although we did not present any direct evidence. In the remainder of this chapter, we briefly review some recent results of the sentence-complement ambiguity that provide more direct support for our assumptions about frequency. In addition, these results address the superficial conflict between the interpretation of the thematic results just presented, which requires immediate access to alternative argument structures, and recent results that have been interpreted as evidence for delayed use of verb-specific argument-structure (subcategorization) information.

Sentence complements can occur immediately after verbs (as in Sentence 3a), or they can be introduced explicitly by the complementizer *that* (as in Sentence 3b).

(3) a. The chef remembered *the recipe was easy to make.*
b. The chef remembered *that the recipe was easy to make.*

An NP immediately after a verb like *remembered* is temporarily ambiguous because *remember* subcategorizes for either an NP complement or a sentence complement. The phrase "the recipe" could be the object of the verb (e.g., "The chef remembered the recipe") or the subject of a sentence complement (e.g., "The chef remembered the recipe was easy to make"). Considerable research has demonstrated that readers typically take the NP to be the object of the verb, resulting in longer reading times at the verb phrase in the sentence complement (e.g., "was easy . . .") for *that*-less complements, compared with *that*-complement controls (e.g., Ferreira & Henderson, 1990; Holmes, Stowe, & Cupples, 1989; Trueswell et al., 1993). This result is predicted by the minimal-attachment parsing principle because an NP-complement attachment requires at least one fewer node than the sentence-complement attachment.

Recently, Ferreira and Henderson (1990) found that readers experience difficulty at the verb phrase ("was easy . . ."), even when the verb strongly prefers to be followed by a sentence complement and typically does not permit an NP complement, e.g., *insist* as in Sentences 4a and 4b (but cf. Holmes et al., 1989). It was concluded that there is a misanalysis, or "garden-path," in sentences like these, even when the main verb does not license a direct object. On this interpretation, these results lend strong support to two-stage models that initially ignore lexically specific information, and are problematic for constraint-based approaches like the one outlined here.

(4) a. The chef insisted the recipe was easy to make.
b. The chef insisted that the recipe was easy to make.

However, we have found results that shed a different light on these findings. As in the case of thematic constraints, the full data pattern actually provides strong evidence for the key assumptions underlying constraint-based approaches with rich lexical representations, especially those assumptions concerning frequency and argument structure.

The first set of data comes from Trueswell et al. (1993) and Garnsey and Lotocky (1992), who demonstrated that, with carefully normed materials, verb-subcategory information is used to eliminate a reanalysis effect at the verb phrase "was very . . ." in sentences like (4) as compared with sentences like (3). For verbs with a strong NP-complement bias (NP-bias verbs, e.g., *remember*), reading times are longer at the verb phrase for *that*-less complements, compared with *that* controls, whereas there is, at best, a small and unreliable difference for sentence-complement-bias verbs (sentence-bias verbs, e.g., *insist*). For a detailed explanation of why Ferreira and Henderson found a different pattern, see Trueswell et al. (1993).

However, Trueswell et al. (1993) and Garnsey and Lotocky (1992) did find that readers have difficulty with *that*-less sentence complements at the NP when

the preceding verb was sentence-biased (e.g., "insisted *the recipe* . . ."). It is possible that this effect is due to rapid lexical filtering. On this account, the parser attached the NP as the object of the verb and then immediately revised the analysis. This interpretation can be ruled out for two reasons. First, the same effect occurs for completely unambiguous sentences, even when subcategorization information is available. Second, the effect is related to frequency: Difficulty with the NP goes away when the preceding sentence-bias verb is of high frequency. Both of these results, outlined next, reveal patterns consistent with a constraint-based approach to syntactic-ambiguity resolution.

The first result comes from a cross-modal naming study in Trueswell et al. (1993, Experiment 1). In the experiment, subjects heard an auditory-sentence fragment, after which they had to name a visually presented target word. On the trials of interest, the fragment ended with an NP-bias or sentence-bias verb (e.g., "The old man accepted/insisted," and the target word was a case-marked pronoun, either *he* or *him*). These were compared with fragments ending with the complementizer *that* (e.g., "The old man accepted/insisted that"). This kind of task is sensitive to grammaticality effects: Naming latencies are longer when the listener has to name an ungrammatical continuation of the sentence fragment (Cowart, 1987; Tyler & Marslen-Wilson, 1977).

Naming latencies to *him* (plotted in Fig. 7.5A) revealed that subcategorization information is available to the listener immediately after hearing the verb. The results show a grammaticality effect that depends on the use of subcategorization information. The pronoun *him* after a sentence-bias verb (e.g., "The old man insisted . . ."—*him*) is ungrammatical because the verb can only be used intransitively. Indeed, naming latencies to *him* in this condition were just as long as naming latencies to the ungrammatical *that* conditions (e.g., "The old man insisted/accepted that"—*him*). Only the grammatical NP-bias verb condition ("The old man accepted"—*him*) was reliably faster.

However, as Fig. 7.5B shows, naming times to *he* were longer when the fragment did not end in the complementizer *that*. Thus, there was a complementizer effect even when the noun was completely unambiguous: An unambiguous subject NP (*he*) is difficult to process following a verb (i.e., in a *that*-less sentence complement). Why should this be the case? The explanation hinges on the relationship between verb frequency and the availability of argument structure.

An NP after a verb can only be integrated if there is an argument structure available to determine the structural relationship. The complementizer *that* is sufficient to introduce the sentence-complement structure, whereas the pronoun *he* is not. This is because a complementizer's lexical structure, by definition, includes the sentence-complement relationship, whereas a pronoun's lexical structure does not. When no complementizer is present, the integration of the noun depends on information made available by the verb. Thus, difficulty in integrating the noun with the verb depends on the availability of verb information

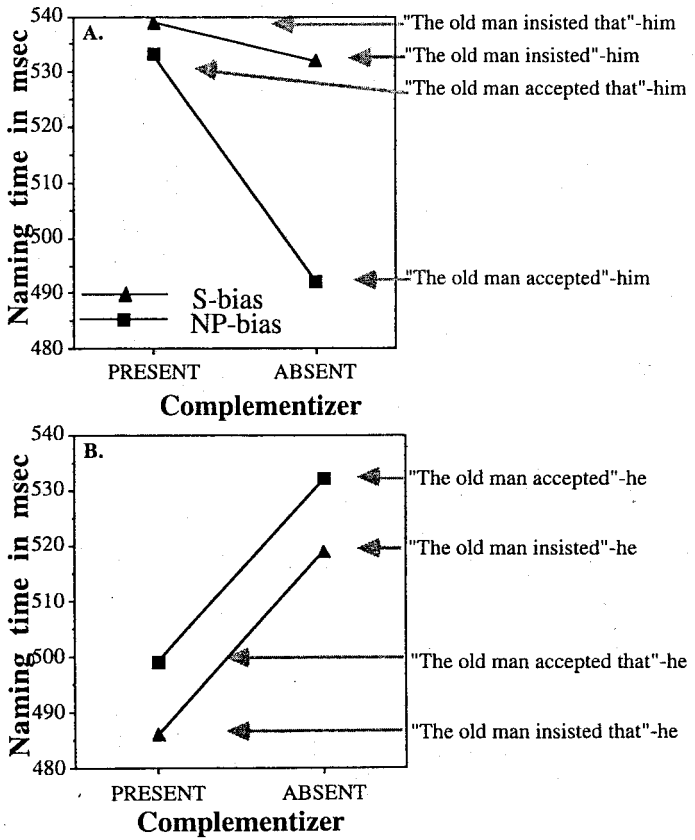

FIG. 7.5. A. Mean latencies for naming *im* aloud after the four different types of sentence fragments. B. Mean latencies for naming *he* aloud after the four different types of sentence fragments (Trueswell, Tanenhaus, & Kello, 1993).

concerning the sentence-complement argument structure. The assumption that frequency of occurrence is related to availability predicts that processing difficulty with a subject pronoun after a verb will depend on the frequency with which the sentence-complement argument structure occurs with that particular verb. Thus, processing difficulty should correlate with the frequency of the verb and the frequency with which the verb occurs with a sentence-complement argument structure without a complementizer, which Trueswell et al. termed a *that preference*. These two frequencies are so highly correlated that it is difficulty to tease them apart, therefore we use them interchangeably.

The prediction that ease of integration of a case-marked pronoun will be

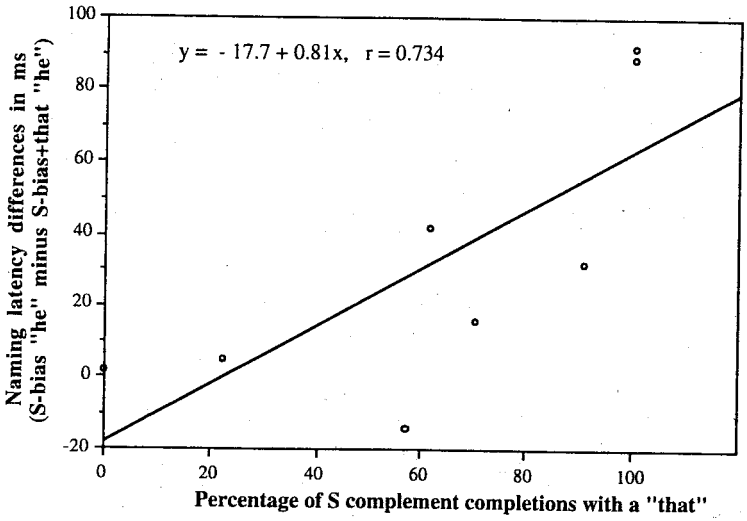

FIG. 7.6. Scattergram plotting the *he* complementizer effect in ms against the percentage of sentence-complement completions that began with a *that* for each Sentence-bias verb (Trueswell et al., 1993).

correlated with *that* preference and verb frequency has been confirmed in several of the experiments reported in Trueswell et al. (1993) and Juliano and Tanenhaus (1993). Figure 7.6, taken from Trueswell et al., illustrates the correlation between *that* preference and naming times to *he* following *that*-less fragments from the study just described.

Now we turn to the second result, which was that processing time for an NP after a sentence-complement verb is (also) correlated with the frequency of the verb. The integration explanation described earlier clearly would explain (and predict) this data pattern. However, there may be another factor at play as well. It is possible that some of the processing difficulty with unmarked nouns is due to the overlap in encoding lexically specific verb information. If access to argument structures is frequency based, some of the syntactic-regularity effects that are captured by parsing principles might emerge from item-specific frequencies, as it has been argued that they do in other lexical domains (e.g., spelling—sound correspondence; e.g., Seidenberg & McClelland, 1989). The preference to take an NP as the object of a verb, rather than as the subject of a sentence complement, is a likely candidate. Because an NP that follows a verb is typically an object, a system that is coding lexically specific co-occurrences will develop an NP bias, as long as we make the noncontroversial assumption that representations for verbs are at least partially distributed (i.e., all verbs will share some similarities). Moreover, verbs that violate this regular pattern (e.g., sentence-bias

verbs) should have difficulty overcoming this regularity, provided that the verb is not highly frequent.

This suggests an interpretation of the complementizer effect that is similar to that given by constraint-based models for the "frequency by regularity" interactions reported in the word-recognition literature (e.g., Seidenberg & McClelland, 1989). For instance, consider the spelling–sound correspondences in English. Although there is a reasonably consistent mapping between letter strings and pronunciation, there are many exceptions. For instance, most syllables ending in *-aste* are pronounced with a long vowel (e.g., *waste, paste, taste*). Words that run against this regular pattern or rule (e.g., exception words like *caste*) typically take longer to read aloud than regular words. However, the difficulty with exception words is modulated by frequency. There is little or no penalty for naming a high-frequency exception word (e.g., *have*), whereas there is a large penalty for naming a low-frequency exception word (e.g., *caste*).

Figure 7.7, taken from Juliano and Tanenhaus (1993), illustrates this frequency-by-regularity interaction in parsing an NP after a verb. Reading times to *the* are longer following a sentence-bias verb than following an NP-bias verb. The magnitude of the difficulty for the sentence-bias verbs interacts with verb frequency (and with *that* preference). A determiner after a verb is typically the beginning of a NP complement. Verbs that do not allow NP complements

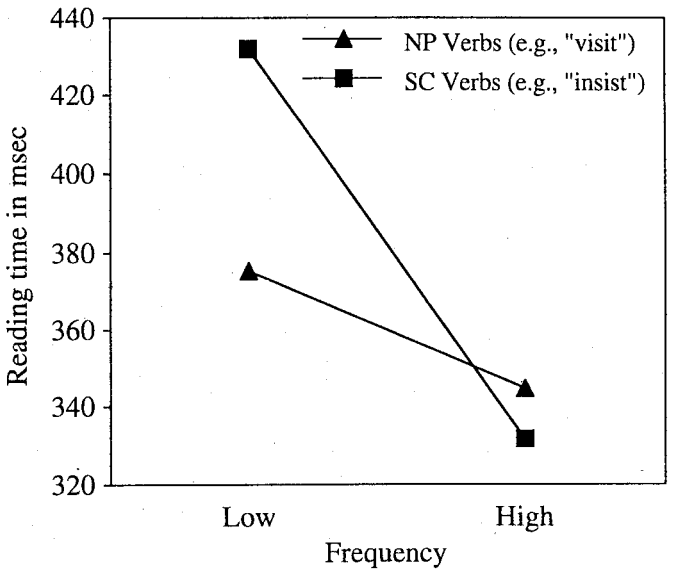

FIG. 7.7. Reading time to the word *the* as a function of the frequency and type of the preceding verb (Juliano & Tanenhaus, 1993).

(sentence-bias verbs) are exceptions to this general pattern. As in word recognition, difficulty with the exceptional pattern should depend on frequency (i.e., how familiar the system is with the particular item). Thus, some of the processing difficulty for an NP after a *that*-less complement may be due to competition from the regular pattern.

Although we have no direct evidence for a competition effect above and beyond an integration effect, we do have clear evidence from a closely related domain. Note that the word *that* after a verb is actually ambiguous. It could be a demonstrative determiner, or it could be a complementizer. However, a *that* after a verb is more frequently a complementizer than a determiner, and readers parse it accordingly (Juliano & Tanenhaus, 1993). On the kind of distributed competition account outlined previously, readers should have difficulty processing the word *that* when it follows a transitive verb that does not permit a sentence complement (e.g., ". . . visited that . . .," where the *that* is a determiner, not a complementizer). The reason is that the interpretation of *that* as a determiner runs counter to a highly regular pattern in the language. This is exactly what we find. Readers have difficulty with the word *that* in a sentence such as "Bill visited that museum" (Juliano & Tanenhaus, 1993). This is essentially the obverse of the effects we discussed earlier for Sentence-bias verbs. Now the preference for an NP structure runs counter to the general pattern in the language.

Note that the set of results we have just discussed, summarized next, is unified by the lexicalist framework outlined previously. As in the case of thematic effects, a subset of the effects is consistent with two-stage models, in which use of lexical information is delayed. However, when the full range of phenomena are considered, the data strongly support the constraint-based model with rich lexical representations.

Phenomena

1. That *preference for case-marked pronouns*. The difficulty of processing an unambiguous case-marked subject pronoun (e.g., *he, she,* or *they*) after a sentence-bias verb is correlated with its *that* preference and with the verb's frequency of occurrence. *That* preference is the percentage of times that a sentence complement after a verb begins with the overt complementizer *that* (Trueswell et al., 1993).
2. That *preference effects for determiners*. Reading times to a determiner that immediately follows a strong sentence-bias verb are correlated with the verb's *that* preference and with its frequency of occurrence (Juliano & Tanenhaus, 1993; Trueswell et al., 1993).
3. That *complementizer bias*. The word *that* is taken to be a complementizer after an NP-bias verb and after a sentence-bias verb (Juliano & Tanenhaus, 1993).

4. That *conflict effect. That* is difficult to process when it follows a verb that does not allow a sentence complement (e.g., "John visited that . . ."; Juliano & Tanenhaus, 1993).

In summary, these results converge on the importance of contingent-frequencies effects in syntactic processing, including effects that emerge from the frequencies with which argument structures occur with particular words and word patterns. The data provide strong support for the assumptions that we outlined about frequency and availability in our discussion o thematic effects on ambiguity resolution for reduced-relative clauses. They are clearly encouraging for approaches to ambiguity resolution that adopt a rich lexicalist framework, in which parsing preferences are not the result of domain-specific principles, but rather emerge from the constraints available from the language.

CONCLUSIONS

The results reviewed herein provide strong support for constraint-based approaches to ambiguity resolution and, in particular, approaches that exploit the richness of lexical representation. We have demonstrated that a syntactically correlated constraint—thematic fit—has immediate effects on syntactic-ambiguity resolution. Moreover, we have shown that the full pattern of results, which emerge when one takes strength of constraint into account, are explained by a lexicalist model, in which the availability of argument structures is determined in part by frequency. We then demonstrated that a set of effects with sentence-complement constructions can also be explained by this framework.

In future work, it will be important to provide a broader empirical base and to implement models that incorporate these principles. The work reported by Pearlmutter, Daugherty, MacDonald, and Seidenberg (1993) is an important step in this direction. In collaboration with Cornell Juliano, we are currently engaged in a modeling effort to determine whether the results outlined previously for the sentence complement will emerge from a system sensitive to co-occurrence patterns of words and argument structures.

It is unlikely that all parsing preferences can be reduced to argument-structure frequency effects. We argue that any successful constraint-based system will need to make use of the kinds of syntactically relevant discourse information emphasized in referential models of sentence processing (Altmann & Steedman, 1988; Crain & Steedman, 1985; Ni & Crain, 1990). However, to the extent that accessing the discourse model depends on contextually dependent "triggering" expressions within a sentence, discourse constraint will interact with—and often depend on—the kinds of local factors we have identified. Spivey-Knowlton and Tanenhaus (chapter 17, this volume) develop this argument in detail and argue that it unifies the literature on referential effects in syntactic processing (see also

Sedivy & Spivey-Knowlton, chapter 16, this volume, for some related discussion).

In developing this approach, we have focused on the combinatory constraints of verbs. Verb argument-structure ambiguities, particularly in a language like English, in which a verb precedes most of its arguments, are a natural domain for exploring hypotheses about rich lexical representation within a constraint-based framework. However, it is likely that the same processing principles will hold in other languages, although not necessarily with the same lexical categories. In fact, in English, we would predict argument-structure co-occurrence effects for lexical items other than verbs. Examples include the *that*-preference effects for sentence-complement structures following adjectives and nouns (e.g., "The man was afraid [that] his plane," "The hypothesis the lexicon is . . .") and co-occurrence effects with function words (e.g., co-occurrence effects between specifiers and prepositions, and the structures that they introduce).

Finally, it should be clear from our discussion that, in contrast to some interactive comprehension systems, we are outlining an approach that is both constrained by, and compatible with, the notions of a richly articulated linguistic system. The fact that thematic constraints can influence syntactic-ambiguity resolution does not mean that there is no distinction between semantic and syntactic information. Nor does it mean any kind of semantic information can affect syntactic processing. Only information that is correlated with syntactic alternatives will have effects. These correlations are most likely to occur at the interfaces between linguistic subsystems (e.g., the discourse function of a syntactic structure, or when a system such as lexical representation cuts across different aspects of representation). Thus, constraint-based systems rely heavily on both the richness of linguistic representation and the fact that different systems make use of the same forms (e.g., the word *the* participates in, and has consequences for, several different systems). It is this basic aspect of natural language that makes on-line processing possible and allows for constraints to be rapidly coordinated. Ultimately, constraint-based systems resolve ambiguity by making use of those constraints that are defined as relevant by linguistic structure and language use, along with an appeal to principles that are characteristic of processing systems in general.

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