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Lexical Nature of Syntactic Ambiguity Resolution

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Ambiguity resolution is a central problem in language comprehension. Lexical and syntactic ambiguities are standardly assumed to involve different types of knowledge representations and be resolved by different mechanisms. An alternative account is provided in which both types of ambiguity derive from aspects of lexical representation and are resolved by the same processing mechanisms. Reinterpreting syntactic ambiguity resolution as a form of lexical ambiguity resolution obviates the need for special parsing principles to account for syntactic interpretation preferences, reconciles a number of apparently conflicting results concerning the roles of lexical and contextual information in sentence processing, explains differences among ambiguities in terms of ease of resolution, and provides a more unified account of language comprehension than was previously available.

One of the principal goals for a theory of language comprehension is to explain how the reader or listener copes with a pervasive ambiguity problem. Languages are structured at multiple levels simultaneously, including lexical, phonological, morphological, syntactic, and text or discourse levels. At any given point in a sentence, the available information can be ambiguous at many levels. To take a simple example, the word *watch* is ambiguous between alternative meanings (e.g., "a timepiece," "to observe"). It is also ambiguous in its grammatical category (noun or verb). The verb sense of *watch* creates further ambiguity because it can participate in several different syntactic structures, including transitive (e.g., *John watched Mary*) and intransitive (e.g., *John watched intently*). Comprehension involves resolving many ambiguities so as to converge on one interpretation, usually the one intended by the speaker or writer.

The purpose of this article is to describe the basic principles underlying a theory of sentence comprehension that explains how this outcome is achieved, given the types of information that are available and the conditions under which sentences are processed. The article has five main sections. First, we briefly summarize previous research on lexical and syntactic ambiguities that has led to theories that treat them much differently, as well as challenges to this dichotomy. In the second section, we develop the idea that a unified treatment of the two types of ambiguities can be achieved because the syntactic ambiguities are caused by ambiguities associated with lexical items. In the third section we consider processing issues: how information is processed within the mental lexicon and how contextual information can influence processing. The central processing mechanism we invoke is the constraint satisfaction process that has been realized in interactive-activation models (e.g., Elman & McClelland, 1984). In the fourth section, we show that the same principles govern the processing of the three types of structures, that these principles provide a basis for resolving apparently conflicting findings in the literature, and that the principles have generated some novel predictions that have been tested in recent studies. We conclude with a discussion of the kinds of research questions suggested by this new framework.

This approach builds on considerable earlier research in sentence comprehension. The idea that syntactic ambiguity resolution is guided by lexical information was proposed by Ford, Bresnan, and Kaplan (1982) and has been addressed extensively by Tanenhaus and colleagues in an important series of articles (Boland & Tanenhaus, 1991; Carlson & Tanenhaus, 1988; Tanenhaus & Carlson, 1989; Trueswell & Tanenhaus, in press; Trueswell, Tanenhaus, & Garnsey, 1994; Trueswell, Tanenhaus, & Kello, 1993). These studies have raised many of the issues considered in this article and greatly influenced our approach. Bever (1970) provided some of the earliest observations about lexical effects in syntactic ambiguity resolution, and his "perceptual strategies" were an early frequency-based account. The view that sentence processing involves constraint satisfaction mechanisms has been proposed by a number of people, most prominently McClelland (1987; St. John & McClelland, 1990). Our approach is also similar in spirit to the competition model of MacWhinney and Bates (1989) and includes specific proposals about the nature of the cues that are central to their account. Our goal has been to develop an integrative theoretical framework that rationalizes much of the literature and provides an orientation for future research.

Lexical Versus Syntactic Ambiguity Resolution

Lexical ambiguity research has addressed how the reader-listener determines the contextually appropriate meaning of a word with multiple senses. Lexical ambiguities pervade natural language, with words exhibiting different types and degrees of

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ambiguity. For example, the alternative senses of ambiguous words can be spelled and pronounced the same (e.g., *rose*), spelled the same but pronounced differently (e.g., *bass* or *wind*), or spelled differently but pronounced the same (e.g., *team* or *teem*). Almost all words in the English lexicon exhibit a nonzero degree of ambiguity, some acutely so. For example, the *American Heritage Dictionary* lists 41 separate meanings of *take*, several of which have multiple related senses.

Syntactic ambiguities arise when a sequence of words has more than one syntactic interpretation. One ambiguity, the main verb/reduced relative (MV/RR) ambiguity shown in Example 1a–1b, has been the object of attention for nearly 25 years (dating from Bever, 1970). In 1a, *raced* is the past tense main verb of the sentence. In 1b, *raced* is a past participle introducing a reduced relative clause, meaning "the horse that was raced past the barn," and *fell* is the main verb.

1a. The horse raced past the barn.
b. The horse raced past the barn fell.

This ambiguity is permitted in English because certain words introducing a relative clause (e.g., *that was*) can be optionally omitted. This omission can create a processing problem because a verb such as *raced* is ambiguous between past tense and past participle forms. If *raced* is treated as a past tense form, 1a will be analyzed correctly but 1b will not. If *raced* is treated as a past participle, 1b will be correctly analyzed but 1a will not.

Like lexical ambiguity, syntactic ambiguity is omnipresent. "Garden path" sentences such as 1b are famous among psycholinguists because they illustrate an ambiguous structure in dramatic fashion, in that they are almost impossible to interpret. The difficulty of such sentences could leave the impression that these ambiguities must be very rare, but in fact examples of the MV/RR ambiguity, resolved with the reduced relative interpretation, occur throughout natural discourse and typically go unnoticed. To illustrate, Table 1 contains examples of reduced relative constructions taken from several recent articles on syntactic ambiguity resolution.

Theories of Lexical and Syntactic Ambiguity Resolution

The theories that have been dominant over the past 15 years suggest that lexical and syntactic ambiguities are resolved by highly different mechanisms. Theorizing about lexical ambiguity resolution has been heavily influenced by the finding that comprehenders briefly activate multiple senses of ambiguous words even in clearly disambiguating contexts (see Simpson, 1984, for a review). Many of these studies have used what Swinney (1979) termed a *cross-modal priming paradigm*, in which an auditory sentence, containing an ambiguous word or unambiguous control, was paired with a visual probe word. The pattern obtained in numerous studies is that when visual targets are presented immediately after the ambiguous word, there is significant facilitation in responding to targets that are related to either alternative meaning of the ambiguous word. If targets are presented somewhat later (e.g., after a delay of 200 ms or after several intervening words), there is facilitation only for the target related to the contextually appropriate meaning (e.g., Swinney, 1979; Tanenhaus, Leiman, & Seidenberg, 1979). These studies suggested a model in which multiple alternative senses of ambiguous words are briefly accessed, followed by the selection of the contextually appropriate meaning. People are consciously aware of only the contextually appropriate meaning that has been chosen, not the initial activation of multiple senses.

Table 2 contains a listing of the characteristics commonly attributed to the process of lexical ambiguity resolution. The alternative meanings of words are thought to be stored in memory and "accessed" in processing. In the initial stage of processing an ambiguous word, multiple meanings are considered in parallel, with contextual information used shortly afterward to select the relevant one and suppress all alternatives. It has been assumed that multiple meanings can be accessed in parallel because this process is automatic and capacity free (in the sense of Posner & Snyder, 1975, and others).

Syntactic ambiguity resolution has been viewed much differently (see Table 2). Most theories have proposed two-stage mechanisms for coping with syntactic ambiguity. In the first stage, a modular syntactic processor, or *parser*, uses syntactic knowledge and parsing principles to construct one or more phrase structure representations of the input. The second stage involves choosing or correcting these phrase structures and integrating them with lexical and discourse information (Abney, 1989; Altmann & Steedman, 1988; Frazier, 1979; Gorrell, 1987; Kurtzman, 1985; Perfetti, 1990; Pritchett, 1992). These alternative models differ in important details, such as the number of parses that are constructed for an ambiguous input and the nature of the time course of the interaction between the first and second stages. Our discussion focuses on the version that is best known, has been most intensely investigated, and makes the strongest claims: the garden path theory of Frazier (1979, 1987, 1989, 1990; Frazier & Rayner, 1982; Rayner, Carlson, & Frazier, 1983). This theory proposes that the first-stage parser constructs a single parse (phrase structure) using only the grammatical categories of the words being processed (e.g., determiner, adjective, noun, verb). By hypothesis, the parser does not have access to their identities or meanings. When this sequence of categories is compatible with multiple phrase structure analyses, the choice of analysis is determined by a processing strategy called *minimal attachment*. This principle dictates that new material be attached into the phrase structure tree using the minimal number of new nodes, so that the parser constructs the simplest syntactic structure. In cases in which alternative analyses are equally simple, a second principle, *late closure*, operates, again guaranteeing that only one analysis will be pursued. For MV/RR ambiguities such as 1a–1b, minimal attachment directs the parser to pursue the main verb interpretation, independent of word meaning or discourse context. Other processing subsystems subsequently confirm or reject the initial syntactic analysis.

Many of the differences between the lexical and syntactic ambiguity resolution mechanisms in Table 2 derive from assumptions about the types of knowledge involved in each domain (Frazier, 1989). Lexical ambiguity is thought to involve meanings that are stored in the lexicon. Processing involves accessing this information, which is assumed to be accomplished automatically and in parallel. Syntactic structures, by contrast, are thought to be constructed on the basis of grammatical rules rather than stored directly in memory. This computation is as-

Table 1
Examples of Sentences With Reduced Relatives

Example	Source
Thus, a noun phrase FOLLOWED BY A MORPHOLOGICALLY AMBIGUOUS VERB (e.g., "The defendant examined") will be temporarily ambiguous.	Trueswell, Tanenhaus, & Garnsey, 1994, p. 287
Referential information PROVIDED BY THE DISCOURSE is of no help.	Britt, Perfetti, Garrod, & Rayner, 1992, p. 305
Recent research REPORTED BY FERREIRA AND CLIFTON (1986) has demonstrated that syntactic processing is quite independent and that the initial syntactic analysis ASSIGNED TO A SENTENCE is little influenced by the semantic information ALREADY ANALYZED.	Frazier & Rayner, 1987, pp. 520–521
The pattern of results OBTAINED WITH GLOBAL READING TIMES is reflected by differences LOCATED ON THE CRITICAL DISAMBIGUATING PHRASE.	Altmann & Steedman, 1988, p. 226
A person PRESENTED WITH *THE EVIDENCE EXAMINED BY THE LAWYER* may interpret *the evidence* as a theme, not an agent, because *examined* requires an animate agent.	Ferreira & Clifton, 1986, p. 350
In all cases, the examples CITED HERE were not the only reduced relatives in these articles.	See table note

Reduced relatives appear in uppercase letters.
Note. In all cases, the examples cited here were not the only reduced relatives in these articles; the rate of reduced relative usage appears to be about one per journal page in this sample of articles.

sumed to place demands on working memory and attentional resources that are limited in capacity (Frazier, 1979; Gibson, 1991; MacDonald, Just, & Carpenter, 1992). In the garden path model, these memory limitations force the parser to pursue only a single analysis at a time.

It is interesting to note that although lexical and syntactic ambiguity resolution differ in fundamental ways according to these theories, both have been explained in terms of Fodor's (1983) concept of modularity, in which the language processing system is composed of a number of components or modules responsible for analyzing different types of information. Each module is "informationally encapsulated," in that it operates autonomously, responding only to the type of information to which it is attuned. Thus, the lexical processor is isolated from nonlexical processors, and multiple meanings of ambiguous words are accessed, even in the presence of potentially disambiguating contextual information. For syntactic ambiguity, the garden path model's parser is similarly isolated, so that the single, simplest parse is pursued even in the presence of prior context favoring an alternative analysis. In both the lexical and syntactic cases, context effects stem from systems that operate on the output of their respective modules.

Challenges for the Standard Theories

Both empirical and theoretical considerations have called into question the accounts of ambiguity resolution shown in Table 2. There have been challenges to the standard assumptions in three areas: context effects, the role of frequency information in modulating ambiguity resolution, and the nature of knowledge representations and processes. These challenges undermine the distinction between accessing a meaning and constructing a syntactic representation. We briefly review how these three issues have arisen in each domain.

Lexical Ambiguity

Context effects. Even though theorizing about lexical ambiguity resolution has focused on the multiple access pattern, several studies failed to yield this outcome (e.g., Seidenberg, Tanenhaus, Leiman, & Bienkowski, 1982; Simpson & Krueger, 1991; Swinney & Hakes, 1976; Tabossi, 1988; Tabossi, Colombo, & Job, 1987). These results were initially attributed to methodological limitations (Swinney, 1979), but later studies obtained both the multiple and selective access patterns using

Table 2
Properties of Ambiguity Resolution Systems

Lexical ambiguity	Syntactic ambiguity
Multiple alternatives initially considered	Single alternative initially considered
Parallel processing	Serial processing
Capacity free	Capacity limited
Context used to select appropriate meaning	Context used to confirm analysis and guide reanalysis
Meanings are stored and accessed	Syntactic structures constructed by rule

the same methods (e.g., Tabossi, 1988). In other cases, the modular theory of lexical access was preserved by attributing the contextual effects to semantic priming within the lexical module (Forster, 1979; Seidenberg et al., 1982). However, this account of context effects has also been called into question by studies in which selective access was observed in sentence contexts that did not contain words that could prime a meaning of the ambiguous word (e.g., Morris, 1994). Thus, a number of studies have yielded selective access of meaning in biasing contexts, but the reasons why contexts apparently yield different effects have been obscure.

Frequency. The meanings of ambiguous words vary in frequency of use. Frequency has a large impact on lexical processing, a fact acknowledged by all models of the lexicon dating from Morton (1969). Studies such as Swinney (1979) and Tanenhaus et al. (1979) examined ambiguous words such as *tire* or *straw* that have two primary meanings that are roughly equal in frequency. Swinney (1979) interpreted the fact that multiple access was observed with such "equibiased" ambiguous words as evidence that access of meaning is "exhaustive": Lexical access makes available all of the meanings of a word, regardless of context. Most ambiguous words have alternative meanings that differ considerably in frequency, however. For example, in the Francis and Kučera (1982) corpus of American English, there are 1,366 words that occur as both nouns and verbs, some with semantically unrelated meanings (e.g., *tire, bluff*) and others with related meanings (e.g., *cap, coin*). For 73% of these words, one grammatical category is used at least twice as often as the other. Analyses of the words that are ambiguous between noun and adjective meanings yield a similar picture. There are 155 such words in Francis and Kučera's corpus (e.g., *special, current*). The frequency ratio is 2:1 or greater for 81% of them.

Simpson (1984) reviewed several studies suggesting that frequency affects the order in which the meanings of ambiguous words are accessed. Important studies by Rayner and Duffy (1986) and Duffy, Morris, and Rayner (1988) have provided additional evidence concerning frequency. Rayner and Duffy (1986) found that in neutral sentence contexts, equibiased ambiguous words (e.g., *pitcher*) yielded longer eye fixations than did matched unambiguous words. This result established that multiple access of meaning is associated with longer fixation durations. Fixation durations did not differ for biased words (e.g., *port*) compared with controls, indicating that for words in which one meaning is much more frequent than all the others, only the dominant meaning is accessed and integrated with the context. Duffy et al. (1988) then examined how a biasing context would affect the processing of these words. Contexts were constructed to favor one meaning of the equibiased ambiguous word and the subordinate (less frequent) meaning of the biased ambiguous word. Contextual bias was achieved without using words that were highly semantically or associatively related to the ambiguous word, eliminating lexical priming as a possible source of context effects. Latencies for equibiased words in a biasing context were equal to those for unambiguous controls. For nonequibiased ambiguous words, however, a context supporting the subordinate meaning resulted in longer fixations than for unambiguous controls, the pattern associated with multiple access in Rayner and Duffy's (1986) study.

These results indicate that equibiased ambiguous words in biasing contexts act like biased words in neutral contexts. In both cases, a single meaning is accessed on-line and integrated with the context; no effect of ambiguity is observed. Thus, context can promote one meaning of the equibiased word, resulting in a "selective access" pattern. Duffy et al. (1988) interpreted the data as evidence for a model in which context can "reorder" access to meanings. Moreover, the biased words in contexts favoring the subordinate meaning acted like equibiased words in neutral contexts: In both cases, latencies were longer in the ambiguous condition than in the unambiguous control condition: the "multiple access" pattern. Thus, contexts that support the less frequent meaning of a biased word promote that reading. However, the effect of contextual information is limited: Whereas the context increases the activation of the lower frequency meaning, it does not inhibit the higher frequency meaning, which still becomes activated.

There are several important findings here. First, the studies provide clear evidence that frequency of meaning has an impact on processing, consistent with earlier studies that examined this factor. Second, contextual information can result in activation of only a single meaning of an ambiguous word. Third, contextual information does not eliminate the effect of frequency: Biasing contexts produce selective access when the alternative meanings are similar in frequency and when they are consistent with the higher frequency meanings of biased words, but not when they favor lower frequency meanings. This interaction between frequency and contextual constraint plays an important role in the theory presented below.

Representation: Are meanings "accessed"? Most models of word recognition developed over the past 20 years have construed the process as one involving the access of lexical information. The words in a person's vocabulary are thought to be encoded as entries in a mental lexicon; recognizing a word involves accessing its entry. For ambiguous words, the issue was whether readers access a single meaning or multiple meanings of such words in context. In recent years, however, researchers have critically evaluated the assumptions about the knowledge representation and processing that are presupposed by the concept of lexical access. For example, the idea that meanings are fixed entries that can be accessed has been questioned. Current theories of the representation of meaning assume that meanings are computed as part of the recognition process and may vary depending on the context in which a word occurs (Barsalou, 1987). Thus, the fact that pianos are heavy is relevant in a context of furniture moving, but their musical aspects are relevant in a context about Artur Rubenstein (Barclay, Bransford, Franks, McCarrell, & Nitsch, 1974). These phenomena are problematical for the view that meanings are accessed. They suggest instead that the pattern of semantic information that becomes available when a word is processed depends on the context in which it occurred, even for apparently unambiguous words such as *piano* or *cat* (Merrill, Sperber, & McCauley, 1981). It may be misleading, then, to think of meanings as distinct, countable entities or of lexical access as an event that is achieved at a distinct "magic moment" in time (Balota, 1990).

These phenomena seem to demand a different notion than that of accessing meanings from memory (Seidenberg, 1993). An alternative is provided by the distributed representations used in connectionist networks. The meaning of a word can be

represented as a pattern of activation over a set of units encoding semantic primitives (Hinton, McClelland, & Rumelhart, 1986); each unit participates in the meaning of many words. In a system using this type of knowledge structure, the meanings of words are not stored as separate entries and therefore cannot be accessed; rather, they are computed, with different patterns activated in different contexts. Moreover, in networks that incorporate attractors (e.g., Hinton & Shallice, 1991; Plaut & Shallice, 1993), the network settles into a pattern of activation over time rather than computing it in a single step, providing a specific computational alternative to the metaphor of accessing a meaning at a fixed latency.

Many of these issues were addressed in a model developed by Kawamoto (1988, 1993), in which each code for a word (i.e., spelling, meaning, phonology, grammatical category) was represented by a pattern of activation over a set of units. The model computed patterns of activation corresponding to these codes. A greatly simplified domain consisting of a small number of words and contexts was used, including some homographs such as *wind* and *bass*, which have unrelated meanings and two pronunciations. The architecture of the system allowed the computation of word meaning to be influenced by contextual information; however, the model computed multiple meanings of homographs even when there was a contextual bias toward one meaning. This result occurred because the association between the meanings of the homograph and its lexical form (e.g., phonology) were much stronger than the associations between an individual meaning and the information in the biasing context. The model therefore exhibited the property Marslen-Wilson (1987) termed *bottom-up priority*.

Kawamoto's (1988, 1993) model showed that the multiple access pattern that had been taken as diagnostic of a modular lexicon could arise from other sources. It placed the explanation for this effect with the nature of contextual constraints, not the architecture of the processing system. It was simply because the contextual constraints were too weak that multiple access occurred in Kawamoto's model, not because the lexical processor was an autonomous module. The model does not show that the modular account is incorrect; rather, it shows that the data are compatible with very different theoretical conclusions. Kawamoto's model also was an early demonstration of how lexical information could be represented in a system without entries for individual words, an idea that was incorporated in subsequent models (e.g., Hinton & Shallice, 1991; Seidenberg & McClelland, 1989). Such models do not preserve a strong distinction between accessing and constructing representations and thus do not maintain the central property of lexical representation that had been used to distinguish it from syntactic representation.

Syntactic Ambiguity

These same issues—the scope of context effects, the role of frequency, and the types of knowledge representations involved—have arisen with regard to syntactic ambiguity resolution.

Context effects. Frazier's (1987; Frazier & Rayner, 1982) garden path theory has provided the focus for sentence processing research for the past 15 years. Whereas lexical ambiguity researchers have asked whether contextual information could override the multiple access pattern, syntactic ambiguity researchers have addressed whether contextual information could override the minimal attachment pattern, such that a nonminimal interpretation would be pursued in an appropriate context. So-called "interactive" models of language comprehension (MacWhinney & Bates, 1989; Marslen-Wilson, 1975; McClelland, 1987) emphasize how the processing of words in sentences depends on the availability of contextual information. This type of theory implies that whether minimal attachment is observed will also depend on context.

Most research on context effects in syntactic ambiguity resolution has focused on the MV/RR ambiguity that was illustrated earlier in 1a–1b. The RR interpretation that is disfavored by the minimal attachment algorithm is the one in which the ambiguous phrase modifies the preceding noun (e.g., *raced past the barn* modifies *horse* in 1b). Two types of context that favor such noun-modification interpretations have been investigated. The first is the plausibility of this interpretation relative to alternatives (e.g., Ferreira & Clifton, 1986; Trueswell et al., 1994). If the RR interpretation is the most plausible one in context, then it could be pursued instead of the MV interpretation favored by minimal attachment. The second context manipulation is a pragmatic one that affects whether or not it is felicitous to modify a noun at a particular point in the discourse. Crain and Steedman (1985) argued that noun modification was not felicitous when the discourse had established only one possible referent for a noun (e.g., only one horse in the discourse), but modification was felicitous and necessary in a discourse in which several potential referents had been established. Thus, the noun modification interpretation in 1b may be preferred in such a context because it would serve to indicate exactly which horse the speaker was discussing.

According to the garden path model, neither type of context manipulation should affect the initial interpretation of syntactic ambiguities because initial parsing decisions are guided only by minimal attachment. The theory predicts that the use of contextual information should be limited to the second-stage reanalysis of incorrect parses. The effects of plausibility and pragmatic context have been investigated with these kinds of sentences using a variety of cross-modal and reading time methodologies. Results from many studies supported the garden path theory, but there have been some notable exceptions.

For example, Ferreira and Clifton (1986) investigated the effect of plausibility in the MV/RR ambiguity by varying the animacy of the subject noun phrase (NP). They examined reading times for sentences such as Examples 2–3 compared with unambiguous control sentences (containing *that was* between the subject noun and *examined*). The plausibility manipulation relied on the nature of the subject NP and ambiguous verb. *Examine* normally takes an animate subject. *Witness*, being animate, is consistent with the simple MV interpretation of *examined* (in which the witness examined something), which turns out to be incorrect. Because inanimate entities such as evidence cannot examine things, the subject NP *the evidence* is incongruent with the MV interpretation and favors the RR alternative, which turns out to be correct. If comprehenders can use this information to guide the initial parse, Example 3 should cause less difficulty compared with an unambiguous control than Ex-

ample 2. Ferreira and Clifton found that subjects had equal difficulty reading the two types of sentences, however. They concluded that the *evidence/witness* context was used only during reanalysis, after the operation of minimal attachment.

2. Unhelpful context: The witness examined by the lawyer was useless.

3. Helpful context: The evidence examined by the lawyer was useless.

In later research, Trueswell et al. (1994) raised several questions about the validity of Ferreira and Clifton's (1986) methods and results. For example, they noted that many of Ferreira and Clifton's helpful context sentences admitted other syntactic interpretations, vitiating the manipulation of contextual bias. When Trueswell et al. performed similar experiments but improved the stimuli, the visual display, and the data analyses, they found a robust context effect, such that helpful contexts removed all difficulty associated with the RR interpretation of the ambiguity. This result favors an account of syntactic ambiguity resolution in which both syntactic and contextual information interact in directing the comprehender to an interpretation of a syntactic ambiguity, and it argues against a first-stage parser that makes initial decisions independent of context. Similar issues have arisen in connection with other studies that failed to find effects of contextual bias (e.g., Ferreira & Henderson, 1990; Trueswell et al., 1993).

These studies suggest that under at least some conditions, context does appear to influence the initial interpretations of syntactic ambiguity, contrary to the garden path theory. However, the kinds of information that contribute to "contextual bias" and the mechanisms by which this information is used in sentence processing have been poorly understood. These issues are addressed by the theory presented shortly. This theory suggests that the prior conflicting results were not solely due to methodological differences between studies; rather, they were also attributable to the fact that the stimulus materials used in different studies varied in terms of factors that were not always recognized as being relevant to ambiguity resolution.

Frequency. Until recently, frequency information has not been considered to be relevant to sentence comprehension, partly because of the influence of Chomsky (1957), whose remarks on the issue in *Syntactic Structures* might have diverted attention away from it. On pages 16–17, Chomsky developed the famous conception of grammar as a theory of the well-formedness of sentences. He argued that this notion of grammar cannot be equated with statistical properties of language, such as the frequencies with which words co-occur. He noted that a sentence may be grammatical but have a low frequency of occurrence (his examples included "Colorless green ideas sleep furiously" and "I saw a fragile whale") and that ungrammatical utterances may occur with relatively high frequency. He said, "I think that we are forced to conclude that . . . probabilistic models give no particular insight into some of the basic problems of syntactic structure" (Chomsky, 1957, p. 17). Most theoretical linguists have accepted this argument and shown little interest in issues concerning statistical properties of language such as the relative frequencies of syntactic structures. It should be noted, however, that Chomsky then made a point of acknowledging that such statistical information could prove to be relevant to understanding language use. Continuing in *Syntactic Structures,* he wrote the following:

> Given the grammar of a language, one can study the use of the language statistically in various ways; and the development of probabilistic models for the use of language (as distinct from the syntactic structure of language) can be quite rewarding. (Chomsky, 1957, p. 17)

In fact, some of the earliest research inspired by this view examined the role of probabilistic factors in sentence processing (e.g., Bever, 1970).

The influential theory by Frazier and colleagues (e.g., Frazier, 1987) represented a shift away from this interest in the role of statistical and probabilistic information in sentence processing. Although Chomsky's (1957) observations concerned the irrelevance of statistical properties of language to the *grammar,* Frazier and colleagues' theory proposed that statistical properties are also irrelevant to the initial syntactic *processing* of sentences. Minimal attachment is a strategy that is based on the relative simplicity of syntactic structures, not on their relative frequencies. The studies that were designed to test this theory examined the ease of processing different structures, ignoring facts about their relative frequencies of occurrence. Thus, Ferreira and Clifton (1986) addressed whether participants would prefer MV or RR interpretations of phrases such as *The witness/evidence examined by the lawyer.* However, if the statistical properties of language are relevant, one may ask, by analogy to lexical ambiguity, whether the verb *examined* is used more often as an MV in simple transitive sentences or as an RR, whether there are verbs in which the relative frequencies are reversed, and whether the comprehension process exploits such frequency information. The garden path model provided little motivation for investigating frequency effects because none are expected during the initial analysis of a syntactic ambiguity: The parser operates only on strings of grammatical categories and has no access to information about frequency. However, there has been a revival of interest in questions concerning the statistical properties of natural language both in computational linguistics (see, e.g., Zernik, 1991) and in sentence processing, as we discuss in detail shortly. If the human sentence processing mechanism exploits such properties of language, it will be necessary to reassess earlier studies in which they were not controlled (as in the Trueswell et al., 1994, reassessment of Ferreira & Clifton, 1986).

Representation: Are syntactic structures "constructed"? The distinction between lexical and syntactic forms of ambiguity has also been affected by developments in linguistic theory. Although current linguistic theories still rely on the notion of computing some sort of independent syntactic structure (e.g., a phrase structure tree), recent work has emphasized how such representations are constrained by properties of lexical items. Early work in generative grammar (e.g., Chomsky's, 1965, Standard Theory) adopted the mechanism of phrase structure rules to generate basic syntactic structures. Nothing in these rules necessarily associated them with particular lexical items, and thus the syntactic component of the linguistic system could be viewed as an independent module with its own idiosyncratic representations and processes. In other syntactic theories and more recently within the generative tradition, however, collec-

tions of phrase structure rules have been abandoned in favor of formulations in which lexical items are directly associated with the information used to construct a complete syntactic representation (e.g., X-bar structures in Government-Binding theory [Chomsky, 1981] and predicate-argument structures in Lexical-Functional Grammar [Bresnan, 1982]). In this view, the lexicon and syntax are tightly linked, and to the extent that information required by the syntactic component is stored with individual lexical items, it will be difficult to find a boundary between the two systems. Thus, whereas Kawamoto's (1988, 1993) model provided an alternative to lexical access, syntactic theory has provided, as an alternative to the concept of constructing a phrase structure representation by rule, the idea that much syntactic information is part of a word's representation in the lexicon. These independent developments suggest the possibility that the computation of both lexical and syntactic information in sentence comprehension is governed by common lexical processing mechanisms. We explore this possibility shortly.

Finally, there are questions as to whether the data interpreted as evidence for the garden path theory necessarily implicate a modular parser. As in the case of lexical ambiguity, there is a signature finding—the garden path effect in sentences such as *The horse raced past the barn fell*—taken as evidence for an autonomous syntactic parsing module. Kawamoto's (1988, 1993) model suggests that this kind of outcome could result from a much different type of architecture. The claim that some types of biasing information are merely too weak to overcome minimal attachment is certainly reminiscent of the claim, embodied by Kawamoto's model, that multiple access of meaning occurs in contexts that are too weakly constraining. This observation also encourages the search for a unified account of the phenomena.

Toward an Integrated Theory of Lexical and Syntactic Ambiguity Resolution

In this section we develop our principal theoretical claim: that both lexical and syntactic ambiguity are governed by the same types of knowledge representations and processing mechanisms. We have shown that highly similar empirical, theoretical, and methodological issues have arisen in both the lexical and syntactic domains: the role of frequency information, the types of information involved in contextual constraints, the extent to which contextual information constrains the interpretation of ambiguities, and whether the processing system is modular or interactive. Moreover, we have argued that recent types of theorizing eliminate the strong distinction between accessing a meaning and constructing a syntactic representation, which was central to previous accounts. We suggest that these parallels between the domains are not coincidental; they reflect common underlying processes and types of knowledge representations. The parallels derive from the fact that the syntactic ambiguities in question are based on ambiguities at the lexical level. The same ambiguity resolution mechanisms apply in both domains because both involve ambiguities over various types of lexical representations.

Representational Issues

The standard view of the lexicon in psycholinguistics is that it is a mental dictionary containing an entry for each word in a person's vocabulary, specifying its semantics, phonology, and orthography (see, e.g., Forster, 1976). The lexical representations we postulate include this information as well as other information relevant to syntactic processing; in this respect we are following suggestions by Carlson and Tanenhaus (1988; Tanenhaus & Carlson, 1989; see also Boland & Tanenhaus, 1991; Trueswell & Tanenhaus, in press; Trueswell et al., 1993, 1994). These claims for a richer lexical representation gain support from linguistic theory, which has become increasingly focused on issues concerning the structure of the lexicon and the relationships between different types of information (e.g., syntactic and semantic) within it.

We assume that comprehension is the process of concurrently deriving a number of linked representations of different types for a given input sentence or sequence of sentences. Sentences are represented at three major levels: (a) lexical, the level that is the focus of this article; (b) syntactic; and (c) discourse. Lexical processing involves activating different types of information associated with a word form and then using this information to compute representations at the other levels. A single appropriate representation must be computed at each level in the course of processing, although a complete record of all of this information will not necessarily be maintained throughout the processing of a sentence.

Argument Structure

In addition to the orthographic, phonological, and semantic codes that have been the focus of previous research, knowledge of words includes what current syntactic theories term *argument structures,* which play a central role in resolving syntactic ambiguities. The argument structures associated with a word encode the relationships between the word and the phrases that typically occur with it (the word's arguments) and capture important facts about correlations between syntactic and semantic information. The concept of argument structure is related to the earlier notion of verb *subcategorization frames* (Chomsky, 1965), which indicate the kinds of syntactic phrases that optionally or obligatorily occur with a verb in a sentence (e.g., that the verb *put* must occur with both a direct object NP and a prepositional phrase [PP]). In addition to this information, an argument structure representation provides some semantic information about the relationship between a word and each of its associated arguments (including, for a verb, its subject, which was typically excluded from its subcategorization frames). For the verb *put,* the argument structure information captures English speakers' knowledge that not just any combination of a subject NP, an object NP, and a PP is acceptable; the subject NP must take the role of agent (the thing doing the putting), the object NP must be the theme (the thing being put), and the PP must specify a location (where the theme is put). This coarse-grained semantic information about a phrase, such as the requirement that the PP mark a location of some sort, is called the *thematic role* assigned to the phrase (Fillmore, 1968, originally used the term *case role;* see also Chomsky, 1981; Gruber, 1976; Jackendoff, 1972). Argument structures, when combined with grammatical knowledge of permissible phrase structures, thus specify two things about each phrase that occurs with a word: the grammatical category of the phrase (NP,

PP, etc.) and the thematic role assigned to the phrase. This conjunction of syntactic and semantic information in one representation captures interdependencies between these types of information that are important for language processing and ambiguity resolution (see Boland & Tanenhaus, 1991, and references therein).

Most discussions of argument structure suggest that the number of discrete thematic roles is relatively small. In addition to agent, theme, and location, some important thematic roles include the following (with the illustrated role in italics): goal (John gave the book *to Mary*), experiencer (The book pleased *Mary*), proposition (Mary thought *that the book was brilliant*), manner (Mary accepted the book *with a smile*), attribute (the book *with a black cover*), and instrument (Mary cut the bread *with a knife*). According to some theories, thematic roles are not themselves primitives in linguistic representation but instead reflect combinations of finer grained semantic features such as animacy, sentience, humanness, volition, causation, and movement (Dowty, 1991). Thematic roles may thus be taken to reflect generalizations about co-occurring clusters of more primitive semantic features.

Argument Structures in the Lexicon

We assume that the lexical entry of each verb, preposition, noun, and adjective includes a representation of argument structure information. Example 4a shows the argument structure for the verb *put*, and 4b shows a corresponding sentence, in which *Mary* is the agent, *the book* is the theme, and *on the table* is the location.

4a. put: ⟨agent, theme⟩ ⟨location⟩
4b. Mary put the book on the table.

The argument structure for *put* contains two subcomponents or "thematic grids," indicated in angle brackets.[1] The "core" thematic grid is on the left; phrases that take the thematic roles specified in the core grid are licensed by the verb and appear in the sentence as NPs (*Mary* and *the book* in 4b), except in the case of the proposition role, which appears as a complete embedded clause. Thematic roles in noncore grids (such as the ⟨location⟩ grid for *put*) can be assigned only indirectly, with the help of prepositions, so they will be assigned to PPs (such as *on the table*). The underlined position in a core grid corresponds to an "external" argument (external to the verb phrase), which is usually the verb's subject (*Mary* in 4b). Nonunderlined positions are internal arguments and are either direct, if they are part of a core grid, or indirect, if they are part of a noncore grid. This same notation applies to the argument structure of words other than verbs. For example, prepositions take direct internal arguments (direct objects, usually), just as verbs do: In the prepositional phrase *with the hammer, with* assigns the instrument role to its direct internal argument (the NP *the hammer*). See the references in Footnote 1 for further details.

Because many words can appear with more than one configuration of arguments, they will be associated with several different argument structures. The examples in 5a–5c illustrate three common English core thematic grids for the verb *cook*.

5a. cook: ⟨agent, theme⟩ John cooked the stew. (transitive)
5b. ⟨agent⟩ John cooked. (intransitive)
5c. ⟨theme⟩ The stew cooked. (intransitive)

In 5a, *John* is the agent and *the stew* is the theme. We refer to argument structures and sentences such as 5a, in which the core grid contains both an external and an internal argument, as *transitive argument structures* and *transitive sentences*, respectively. The examples in 5b–5c are *intransitive argument structures* and *intransitive sentences* because either an internal (5b) or external (5c) argument is not present.

Other Lexical Representations

Other grammatically relevant features include tense (past, present, future), finiteness (finite or infinitive), voice (active or passive), number (singular or plural), person (first, second, third), and gender (masculine, feminine, neuter; in English, this is limited to the pronominal system: *him, her, it*, etc.). Morphological information is available as well, although English morphology is incomplete in a number of respects and is often another source of ambiguity. For example, only about 50 English verbs have different past tense and past participle forms (e.g., *broke/broken, wore/worn*); for the rest, the two forms are identical (*raced, walked, sat*, etc.). The latter verbs are thus associated with a morphological ambiguity.

We also assume that the lexical representation of a word includes other syntactic information. Work within several syntactic theories (e.g., Chomsky, 1981, 1992; Gazdar, Klein, Pullum, & Sag, 1985) has relied on the idea that complete syntactic trees are built from subcomponents called *X-bar structures*, which is often written as *X'* (Chomsky, 1970; Jackendoff, 1977; tree-adjoining grammar formalisms rely on a similar notion, e.g., Joshi, 1985). X-bar structures are generic pieces of phrase structure consisting of a head (X, a grammatical category such as noun or verb, associated with a lexical item) and various other nodes or projections, as shown in the left half of Figure 1. We treat X-bar structures as yet another type of representation in the lexicon, so that just as a word has associated argument structures in its lexical entry, it will have associated X-bar structures. A noun will have associated N, N' (the node above N), and NP nodes, as in the right half of Figure 1; a verb will have the same structure but with V, V', and VP nodes, and so forth. Words that are ambiguous between multiple grammatical categories will have multiple X-bar structures.

With X-bar structures in the lexicon, it is possible to treat the entire process of constructing a syntactic structure as a matter of connecting X-bar structures to each other in the appropriate syntactically required manner (see Stevenson, 1990, 1993, for a similar proposal; see also Chomsky, 1992; Frank, 1992; Joshi, 1985). As discussed earlier, argument structures do much of the work of constraining what the phrases appearing with a word are like, and these constraints are enforced by syntactic princi-

[1] Our thematic grid notation differs slightly from related forms in the literature (e.g., Levin & Rappaport, 1986). However, the notion *thematic grid* is at best shorthand for a more complex argument structure representation, in which a number of distinctions (core–noncore, external–internal, direct–indirect, and probably argument–adjunct), as well as the identity of assigned thematic roles, are all derivable from more basic properties of the representation, possibly in interaction with the syntactic system. See Hale and Keyser (1992), Pinker (1989), and Rappaport and Levin (1988).

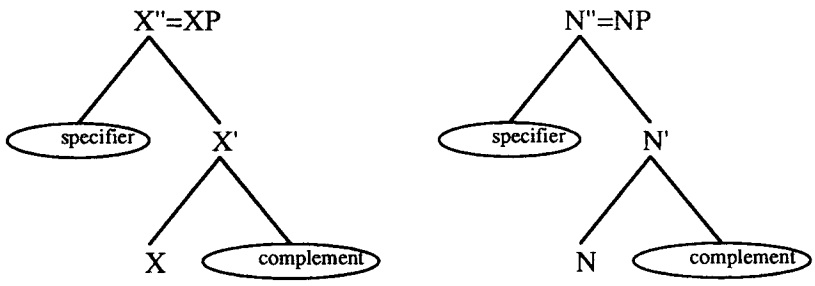

Figure 1. A generic X-bar (X') structure on the left and an X-bar structure for a noun on the right. NP = noun phrase.

ples (e.g., the Theta Criterion and the Projection Principle in Government-Binding theory [Chomsky, 1981]; other theories have alternative formulations), in combination with a set of rules linking positions in argument structures to positions in syntactic structures.[2] With X-bar structures linked directly to individual lexical items, the rules linking arguments to syntactic positions can be specified by directly linking positions in a lexical entry's argument structures to the corresponding positions in the lexical entry's X-bar structures. These and other syntactic constraints (e.g., to enforce relationships between pronouns and their antecedents) will have the effect of preventing or promoting connections between different X-bar structures, and thus this proposal assumes a central role for syntactic constraints in processing. Although the theory does not include a separate parser to construct a phrase structure representation independent of the lexical items in a sentence, that should not be confused with the claim that no syntactic constraints or representations are present at all.

Putting together all of the information just described, the lexical representation for a word includes a representation of the word's phonological form, orthographic form, semantics, grammatical features (including grammatical category), morphology (at least inflectional), argument structure, and X-bar structure. Words associated with more than one representation at one of these levels have all representations listed as alternatives. Comprehension involves computing a single alternative at each level when a word (ambiguous or not) is encountered.

Grammatical and Probabilistic Relationships Among Types of Lexical Information

Previous models of the lexicon have assumed that it represents associations among the orthographic, phonological, and semantic codes for words. In Forster's (1976) model, words were represented in a master file or lexicon with pointers to entries in orthographic, phonological, and semantic slave systems. This model represents an early instantiation of the idea that the connection structure of the lexicon encodes relationships among different types of lexical information. In McClelland and Rumelhart's (1981) model, the pattern of connections between units encoded hierarchical information about words, letters, and letter features. Extending this general idea to the other types of information that we have situated in the lexicon allows many aspects of grammatical knowledge to be represented. Consider, for example, the fragments of lexical representations in Figure 2 for verbs that can trigger the MV/RR ambiguity (e.g., *examined, raced*). The left half of the figure illustrates an obligatorily transitive verb such as *examined,* which has ambiguous tense morphology and voice but is unambiguous in its argument structure. The right half of the panel illustrates a verb, such as *raced,* which has two alternative argument structures; other verbs can have even more argument structure options. Only three levels of representation are shown in this simplified figure, with separate units representing the alternatives. Thus, the tense morphology level has the alternatives past tense and past participle, the voice level has the alternatives active and passive, and the argument structure level is shown with the transitive (assigning both an agent and a theme thematic role) and, in the right-hand figure, the intransitive (assigning only an agent) core thematic grid.[3]

As in earlier models, we can encode what people know about the relations among these types of information in terms of the connections between units. We assume, first, that where syntactic constraints permit a relationship between two types of information (e.g., passive and past participle, active and transitive),

[2] Specifying the linking rules is beyond the scope of this article. Their formulation depends on a number of theory-internal syntactic details and on a more finely articulated theory of argument structure. See most of the references cited previously in the discussion of argument structure.

[3] It should be apparent that these units are placeholders for more complex representations whose details are important but not immediately relevant to the level at which we are describing the behavior of the system. For example, we have made the simplifying assumption that these two lexical representations are independent of one another and are essentially linked bundles of features. An alternative formulation is a much more distributed lexical representation, such that abstract features such as *active voice* are connected to all verbs with frequency-determined weights. In the examples in Figure 2, both *raced* and *examined* would be connected to the same transitive and intransitive nodes, but with varying weights (e.g., the weight on the connection between *raced* and intransitive would be strong, but the weight between *examined* and intransitive would be effectively zero). This more distributed representation has desirable consequences discussed in later sections, but it admits the classic "binding problem" in networks (Hinton, McClelland, & Rumelhart, 1986): Abstract units such as agent, transitive, and so on, may need to be activated and linked to several different words in all but the simplest sentences.

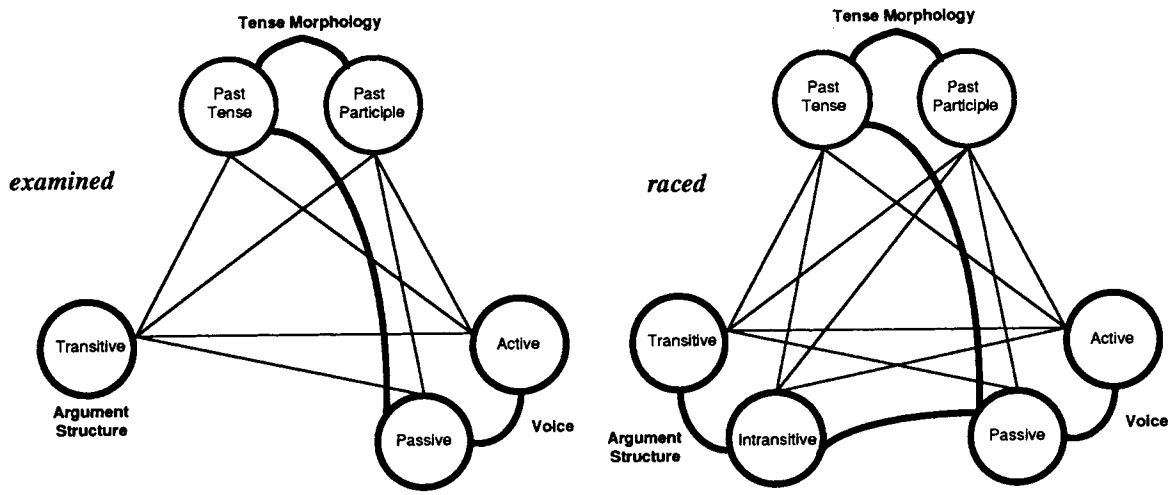

Figure 2. A portion of the lexical representation for the verbs *examined* (left) and *raced* (right).

the connections are excitatory, as shown with straight lines; where the grammar rules out a relationship between two alternatives (e.g., past tense and passive), the connection between the relevant units is inhibitory, shown with thick curved lines.[4] Second, we assume that alternatives of the same type (e.g., active and passive voice) are mutually inhibitory (Elman & McClelland, 1984). Structured in this way, the lexical entry captures some important interdependencies between these three levels of representation, particularly that the passive voice (as in the reduced relative construction or in simple passives such as *The horse was raced*) is congruent with only one alternative at each of the other two levels: the transitive argument structure and past participle tense morphology, respectively.

Also in keeping with earlier models of the lexicon, we assume that each component of a lexical entry carries information about its frequency of occurrence in the language. For example, the representation of the verb *raced* includes the information that it has two associated morphological tense forms, simple past tense and past participle; the frequency with which *raced* occurs with each form would be encoded as part of this representation (Burgess, 1991; Trueswell et al., 1994). As in many models of word recognition, we assume that frequency information is encoded by activation level, although there are other possible implementations (e.g., by encoding individual instances, by the values of weights on connections).

Processing Issues

In resolving ambiguities, the processing system exploits four main characteristics of language: First, grammatical knowledge strongly constrains the potential interpretations of an input. Second, the different types of information associated with a word are not independent of one another, so that progress in resolving an ambiguity at one level provides information relevant to resolving ambiguities elsewhere in the system. Third, a word will not necessarily be equally ambiguous at all levels of representation. For example, a word can be ambiguous as to tense but unambiguous with regard to grammatical category. Fourth, even when the grammar admits multiple alternatives at a given level of representation, they often differ substantially in frequency and thus a priori probability of occurrence. Ambiguity resolution is therefore a classic example of a constraint satisfaction problem (McClelland, Rumelhart, & Hinton, 1986): Multiple interdependent, partially redundant, probabilistic sources of information interact to allow the system to settle on an interpretation at each level.

The computational properties of the constraint satisfaction mechanisms relevant to our proposal have been studied in considerable detail (MacWhinney & Bates, 1989; McClelland, 1987; Rumelhart, 1977; St. John & McClelland, 1990). Constraint satisfaction concepts are beginning to have a significant impact on linguistic theory as well, particularly in morphology and phonology (e.g., Prince & Smolensky, in press, and citations therein). Connectionist models provide one way of implementing constraint satisfaction, but there are also nonconnectionist schemes (e.g., Mackworth, 1977). Our focus is on the nature of the constraints that enter into the processing of syntactic ambiguities; our claims are largely neutral with respect to whether this process is realized by a connectionist network, a production system, or some other means.

For descriptive purposes, we assume the general framework of an interactive-activation model (Elman & McClelland, 1984; McClelland & Rumelhart, 1981). Such models use a basic activation metaphor in which units (or sets of units) corresponding to each type of information are activated in the course of processing. Although it appears innocuous and well grounded in previous modeling research, this assumption has some potentially controversial implications concerning the treatment of syntactic information. Syntactic structure, in our view, consists primarily of connected pieces of X-bar structure encoded with

[4] These inhibitory connections reflect grammatical prohibitions; we leave aside the issue of whether these grammatical constraints are represented elsewhere as part of syntactic knowledge or whether the inhibitory connections themselves are the comprehender's primary representation of the grammatical constraints.

individual lexical items. Like meanings, tenses, argument structures, and every other part of a lexical representation, X-bar structures are assumed to be activated in the course of processing. Thus, our approach entails the idea that syntactic structures can be partially activated, a concept at odds with the earlier view that syntactic processing involves constructing one or more representations incrementally.

The interactive–activation model entails several other claims, which can be considered with respect to Figure 2. First, processing involves the spread of activation between units in the system (initiated by input from orthographic or phonological representations not shown). The degree of activation is an index of the amount of evidence in favor of a particular hypothesis (e.g., that the morphological form is past tense or past participle), and the behavior of each unit in the system depends on the behaviors of the other units to which it is directly or indirectly connected. The net activation of a unit is dynamically updated to reflect these effects. Second, disambiguation involves activating one alternative of a given type and inhibiting all others of this type. We view this as a winner-take-all process of the sort implemented in previous interactive–activation models (e.g., Elman & McClelland, 1984). Third, processing is *analytically exhaustive,* meaning that disambiguation must be achieved at all levels of representation. It is the contingencies among different aspects of lexical representations that enable the constraint satisfaction process; thus, the comprehension system does not have the option of ignoring individual types of lexical information. This strong assumption will probably have to be relaxed in order to accommodate cases in which the communicative goals of the reader or listener can be achieved with only a partial analysis of a sentence, but we view these as degenerate cases.

Contextual Constraints

In addition to constraints that hold between various aspects of lexical representations, sentence and discourse contexts also constrain lexical representations during processing (e.g., Rayner & Pollatsek, 1989). Although it is clear that context affects lexical processing, questions remain concerning what kinds of contextual information facilitate processing, what processes are facilitated, and what factors influence the degree of contextual effect. For example, many studies have assessed the processing of words in congruent, incongruent, or neutral contexts (Fischler & Bloom, 1979; Stanovich & West, 1979). Congruency is defined operationally, on the basis of ratings, intuition, or Cloze value, rather than in terms of the types of information that cause the context to be congruent or incongruent. The same questions arise in connection with MacWhinney and Bates's (1989) competition model, which assumes that languages provide "cues" that interact ("compete") with one another during processing; Gibson (1992) criticized this model for failing to provide an independent characterization of what kinds of information could potentially serve as cues.

One way to view context effects is in terms of their relevance to the task of resolving lexical ambiguities. By hypothesis, contexts are informative to the extent that they affect choices between alternatives at one or more levels of lexical representation. A highly constraining context is one that provides information that disambiguates at several levels. The limiting case is a context in which a target word is entirely predictable; that is, the context provides information that disambiguates the identity of the word itself. A less constraining context provides information relevant to some of the ambiguities associated with a word. For example, the past versus past participle tense morphology ambiguity of *raced* is resolved from the immediately preceding context *had,* which forces the past participle interpretation, but encountering *had* in no way guarantees that the next word will be *raced* or even that it will be a verb.

These considerations suggest that there are two main sources of information relevant to ambiguity resolution. First, there are dependencies among the different types of information stored as part of a word's lexical entry, as discussed earlier. There are also dependencies between a word and the context in which it occurs, emphasized in earlier discussions of interactive processing (e.g., Marslen-Wilson, 1975; McClelland, 1987). These dependencies hold wherever contexts provide information that is relevant to resolving an ambiguity at one of the levels of representation in the lexical entry. We would therefore expect to observe a broad range of outcomes from the interaction between lexical and contextual sources of constraint in the course of the ambiguity resolution process. In the well-studied area of meaning ambiguity, this broad range of outcomes has been obtained: Some studies show activation of multiple meanings of ambiguous words in biasing contexts (e.g., Swinney, 1979; Tanenhaus et al., 1979), whereas other studies using similar methodologies have yielded evidence for selective activation of the contextually appropriate meaning (e.g., Simpson, 1984; Tabossi et al., 1987).

Although the processing system permits this broad range of outcomes, some general tendencies regarding these interactions have been noted; recall Marslen-Wilson's (1987) observation about bottom-up priority in lexical processing and the Duffy et al. (1988) result that context could promote an alternative but not eliminate competitors. Kawamoto's (1988, 1993) model instantiates this view, insofar as it was structured so that the associations between different types of lexical information (alternative meanings, orthography, phonology) were stronger than the associations between contextual information and specific parts of the lexical entry (e.g., one of the meanings). In our view, bottom-up priority derives from a basic characteristic of language: The kinds of information provided by natural language contexts tend to be useful in deciding between alternatives at a given level of representation but much less effective at preselecting one of the alternatives (Seidenberg et al., 1982), as in the *had raced* example. Certainly, some contexts are so constraining as to make a particular word highly predictable (*I drink my coffee with cream and),* and the processing system can apparently exploit this degree of contextual constraint when it is available (Fischler & Bloom, 1979). However, this high degree of predictability seems to be achieved relatively infrequently, at least in English texts (Gough & Cosky, 1977). Thus, the nature of contextual constraints is such that they will typically provide useful information once lexical processing has yielded partial activation of multiple alternatives, but they typically do not provide sufficient information in advance to restrict activation to the contextually appropriate alternative. The combination of these properties of contexts with the availability of frequency information at each level of ambiguity in the lexicon yields a

processing system that is contextually constrained but lexically dominated.

Processing a Sentence

Having described both the representations and the processes that operate in this framework, we can now illustrate how they function together by working through a simple example, the sequence *John cooked.* A subset of the representations that will be activated as these two words are interpreted is shown in Figure 3. The top part of the figure shows information about *John,* the middle shows *cooked,* and the bottom shows the linkages between the two words.

When *John* is encountered in the input, its associated X-bar structure (an NP) is activated, as is its grammatical category (noun). Because of its semantics (animate, human, etc.), the representation of the agent role in its lexical entry is activated, with other roles (experiencer, theme, goal, etc.) activated to a lesser degree.[5] Lexical representations also include a representation of argument structure, but as *John* has no arguments, its structure is null. In addition, various other elements of *John*'s lexical representation are also activated even though they are not shown in the figure, including third person, singular number, and male gender.

The next word is *cooked,* shown in the middle panel. Its semantics, grammatical category, and voice are activated, among other representations. Because of a frequency bias, and perhaps because of contextual factors, the active interpretation of voice is more strongly activated than the passive interpretation. The middle panel of Figure 3 also shows the three alternative core thematic grids for *cooked,* each associated with an X-bar structure, with each of the roles in each grid linked to some position in the associated X-bar structure.[6] These X-bar and argument structures become activated (to varying degrees depending on frequency), along with all other components of the lexical entry. During the course of processing, the system must settle on a single argument structure and X-bar structure for *cooked.* Syntactic constraints will also force a thematic role to be assigned to each noun phrase, and the thematic role assigned will have to be the role linked to the position where the noun phrase attaches in the syntactic structure.

For the sake of this illustration, we have assumed that the ⟨agent theme⟩ (transitive) grid is more highly activated than the two other alternatives in the middle panel of Figure 3. A bias toward a particular argument structure for *cooked* will also affect the choice of the X-bar structure, as indicated by arrows in Figure 3 between argument structures and X-bar structures.[7] Even prior to the selection of a single argument structure, however, syntactic constraints permit only a few candidate syntactic structures, with each one corresponding to a different choice of X-bar structure for *cooked.* These X-bar structures will each be partially activated to some degree, depending on the strength of their support from the syntax and from other parts of the system (e.g., their associated argument structures), and they will compete with each other just as other representations at the same level do within a single lexical entry. Thus, throughout the processing of an input, current syntactic hypotheses (partially activated X-bar structures and partially activated connections between X-bar structures) will continue to interact with other lexically based frequency and contextual biases (over argument structure, tense, voice, etc.).

With both *John* and *cooked* in the input, the computation of the relationship between them begins. The system must determine how their respective X-bar structures are connected as well as which thematic role *John* receives (and from which grid it is assigned). In practice, because argument structures and X-bar structures are tightly linked, determining how *John* is assigned a role will determine how the X-bar structures are linked, and vice versa. Large parts of these operations will depend on which thematic role *John* is assigned, and a number of constraints will enter into this decision. First, the thematic role options that are provided by the argument structure options of *cooked* will constrain the choice of role for *John.* The only possibilities are agent, assigned either from the ⟨agent⟩ (intransitive) or ⟨agent, theme⟩ (transitive) grids, or theme, assigned from the ⟨theme⟩ or ⟨agent, theme⟩ grid. The role assignment process will be affected by (a) frequencies of alternative argument structures (which contain different roles), (b) semantic constraints or frequency biases in the lexical entry of *John* for certain roles (e.g., agent) over others, and (c) contextual constraints (e.g., plausibility, various discourse biases). These factors will operate as parallel constraints and will directly influence the activation of the various thematic role alternatives in the lexical entry for *John.* Similarly, the process of choosing an argument structure for *cooked* will involve constraints from frequency biases and possibly from contextual influences; of course, choosing a thematic role and choosing an argument structure will proceed in tandem and will strongly constrain each other.

The bottom of Figure 3 shows the final linking of *John* and *cooked,* with the assumption that the agent role for *John* is most active and that the transitive ⟨agent, theme⟩ grid and its associated X-bar structure are more highly activated than both the

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[5] Partial activation of alternative roles for nouns, in advance of any verbs in the input, will be crucial for accounts of language comprehension and ambiguity resolution in languages such as Japanese and German, in which the verb can appear sentence-finally. In this view, comprehenders of these languages will have partially activated hypotheses about the roles of the various nouns in the sentence well in advance of encountering the verb. Such languages tend to have rich case marking on nouns (Hawkins, in press); this information signals grammatical roles such as subject and object to the comprehender and clearly would provide strong constraints on thematic role activation.

[6] We assume that the X-bar structures for the lexical entries of verbs are linked directly to higher level X-bar structures (represented by the node labeled *S* in Figure 3; however, see Chomsky, 1986, for a more recent proposal), so that when a verb phrase (VP) X-bar structure is activated, the associated higher structure is also activated. This is particularly relevant to the claim that thematic roles are linked directly to positions in X-bar structures, because we assume that external arguments (and some internal arguments) are linked to positions in these higher X-bar structures. This stipulation could be eliminated, but this is well beyond the scope of the current work.

[7] Additional syntactic constraints, beyond the argument structure/X-bar linking, will also influence the choice of structure. We are obviously glossing over some significant syntactic detail here, as elsewhere. The detailed explanation of the operation of the syntactic component of the system will depend hugely on a choice of syntactic theory, and as our focus is on lexical mechanisms, we remain neutral on syntactic detail.

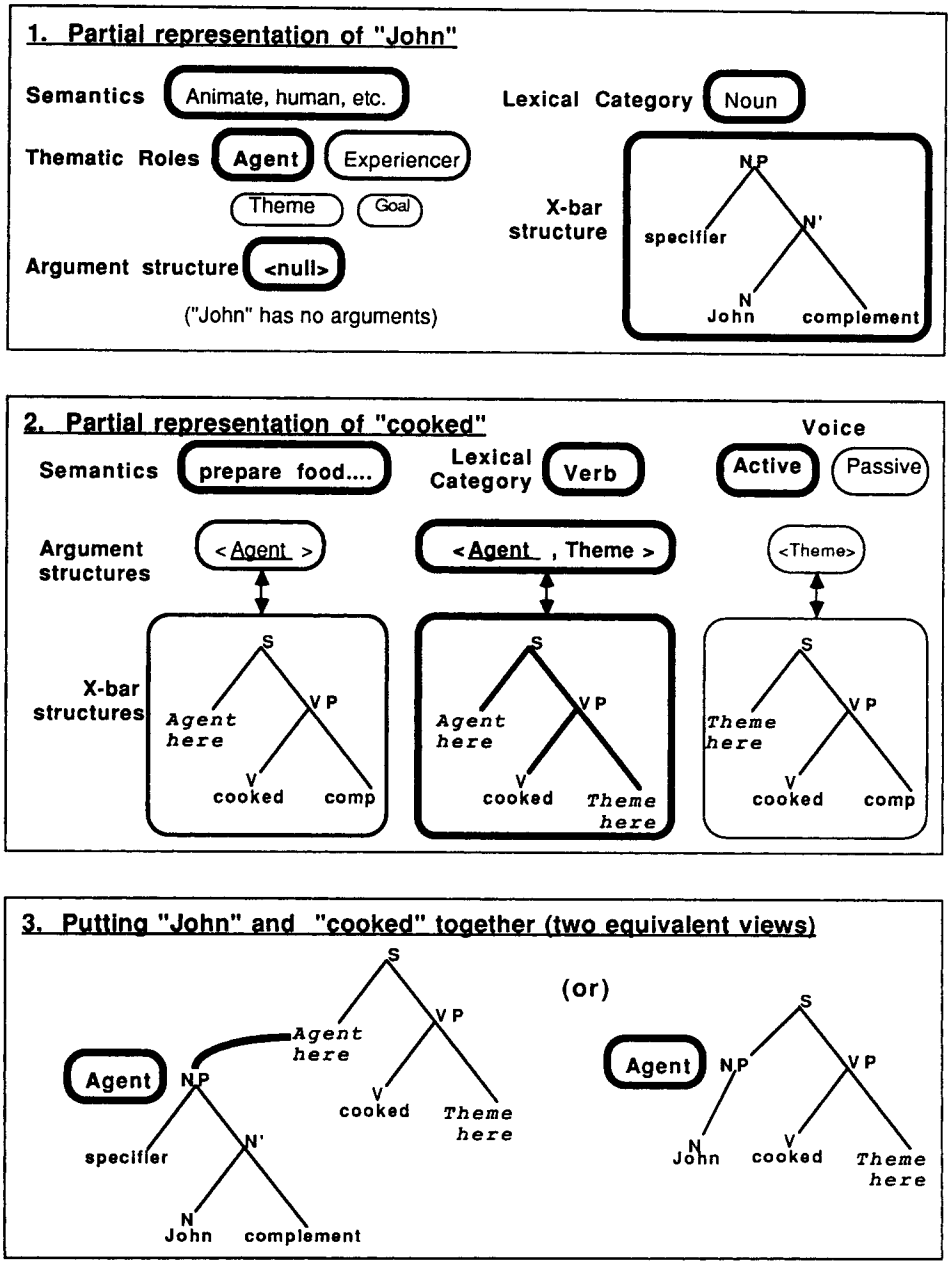

Figure 3. The process of comprehending *John cooked.* Parts 1 and 2 are partial lexical representations of these words. For simplicity, most excitatory and inhibitory connections between components of lexical representations have been omitted from Parts 1 and 2, and some intermediate nodes have been omitted from the verb (V) X-bar structures (e.g., V'). Part 3 shows the linking of X-bar structures and thematic role assignment. A simplified X-bar structure, omitting some nodes, is shown at the right of Part 3. NP = noun phrase; N = noun; VP = verb phrase; comp = complement; S = sentence.

⟨theme⟩ grid (because of the bias to assign the agent role to *John*) and the intransitive ⟨agent⟩ grid (perhaps because of a frequency or discourse bias for the transitive interpretation of *cooked*). The X-bar structure of *John* links to the X-bar structure for the transitive argument structure of *cooked,* with the result that *John* receives the agent thematic role and the system is now waiting for an additional NP to receive the theme role that the transitive argument structure contains. This process can be viewed as simultaneously satisfying multiple constraints over multiple levels of representation, with the activation of alternative lexical representations varying as a function of the constraints.

The processing of this simple two-word input is thus a form of ambiguity resolution. The fact that the noun may receive sev-

eral alternative thematic roles and the fact that the verb is associated with more than one argument structure create ambiguities that must be resolved in the comprehension process. This example illustrates a crucial difference between this approach and the garden path model. The focus of the garden path model was on syntactic phrase structure ambiguity; in this example, the syntactic ambiguity concerns the sort of verb phrase to construct for *cooked*. Syntactic structures were assumed to be built on the basis of phrase structure rules, and proposals about the architecture of the parser described strategies for dealing with ambiguities defined at this level. The assignment of thematic roles and other aspects of comprehension were secondary and temporally distinct. By contrast, we are claiming that this ambiguity has a fundamentally different character: It is lexical insofar as it derives from the fact that the lexical representation of a verb such as *cook* contains multiple argument structures. The ambiguity is resolved not by strategies governing the application of structure-generating rules but by the processes that govern the resolution of other types of lexical ambiguities.

Applications to Minimal Attachment Ambiguities

Having worked through a simple example, we are now prepared to apply our account to three well-studied syntactic ambiguities in English. Previous accounts have viewed these ambiguities as subject to the minimal attachment heuristic. We begin with the MV/RR ambiguity that was introduced previously and then show how two other syntactic ambiguities can also be handled by the lexically based account.

The MV/RR Ambiguity

Given our view of the lexicon, the MV/RR structure can be seen as ambiguous over five different levels of lexical representation: (a) syntactic structure—the MV interpretation has a different syntactic structure (i.e., different linkages of X-bar structures) than the RR interpretation; (b) tense morphology—the *-ed* ending on the ambiguous verb is interpreted as a past tense marker in the MV interpretation and as a past participle marker in the RR interpretation; (c) voice—active for MV, passive for RR; (d) argument structure—the RR interpretation requires a transitive (typically ⟨agent, theme⟩) argument structure, whereas the MV interpretation may take a variety of structures (transitive, intransitive, etc.); and (e) assignments of thematic roles to nouns in the sentence—the NP preceding the verb is the external argument in the MV sentence (receiving the agent role when the grid is ⟨agent, theme⟩), whereas it is the direct internal argument (usually theme) in the RR sentence.

These alternative interpretations are not independent of one another: Some pairs of alternatives cannot co-occur, some rarely co-occur, some frequently co-occur. Our theory is that the resolution of the MV/RR ambiguity depends on complex interactions among these factors that are determined by the properties of specific verbs and sentence contexts. In order to explore the interactions among these constraints, we first consider the simpler case of verbs that create MV/RR ambiguities but have no argument structure ambiguity because they are unambiguously transitive. These are verbs such as *examine* and *enjoy* for which the intransitive form is ungrammatical (e.g., **John examined; The audience enjoyed*). A fragment of a lexical representation for such verbs was shown in the left panel of Figure 2; there we also showed the relationship between two other levels of lexical ambiguity, tense morphology and voice. Now it is necessary to introduce a bit more complexity, as we want to consider not just the ambiguity of a verb such as *examined* in isolation but the range of options that are available when it appears in a string that creates the MV/RR ambiguity. For example, in the string *The witness examined,* there is no argument structure ambiguity for the obligatorily transitive *examined,* but the four other ambiguities listed earlier remain. The interrelationships among the alternatives at these levels of representation for *The witness examined* are illustrated in Figure 4.

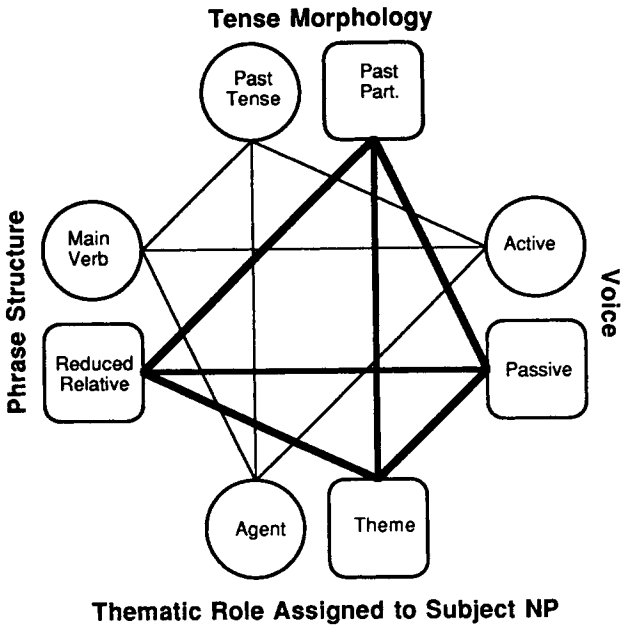

Figure 4. Input properties allowed to co-occur by grammatical constraints. The lines indicate permitted co-occurrences. Thin lines and round nodes correspond to the main verb interpretation; thick lines and square nodes represent the reduced relative interpretation. NP = noun phrase; part = participle.

Each of the levels of information over which *The witness examined* is ambiguous admits two alternatives. The alternatives that participate in the MV interpretation are shown with circles, and those that participate in the RR interpretation are shown with squares. Two of the four alternatives—tense morphology and voice—are parts of the lexical representation of the verb *examine.* The phrase structure units, MV and RR, represent the corresponding phrase structures, so each unit is shorthand for a particular set of X-bar structures and connections between X-bar structures that can become activated during processing. "Thematic role assigned to subject" represents processes of assigning thematic roles to arguments, specifically to the subject NP *the witness.* The transitive argument structure unambiguously requires the thematic roles agent and theme, but the order in which these roles are assigned to the NPs can vary. In *The witness examined by the lawyer was lying,* the subject NP *the witness* is assigned the theme role by *examined,* and

the lawyer the agent role. In *The witness examined the evidence,* agent is assigned to *the witness* and theme to *the evidence.* The decisions about which NP receives which role are determined both by syntactic context (an argument must be in the correct position in the syntactic structure to receive a thematic role from something that has a role to give) and context (e.g., whether it is more plausible for *the witness* to be the agent or the theme).

In Figure 4 we have used connections between units to represent which combinations of properties are permitted by the grammar of English. The connections admit two parses, the MV interpretation, shown with thin lines, and the RR interpretation, shown with thick lines. Because Figure 4 represents the grammatical constraints that apply and the alternative interpretations that are available at the point that *The witness examined* has been encountered during parsing, some possibilities that are admitted by the verb *examined* in isolation (shown previously in Figure 3) have been ruled out by the syntactic context. For example, an active past participle interpretation of *examined,* as in *the witness had examined,* is eliminated because no form of *have* is in the input. With this and other alternative hypotheses already ruled out, each node in Figure 4 participates in only one parse. Any information concerning which interpretation at any level is correct will therefore affect both that level of representation and the other levels as well.

One such source of constraint is the relative frequency of alternative argument structures. Although they are not shown for the obligatorily transitive verb *examined* in Figure 4, the MV interpretation can accommodate several argument structures, including both transitive and intransitive. By contrast, the RR interpretation requires a transitive argument structure. Argument structure frequency should therefore have a substantial effect on MV/RR ambiguity resolution because verbs that do not permit a transitive argument structure (e.g., *sleep*) cannot appear in the RR construction, and verbs that only rarely appear with a transitive argument structure only rarely appear in the RR construction. Thus, the extent to which an ambiguity is resolved in favor of the RR construction is predicted to be in part a function of the frequency of a verb's alternative argument structures: The lower the frequency of the transitive argument structure for a verb, the less likely the ambiguity will be resolved with the RR interpretation.

MacDonald (1994) tested this prediction by using verbs with varying argument structure frequencies in RR sentences, such as *The rancher knew that the nervous cattle pushed/moved/driven into the crowded pen were afraid of the cowboys.* The biased transitive condition contained ambiguous verbs (e.g., *pushed*) that were selected to have a higher frequency transitive than intransitive argument structure. In the biased intransitive condition, ambiguous verbs (e.g., *moved*) were more frequent in intransitive than transitive structures. These two conditions were compared with a control condition with morphologically unambiguous verbs such as *driven.* MacDonald compared self-paced reading times in the disambiguation region (*were afraid*) for the two ambiguous conditions with the unambiguous control. Reading times for the biased intransitive (*moved*) sentences were 33 ms per word longer in this region than in the unambiguous condition, a reliable difference, but when the ambiguous verb was biased transitive (*pushed*), reading times at the disambiguation did not differ from unambiguous times. This result indicates that lexical frequency asymmetries in the alternative argument structures have a strong effect on interpretation of the MV/RR ambiguity.

A second source of constraining information is tense morphology: Whereas *examine* has the same forms for past tense and past participle, verbs such as *take* and *wear* have different inflections in the two cases. Thus, *examined* in *The witness examined* is ambiguous regarding tense morphology and is therefore compatible with both MV and RR structures, but *took* in *The witness took* can only be a past tense form and therefore is compatible only with the MV structure. Once the morphological information associated with verbs such as *take* has been recognized, it completely resolves the ambiguities at the other levels of representation.

When a verb is morphologically ambiguous, such as *examine,* the relative frequencies of the alternative tenses are informative (Burgess, 1991; Tabossi, Spivey-Knowton, McRae, & Tanenhaus, 1994; Trueswell et al., 1994). For example, consider the three obligatorily transitive verbs *enjoyed, examined,* and *reviewed.* According to Francis and Kučera's (1982) corpus, *enjoyed* is used much more often as a past tense than as a past participle, *examined* is approximately equibiased between the two forms, and *reviewed* is more often a past participle than a past tense. Assuming that the processing system exploits this frequency information, as it does in the case of meaning and argument structure ambiguity, then *enjoyed* should be easier to comprehend in a past tense construction than a past participle, whereas *reviewed* should be comprehended more easily in a past participle construction than in a past tense construction. That is, frequency should exert effects similar to morphological information on ambiguity resolution. The only difference is that whereas unambiguous morphology is associated with only a single alternative, frequency provides more probabilistic disambiguation in favor of one alternative. The specific prediction from these observations is that reduced relative sentences such as *The performance reviewed/enjoyed by the critic was a great success,* should be more readily comprehended with a past participle-biased verb such as *reviewed* than with a past tense-biased verb such as *enjoyed.* To our knowledge, experiments specifically manipulating tense frequency have not been conducted; however, MacDonald, Pearlmutter, and Seidenberg (in press) and Tabossi et al. (1994) reported post hoc examinations of stimulus sets and found a relationship between past participle frequency and the acceptability of RR interpretations. There also appears to be a clear role for tense information in conjunction with contextual constraints, to which we now turn.

Contextual Constraints

In addition to lexical frequency information, the MV/RR ambiguity is also affected by constraints provided by the surrounding context. Obvious examples of contextual effects include the elimination of alternative interpretations such as *the witness had examined* and *the witness was examined* for the string *the witness examined,* by virtue of the fact that the crucial words *had* or *was* are not in the input. More subtle effects are also possible with contexts that do not definitively eliminate alternatives but merely make one interpretation more plausible

than others. Consider again the animacy manipulation investigated by Trueswell et al. (1994) in sentences such as *The witness/evidence examined by the lawyer was useless.* Trueswell et al. (1994) found that ambiguous sentences resolved with the RR interpretation were more difficult than unambiguous controls only when the subject NP was animate (*witness examined*), supporting the MV interpretation, but not when the subject NP was inanimate (*evidence*), which promoted the RR interpretation. These effects have been replicated and extended to include plausibility effects that do not depend on animacy (Burgess, 1991; MacDonald, 1994; Pearlmutter & MacDonald, 1992; Tabossi et al., 1994), and similar kinds of context effects have been demonstrated for discourse-level contexts (Ni & Crain, 1990; Spivey-Knowlton, Trueswell, & Tanenhaus, 1993; Trueswell & Tanenhaus, 1991, 1992), as initially suggested by Crain and Steedman (1985; Altmann & Steedman, 1988).[8]

These results provide strong evidence for immediate effects of contextual constraints on the resolution of MV/RR ambiguities, but other studies in the literature have failed to show such effects. Four studies (Britt, Perfetti, Garrod, & Rayner, 1992; Ferreira & Clifton, 1986; Rayner et al., 1983; Rayner, Garrod, & Perfetti, 1992) found that in helpful contexts, the ambiguous RR interpretation still yielded reliably longer reading times than unambiguous control sentences, results that provided important support for the garden path model. Eight other studies have provided evidence for an early effect of discourse context on ambiguity resolution. The presence of helpful context yielded ambiguous RR reading times that were not reliably longer than unambiguous control sentences (Burgess, 1991; MacDonald, 1994; Ni & Crain, 1990; Pearlmutter & MacDonald, 1992; Spivey-Knowlton et al., 1993; Tabossi et al., 1994; Trueswell & Tanenhaus, 1991, 1992; Trueswell et al., 1994).

There has been considerable controversy regarding why such seemingly similar studies should yield such disparate results. Some researchers have pointed to differences in reading time measures as the source of the inconsistent results (e.g., Clifton & Ferreira, 1989). The different findings do not appear to be due solely to the choice of measure, however, as both self-paced reading (by word or by phrase) and eyetracking measures have been used in studies that yielded results favoring minimal attachment (e.g., Ferreira & Clifton, 1986) as well as studies favoring early interaction with context (e.g., Trueswell & Tanenhaus, 1991, 1992). The exact relationship between these measures is still controversial; some have suggested that self-paced reading measures overestimate the effects of context compared with eyetracking (Ferreira & Clifton, 1986; Rayner et al., 1992), but others have suggested that single-word, self-paced reading underestimates context effects, particularly in cases in which the ambiguous word and contextual information may be perceived in the same eye fixation (Burgess, 1991; Spivey-Knowlton et al., 1993; Tabossi et al., 1994). Whatever the outcome of that debate, the choice of reading measures alone does not appear to dictate whether context effects are observed.

The choice of contextual constraint also does not by itself differentiate the two types of results. Three kinds of contextual information have been investigated. One, the manipulation of verb tense to affect the felicity of noun modification, has been investigated by Trueswell and Tanenhaus (1991, 1992), who obtained results favoring the early effects of context on syntactic ambiguity resolution. The other two contextual manipulations have been associated with both minimal attachment and interactive results. The plausibility manipulation of the *evidence examined* type has been used in studies supporting minimal attachment (Ferreira & Clifton, 1986; Rayner et al., 1983) and in ones supporting an interactive account (Burgess, 1991; MacDonald, 1994; Pearlmutter & MacDonald, 1992; Tabossi et al., 1994; Trueswell et al., 1994). Similarly, discourse manipulations that affect the felicity of noun modification have been used in studies supporting both minimal attachment (Britt et al., 1992; Rayner et al., 1992) and the interactive position (Ni & Crain, 1990; Spivey-Knowlton et al., 1993). Of course, the contextual manipulations in all of these studies were not necessarily equally strong, and some failures to find context effects may be due to weak context manipulations (McClelland, 1987; Trueswell et al., 1994). It nonetheless appears that the type of context manipulation alone does not adequately explain the differing outcomes in the experiments.

A factor that is relevant is the lexical frequency information associated with the verbs that trigger the MV/RR ambiguity (MacDonald, 1994; Pearlmutter & MacDonald, 1994; Spivey-Knowlton et al., 1993; Tabossi et al., 1994; Trueswell et al., 1994). As discussed earlier, the Duffy et al. (1988) lexical ambiguity resolution data and Kawamoto's (1988, 1993) model suggest that for words with a strong frequency bias, contextual support for the lower frequency meaning is generally not strong enough to eliminate the frequency advantage of the higher frequency meaning. The same effects should hold for the aspects of lexical representation relevant to the MV/RR ambiguity: Contextual information should be able to affect the interpretation of the MV/RR ambiguity most clearly when the ambiguous verb is roughly equibiased in its alternative interpretations for tense morphology, argument structure, and voice. The left panel of Figure 5 illustrates this situation for a verb such as *examined,* which has roughly equal past and past participle frequencies. A strong effect of context from *the evidence examined* promotes the RR interpretation, shown with thick lines. When one alternative at some level of representation is much more frequent than another, however, context supporting the subordinate interpretation will be much less effective. This situation is presented in the right panel of Figure 5, which depicts a verb, such as *enjoyed,* that is more frequent as a past tense than as a past participle. This frequency information strongly promotes the MV interpretation, despite the fact that contextual information favors the thematic role assignment corresponding to the

[8] Despite the similarity of their methods and goals, some of these studies arguing for context effects in syntactic ambiguity resolution stem from a much different theoretical position than the one advocated here. Crain, Steedman, Altmann, and colleagues (Altmann & Steedman, 1988; Crain & Steedman, 1985; Ni & Crain, 1990) proposed a two-stage theory in which a modular parser constructs multiple syntactic parses and rapidly passes them to the discourse processor, where one alternative is chosen in light of the current context. In a sense, this position is the syntactic ambiguity equivalent of the "exhaustive access" model of lexical ambiguity resolution (Swinney, 1979), in which multiple interpretations of ambiguous words were passed to a higher level in which one interpretation was chosen. Spivey-Knowlton, Trueswell, and Tanenhaus (1993) provided additional discussion and evaluation of the lexically based versus discourse-based models.

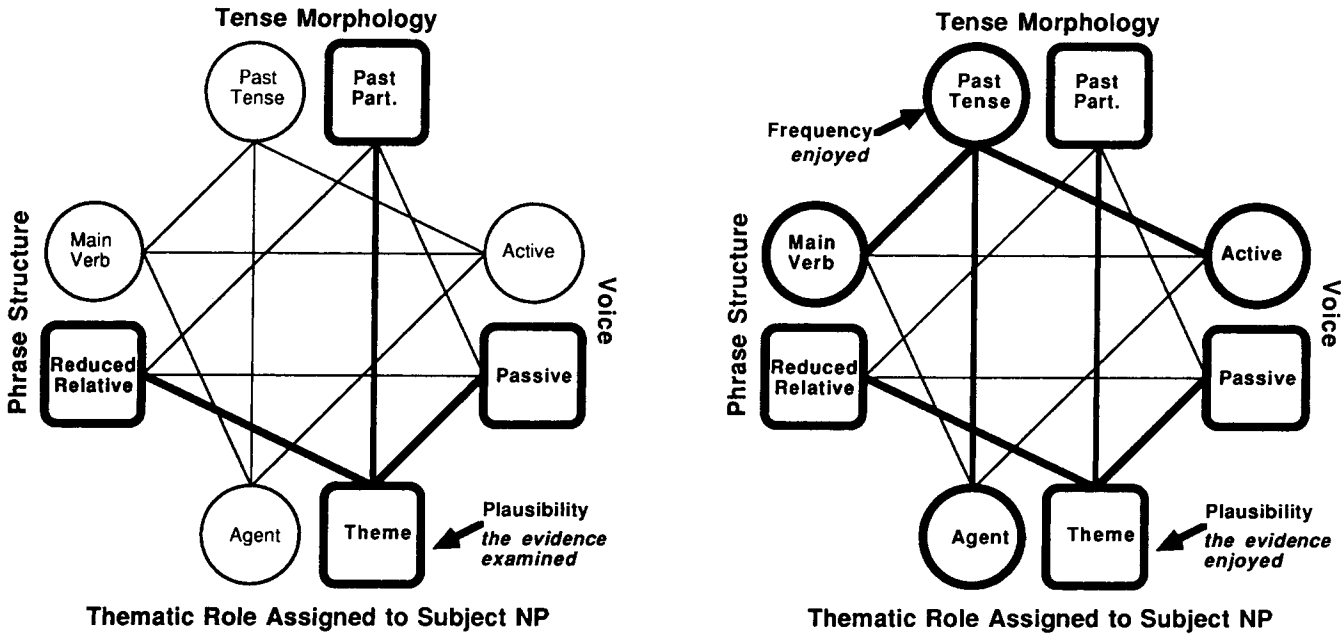

Figure 5. Input properties allowed to co-occur by the grammar. On the left plausibility (*evidence examined*) is supporting assignment of theme role to subject noun phrase (NP), shown by thick lines. On the right, frequency is supporting past tense morphology and plausibility is supporting assignment of the theme role to the subject NP. Part = participle.

reduced relative. This situation is comparable to a sequence such as *The evidence enjoyed.* Here, *enjoyed* is biased to be past tense, but *evidence* does not make a plausible agent of *enjoyed.* The result is that the context does not successfully promote the components of the RR interpretation.

If the effects of contextual information are modulated by lexical frequencies, then it should be possible to reconcile some conflicts in the literature by examining the frequency biases of the ambiguous verbs that were used in different studies. The prediction is that those studies that found that context did influence MV/RR ambiguity resolution tended to use more equibiased verbs, whereas the studies in which helpful context did not affect MV/RR ambiguity resolution used many items that were strongly biased to the MV interpretation, by virtue of frequency biases to one or more components of this interpretation: the past tense, the active voice, or a nontransitive argument structure. Ideally, all three of these frequency biases should be examined for the verbs that were used in previous experiments, and our own intuitions suggest that stimulus materials in these studies do differ on all three dimensions. However, there is currently not enough normative data available about voice or argument structure frequencies to assess even 20% of the verbs that have been used in previous context studies. We therefore tested the frequency bias prediction using only more readily available morphological tense information.

The relative past versus past participle tense frequencies were obtained from Francis and Kucera's (1982) corpus for the ambiguous verbs in the stimuli from 12 studies of context effects in MV/RR ambiguities. The mean past participle frequency was 49.7% for the ambiguous verbs in the four studies that found no context effects (Britt et al., 1992; Ferreira & Clifton, 1986; Rayner et al., 1983, 1992). By contrast, the eight studies that did show that helpful context aided interpretation of the MV/RR ambiguity (Burgess, 1991; MacDonald, 1994; Ni & Crain, 1990; Pearlmutter & MacDonald, 1992; Spivey-Knowlton et al., 1993; Tabossi et al., 1994; Trueswell & Tanenhaus, 1991, 1992; Trueswell et al., 1994) had a mean past participle frequency of 63.0%, a reliable difference, $t(10) = 2.47$, $p < .05$.[9] This result did not change when verbs with fewer than five observations in Francis and Kucera (1982) were removed from the analysis, which indicates that the effect is not attributable to unstable measurements from rare items.

This result clearly shows the interaction between lexical and contextual information: Given a verb with frequency biases that make the reduced relative interpretation a viable option, contextual information can guide the comprehender to one or the other interpretation. The context will have little effect, however, if the lexical biases of the ambiguous verb overwhelmingly favor the main verb interpretation.[10] This pattern is the analog

[9] Trueswell and Tanenhaus (1991, 1992) are treated as one study in the meta-analysis because the same stimulus items were used in both the 1991 and 1992 work. The mean past participle relative frequency for each study can be found in MacDonald, Pearlmutter, and Seidenberg (in press), along with more detailed information about the biasing contexts and reading measures used in each study.

[10] Recall that it is the conjunction of tense, argument structure, and voice information that is important for the reduced relative interpretation. Thus, although the mean 49.7% past participle frequency in the four "minimal attachment" studies is close to equibiased for the tense morphology level of representation, a 63% past participle frequency is more likely to yield an equibiased *conjunction* of all three factors.

in syntactic ambiguity resolution of the Duffy et al. (1988) results for meaning ambiguity: Lexical frequency information has a substantial effect on interpretation of the ambiguity, and contextual information can have the effect of promoting one interpretation of an equibiased item but cannot overcome strong frequency biases to promote a subordinate interpretation over the (frequency) dominant alternative. These results strongly indicate the lexical basis of syntactic ambiguity resolution. We next consider whether a similar account can be applied to two other syntactic ambiguities.

The Noun Phrase/Sentential Complement (NP/S) Ambiguity

This ambiguity, like the MV/RR ambiguity, is triggered by an ambiguous verb, in this case one with both a transitive argument structure and an argument structure assigning the proposition role to a direct internal argument. In the NP interpretation in 6a, the NP *the answer* is assigned the theme role from *knew's* transitive argument structure. In the S (sentential complement) interpretation in 6b, *knew* assigns the proposition role to the embedded clause *the answer was correct.*[11] As in the MV/RR ambiguity, the alternative phrase structures (NP vs. S) are tied to alternative representations of ambiguous verbs. Much like MV/RR ambiguities, NP/S ambiguities can be eliminated for one interpretation with the addition of an optional word, *that,* as in 6c.

6a. knew: ⟨agent, theme⟩ John knew the answer.
6b. knew: ⟨agent, proposition⟩ John knew the answer was correct.
6c. knew: ⟨agent, proposition⟩ John knew that the answer was correct.

The minimal attachment algorithm, when applied to the NP/S ambiguity, yields an initial parse in favor of the syntactically simpler NP interpretation, but a lexically based analysis makes a different prediction: If the relative frequency of the alternative argument structures is coded in the lexicon for each verb, then the extent to which the NP or S interpretation will be preferred for an ambiguous sentence should vary with the argument structure frequencies of the verb. For verbs that are used more frequently with S complements (assigning the proposition role) than NP direct objects, there should be little or no difference in comprehension difficulty between ambiguous and unambiguous sentences requiring the S interpretation, as in 6b versus 6c.

This clear contrast between the lexical and minimal attachment predictions has been intensively investigated, with mixed results. A number of studies have provided evidence for the lexical view (Garnsey, Lotocky, & McConkie, 1992; Holmes, 1987; Holmes, Stowe, & Cupples, 1989; Mitchell & Holmes, 1985; Trueswell et al., 1993). Others have shown support for minimal attachment: that even when verbs are biased toward the S-complement interpretation's ⟨agent, proposition⟩ argument structure, ambiguous S-interpretation sentences (e.g., 6b) were more difficult than their unambiguous counterparts (6c; Ferreira & Henderson, 1990; Frazier & Rayner, 1982). As with the MV/RR ambiguity, these different results do not appear to be due to the choice of reading time measure, as several researchers have found that both eyetracking and self-paced reading produced similar patterns on the same set of materials (Ferreira & Henderson, 1990; Trueswell et al., 1993). Instead, important evidence from Trueswell et al. (1993) points to other lexical effects in this construction.

First, Trueswell et al. (1993) observed that some verbs such as *pray* and *agree,* which some researchers had included in the "S-biased" class, are actually rare in both the S and NP interpretations. These verbs instead appear more frequently in some third construction, such as an intransitive (e.g., *John prayed every night*) or an infinitival complement (e.g., *John agreed to wait in line*). Thus, the presence of a postverbal NP (e.g., *the book* in *John prayed/agreed the book*) indicates that the verb's preferred argument structure is not correct and that some nonpreferred structure is needed. Trueswell et al. argued that slow reading times in such cases, which Ferreira and Henderson (1990) had attributed to the operation of minimal attachment, actually reflect a lexical frequency effect: Contextual information (the postverbal NP) conflicts with a strong frequency bias in favor of the intransitive or infinitival complement argument structure, resulting in a slowdown. This pattern is just what Duffy et al. (1988) found when a semantic context conflicted with a strong frequency bias in favor of one meaning of a word.

Trueswell et al.'s (1993) second observation concerned the cooccurrence information between verbs and the complementizer *that.* In a fragment-completion study, they found that on those occasions when subjects completed a fragment (e.g., *John hinted*) with an S-complement phrase, the extent to which the optional complementizer *that* was included in the completion depended on the verb. For example, 100% of the S-complement completions of *hinted* included *that,* whereas only 17% of the S completions for *wished* included *that.* Juliano and Tanenhaus (1993) subsequently traced the source of *that* preference effects to lexical frequency: Higher frequency verbs omit *that* more often (see also Elsness, 1984; Thompson & Mulac, 1991). Trueswell et al. (1993) found that the variations in *that* preference across verbs accounted for a sizable portion of the variance in reading times of postverbal NPs in strings such as *hinted/wished the hallway.* When the NP (e.g., *the hallway*) followed a verb with a low *that* preference, reading times were short, but when the NP followed a verb with a high *that* preference, reading times on the NP increased. These data show that resolution of NP/S ambiguities is a function of two lexical effects: (a) the relative frequencies of the alternative argument structures, both the argument structures corresponding to the NP and S interpretations and the argument structures for other interpretations such as intransitive and infinitival complement sentences (Trueswell et al., 1993), and (b) a verb's *that* preference (Trueswell et al., 1993), which is dependent on the verb's frequency in the language (Juliano & Tanenhaus, 1993).

Although our account suggests that like the MV/RR ambiguity, NP/S ambiguities should exhibit effects of context, the literature provides little evidence bearing on this prediction. As with

[11] Traditional descriptions of this ambiguity distinguish the noun phrase (NP) and sentential complement (S) phrase structures (reflecting the traditional emphasis on the phrase structure nature of the ambiguity), whereas we are stressing the importance of the ⟨agent, theme⟩ versus ⟨agent, proposition⟩ argument structure ambiguity. We continue to use the traditional NP/S terminology, but we also refer to the argument structure ambiguity when necessary.

the MV/RR ambiguity, one source of contextual constraint is the plausibility of thematic role assignment, in this case role assignment to the NP after the verb. Consider the pair *John admitted the error/hallway.* The NP *the error* makes a plausible theme for the verb *admitted,* but *the hallway* is a highly implausible theme. Because the theme role can be assigned by *admitted* only from its transitive grid, requiring the NP interpretation, this interpretation is favored in the *error* example and discouraged in the *hallway* example. Holmes et al. (1989) did find small effects of thematic role plausibility, but they did not control all of the important lexical factors that Trueswell et al. (1993) have since identified. Indeed, if ambiguity resolution for the NP/S ambiguity works in the same way as resolution of the MV/RR ambiguity and other lexical ambiguities, then a specific pattern of frequency and context effects is predicted: Context effects of the sort studied by Holmes et al. (1989) should be most evident when the ambiguous verb is roughly equibiased in its alternative argument structures. If a verb is overwhelmingly biased toward the NP interpretation, then the relative plausibility of thematic role assignments should have minimal effects. Similarly, the effects of discourse contexts that influence the probability of the use of *that,* such as the formal–informal nature of the discourse (Elsness, 1984) and the presence of adverbs (Thompson & Mulac, 1991), should also be more evident in comprehension of sentences with equibiased verbs than with verbs with a strong "that" preference.

The Prepositional Phrase (PP) Attachment Ambiguity

The third structure we consider is the PP attachment ambiguity, which arises when a PP appears following a verb and its direct object noun. The ambiguity is whether the PP modifies the verb (the verb attachment interpretation) or the direct object noun (noun attachment). In contrast to the other structures discussed earlier, these ambiguities usually do not contain a definitive syntactic disambiguation later in the sentence; only the relative plausibility of the alternatives suggests the preferred interpretation. Some examples can be seen in 7a–7d in which the ambiguous PPs are shown in uppercase letters and the thematic role assigned by the preposition is also shown. Example 7a is most plausible with noun attachment, as shown by the brackets, 7b is most plausible with verb attachment, and 7c–7d show the alternative interpretations for a more ambiguous sentence.

7a. Fred [ordered [a pizza WITH PEPPERONI]] N attachment, attribute
7b. Susan [read [the book] IN A HURRY] V attachment, manner
7c. The spy [saw [the cop WITH THE BINOCULARS]] N attachment, attribute
7d. The spy [saw [the cop] WITH THE BINOCULARS] V attachment, instrument

The brackets in Example 7 suggest that both interpretations are equally syntactically complex, as assumed in many syntactic analyses (e.g., Smith, 1988). However, the syntactic analysis adopted by Frazier (1990) suggests that noun attachment involves the more complex syntactic structure, so that application of minimal attachment yields the verb attachment. As with the other syntactic ambiguities, the results in the literature are mixed: Some studies have shown a verb attachment preference independent of context (Clifton & Ferreira, 1989; Clifton, Speer, & Abney, 1991; Rayner et al., 1983), but others have indicated that certain lexical or discourse conditions can affect attachment preference (Altmann & Steedman, 1988; Britt, 1994; Britt et al., 1992; Rayner et al., 1992; Spivey-Knowlton & Sedivy, 1994; Taraban & McClelland, 1988). Again, these conflicts in the literature may be resolved by close scrutiny of the lexical and contextual effects that enter into ambiguity resolution in this case.

There are three potentially highly constraining sources of biasing lexical frequency information for interpreting this ambiguity (prior to encountering the NP within the PP): the verb, the direct object noun, and the preposition. As noted earlier, the ambiguity relies on the choice of argument structure, and most verbs and nouns allow a number of possible noncore thematic grids with varying frequencies. For example, Spivey-Knowlton and Sedivy (1994) observed that action verbs tend to occur with modifying PPs (conveying instrument or manner roles) more than perception or psychological (mental state) verbs. Although the range of possibilities is often more limited, nouns, which also have argument structure representations in our view, behave similarly. For example, nouns related to communication (*mail, message,* etc.) occur often with theme (*mail about the parking situation*) and goal PPs (*message to Jane*), and, although most nouns are natural with location PPs (*in the room, next to the nightstand*), few occur frequently with a temporal PP such as *in three minutes.* Thus, both the verb and the noun in a given PP attachment ambiguity often have preferences about which thematic role is likely to be assigned by the preposition.[12]

Prepositions also provide highly constraining information, particularly in combination with specific nouns and verbs. Like nouns and verbs, prepositions are associated with argument structures specifying the different thematic roles they are allowed to assign. *Of,* for example, nearly always attaches to a preceding noun (Hobbs & Bear, 1990) and assigns an attribute (*book of poems*) or theme role (*destruction of the city*), whereas prepositions such as *into, onto,* and *to* nearly always assign a goal role (*took the dog into the house*). *With,* on the other hand, assigns a broader range of roles, including manner, instrument, attribute, and location. Disambiguating between noun and verb attachment is therefore a matter of combining preposition-, verb-, and noun-based argument structure frequency biases to determine (a) which role the preposition is assigning and (b) whether the role assigned by the preposition is associated with a grid in the argument structure of the verb or of the noun.

[12] This frequency coding of preferences for different prepositional phrases (PPs), particularly in a distributed representation described earlier, largely eliminates the argument–adjunct distinction that is common to many discussions of PP attachment ambiguities (e.g., Britt, 1994; Clifton, Speer, & Abney, 1991). In our view, an argument is a PP that is strongly (frequently) linked to a word (e.g., the location role for *put*) and an adjunct is one that is weakly (infrequently) linked (e.g., the manner role for *put*). It is possible that the frequency biases that we have described derive from deeper relationships between the semantics of the verbs, nouns, and thematic roles; see, for example, Levin and Rappaport Hovav (1992) and Pinker (1989). This would be perfectly compatible with the current theory; the crucial points here are simply that potentially useful frequency asymmetries exist and that the system is able to keep track of them.

Several studies provide evidence for the importance of some of these lexical factors. Taraban and McClelland (1988) noted that noun versus verb PP attachments yield different thematic role assignments, as in Example 7, and they hypothesized that comprehension difficulties resulted from encountering an unexpected thematic role assignment. They found that the largest determinant of difficulty in interpretation of PP attachments was whether the role assigned by the preposition conformed with the expectations derived from the prior sentence context, not whether it was verb or noun attached. They also demonstrated that contexts could create biases for either the verb or the noun attachment interpretation and concluded that the verb attachment preference, which Rayner et al. (1983) had attributed to minimal attachment, should instead be attributed to biases created by particular lexical items.

Taraban and McClelland (1988) did not investigate whether the thematic role effects were attributable to biases of the verb, the direct object noun, the preposition, or some combination, but more recent research has begun to identify specific constraints. For example, Spivey-Knowlton and Sedivy (1994) found that verb type had a strong effect on interpretation of PPs, in that PPs were much more likely to be attached to action verbs such as *hit* than to perception verbs such as *see*. The computational linguistics literature also suggests that lexically based preferences are a potentially powerful source of constraints. Hindle and Rooth (1993), for example, found that lexically based preferences alone were sufficient to predict correct attachment in more than 85% of their 880-sentence test corpus, whereas minimal attachment was correct only 33% of the time. Thus, a parser that relies on such information will make appropriate attachment decisions more reliably than systems that rely on structure-based heuristics.

We would also expect that the broader discourse context could provide additional relevant information. As with the MV/RR ambiguity, the noun attachment interpretation of this ambiguity involves noun modification. Crain and Steedman (1985) observed that such modification is infelicitous in isolated sentences. Thus, it makes no sense to distinguish the cop in 7d as the one who had binoculars when there is only one cop in the discourse. In the context of several different cops, however, modification becomes much more felicitous, and a number of studies have demonstrated that attachment preferences are modulated by the extent to which it is felicitous to modify the direct object noun (Altmann & Steedman, 1988; Britt et al., 1992; Rayner et al., 1992). Moreover, Spivey-Knowlton and Sedivy (1994) found an interaction between pragmatic and lexical constraints, in that a pragmatic factor affecting felicity of noun modification was limited by the nature of the verb's PP attachment bias. For action verbs, which are strongly biased to have attached PPs, pragmatics had little effect on attachment preferences, but for perception verbs, which are equibiased or have a bias against verb attachment, NP pragmatic constraints had a strong effect on whether the PP would attach to the NP or VP. Britt (1994) found a similar result: that discourse-level effects could override weak verb preferences for PP attachments but not strong ones. These results suggest that the same contextually constrained but lexically dominated relationship that guides resolution of the MV/RR ambiguity and the NP/S ambiguity also guides the interpretation of PP attachments.

Different Context Effects Across Ambiguities?

We have argued that three different kinds of syntactic ambiguity—MV/RR, NP/S, and PP attachment—exhibit the same types of lexical and contextual effects. However, it has been suggested that these structures are not equally affected by contextual manipulations. Some researchers have noted that context effects seem to be more powerful in the PP attachment ambiguity than in the MV/RR ambiguity (Britt et al., 1992; Rayner et al., 1992), perhaps indicating that different parsing heuristics are used in the two syntactic constructions. The lexical approach offers an alternative interpretation, however (see also Spivey-Knowlton et al., 1993). Variations in the effectiveness of context are a result of the nature of the frequency asymmetries in the lexical items that trigger these two kinds of ambiguities. We have shown that context effects are most apparent when the alternative interpretations of an ambiguous word are roughly equibiased; when an item is strongly biased, context effects are unable to override the bias. For the MV/RR and PP attachment ambiguities, both strongly biased and equibiased lexical items exist, but the distributions of items appear to be much different in the two cases. The combination of verb, noun, and preposition biases in the PP attachment case tends to result in a higher proportion of relatively equibiased ambiguities, so that context effects tend to be more evident for this ambiguity than for the MV/RR ambiguity.

Although data concerning relative frequency biases across ambiguities are scarce, several pieces of information support this interpretation. Several corpus studies of PP attachment point to the relatively equibiased nature of PP attachment ambiguities (Hindle & Rooth, 1993; Spivey-Knowlton & Sedivy, 1994; Whittemore, Ferrara, & Brunner, 1990). Although we know of no formal studies of the relative frequency of the main verb versus the reduced relative interpretation, our own examination of more than 100 verbs in the *Wall Street Journal* corpus is suggestive: In this sample, MV/RR ambiguous sequences were resolved with the RR interpretation 0–40% of the time, with most verbs having less than 10% RR resolutions of the ambiguity. Tabossi et al. (1994) reported similar results. This is exactly the situation in which we would expect context effects to be limited, and it happens to occur more often for the lexical items that trigger the MV/RR ambiguity than in the ones that trigger the PP attachment ambiguity.

Constraint Use in Initial Interpretation Versus Reanalysis

To this point, we have suggested that results that have been taken to support the two-stage parsing accounts such as the garden path model can be accommodated in the lexically based account we are proposing, that our account also reconciles apparent conflicts in the literature, and that it offers deeper generalizations concerning the relationship between lexical and syntactic ambiguity and the extent to which contexts will be effective. However, Frazier (1994) recently argued against this account, concluding that all evidence for rapid interaction of lexical and contextual information in ambiguity resolution can be construed as consistent with the garden path model. We now examine this argument and the evidence that bears on it.

Frazier's (1987, 1994) position is based on the assertion that evidence for use of context in comprehension does not indicate at which stage the context is being used (Forster, 1979). Evidence for early use of context to promote a syntactically complex interpretation, which we take as evidence that context influences the initial interpretation of syntactic ambiguities, can be viewed within the garden path model as evidence that the second stage (context-sensitive reanalysis) occurs rapidly after the autonomous parser's initial misanalysis. This interpretation of all context effects as part of a second stage, no matter how early they appear in the behavioral data, is permitted because the garden path model provides no specification of the length of the delay between the first-stage context-insensitive parser and the context-sensitive reanalysis mechanisms. Early accounts of this model implied that the lag between the two stages was large enough to be detected easily; for example, Rayner et al. (1983) reported that context had no effect on any reading time measure (taken to reflect the first stage), but context affected performance on sentence-final comprehension questions (reflecting second-stage reanalysis). Later work suggested that context-insensitive parsing could be detected with eyetracking measures, but possibly not with other measures such as self-paced reading (e.g., Ferreira & Clifton, 1986). However, more recent studies have shown early context effects using even the putatively more sensitive eyetracking measures (e.g., Trueswell et al., 1993, 1994). In order to preserve the two-stage model in the face of this evidence, the hypothesized lag between the two stages must shrink even more. For example, Clifton and Ferreira (1989) suggested that for at least some readers, even eyetracking measures may not be able to detect the first-stage parser's operation.

If the lag between the two stages is too small to be reliably measured by any available technique, the existence of the first-stage parser cannot be falsified: All early context effects can be attributed to second-stage reanalysis at an undetectable delay. At least for the three ambiguous constructions that we have considered, the postulation of a precontext parsing stage adds no predictive value over the constraint-based account, and so the latter would seem to be preferable (see also MacDonald, 1994; Steedman & Altmann, 1989; Trueswell et al., 1994).

Note, however, that it is not necessary to rely merely on parsimony to distinguish between the two types of models. There is another relevant body of evidence, concerning ambiguities that are resolved in favor of the syntactically *simple* interpretation preferred by minimal attachment. As Frazier (1994) noted, the garden path model predicts no effects of the plausibility of other, nonminimal analyses in this case, because no reanalysis is necessary. By contrast, our theory claims that frequency and contextual information will modulate the activation of alternatives even when they are resolved in favor of the simple (minimal attachment) interpretation.

Few researchers have examined ambiguities resolved with simple structures. MacDonald et al. (1992) and Pearlmutter and MacDonald (1994) investigated MV/RR sentences resolved with the simple MV interpretation, such as *The soup cooked in the pot but was not yet ready to eat.*[13] In both studies, comprehenders who had high scores on Daneman and Carpenter's (1980) reading span task had longer reading times for these ambiguities at the disambiguation that forced the MV interpretation (*but was*) compared with unambiguous controls. In regression analyses, Pearlmutter and MacDonald showed that these subjects' reading times at the disambiguation were reliably correlated with the plausibility of alternative interpretations ($r = .83, p < .001$).[14] This effect was crucially not due to awkwardness or implausibility of the MV interpretations of the stimulus sentences (all of which were rated as highly plausible); rather, it is an effect of the plausibility of this interpretation relative to alternatives. This result is wholly unexpected from the perspective of the garden path model, for which the plausibility of the alternative interpretations is irrelevant when ambiguities are resolved as plausible MV sentences. This result is entirely expected, however, if ambiguity resolution is guided by partial activation of the alternative lexical interpretations, subject to frequency and context.

General Discussion

We have presented a generalized theory of ambiguity resolution that subsumes both syntactic and lexical types. The major component of this theory is a greatly enriched conception of the mental lexicon. This involved two major adjustments to previous views of the lexicon in psycholinguistics: We assumed that (a) the lexicon is the repository for all types of knowledge associated with words, including their syntactic functions, and that (b) rather than merely listing these different types of information, the lexicon encodes the grammatical and probabilistic relationships that hold among them.

Our account of ambiguity resolution follows from pursuing implications of this conception of the lexicon. First, this approach permits a radical rethinking of the syntactic ambiguities that have been at the center of research on language comprehension. Rather than resting in the construction of phrase structure trees, they can be seen as deriving from ambiguities inherent in lexical items. Second, knowledge of the grammar (e.g., the fact that certain features of representations can or cannot co-occur, the fact that only some phrase structures are well formed) can largely be encoded in the structure of the lexicon itself (e.g., by the weights on connections between units representing different types of information). Third, we can derive the beginnings of a theoretical account of the role of context in language processing. Contextual information is relevant to the extent that it provides information that facilitates resolving the different types of ambiguities in the lexicon. Finally, insofar as syntactic structures have a lexical basis, we predicted that syn-

[13] Similar results may also hold in investigations of the minimal attachment-favored interpretation of other ambiguities, including the prepositional phrase attachment ambiguity and a relative clause–complement ambiguity we have not discussed here (Altmann & Steedman, 1988, who with Crain & Steedman, 1985, particularly emphasized the need to study both minimal and nonminimal resolutions of ambiguities; Altmann, Garnham, & Henstra, 1994; Mitchell & Corley, 1994). The fact that unambiguous control conditions are extremely difficult to construct for these ambiguities may make the data less clear, however.

[14] Low-span subjects did not show effects of ambiguity in the factorial manipulation. Pearlmutter and MacDonald (1994) interpreted the more robust effects for high-span subjects as evidence that these subjects were sensitive to a wider range of probabilistic constraints than were the low-span subjects (see also Just & Carpenter, 1992).

tactic processing should be governed by independently established principles concerning lexical processing in general and lexical (i.e., meaning) ambiguity resolution in particular. Principal factors include properties of the ambiguous word (e.g., the relative frequencies of meanings) and the extent to which the context provides information relevant to distinguishing between the alternatives.

Together these assumptions yield a picture in which ambiguity resolution (and language processing in general) is a constraint satisfaction problem, with multiple, overlapping constraints being used to resolve ambiguities at different levels of representation. Processing involves activation of different alternatives and settling into a stable pattern in which only one alternative is active at each level of representation. Thus, the comprehender can be said to converge on the correct interpretation or "relax" into it (Hummel & Zucker, 1983).

Our theory suggests that many of the conflicting results in the literature stem from the use of stimulus materials that varied with respect to factors that govern ambiguity resolution. The factor implicated by the garden path theory, structural simplicity, is confounded with frequency: Simpler structures also tend to be used more often. The two factors can be unconfounded by looking at how the relative frequencies of alternatives vary across items. The minimal attachment pattern may in fact predominate merely because it happens to be more frequent in the language, but the entire range of outcomes can be understood in terms of a more basic factor, how frequency information for individual lexical items affects processing.

This theory also sheds light on the question of the scope of context effects on processing. Previous research assessed whether information provided by the context could be used to "override" the minimal attachment pattern, with the studies yielding a mixed pattern of results. From our perspective, framing the question in this way ignores two critical factors: (a) the nature of the information provided by the context and (b) facts about the lexical items creating the ambiguity that constrain context effects. Contexts obviously differ in the extent to which they provide disambiguating information; those that are only weakly constraining would not be expected to have a large impact in any theory. We have attempted to provide a characterization of degree of contextual constraint in terms of the extent to which it differentiates among alternatives at different levels of representation. We have also suggested that most contexts probably are weakly constraining, in the sense that they provide an effective basis for deciding between a small number of alternatives but are less effective in isolating a single alternative in advance. Moreover, the effects of contextual information are limited by lexical factors, specifically the frequencies of the alternatives. Putting these factors together yields a system that is "contextually constrained but lexically dominated." In summary, with the emergence of a theory of relevant aspects of lexical structure and contextual information, we are able to replace the question of whether the parser does or does not follow the minimal attachment principle with questions concerning the ways in which a variety of grammatical and probabilistic constraints interact to yield the range of outcomes that are observed.

Directions for Future Research

As the dominant theory of sentence processing, the garden path theory suggested what kinds of empirical questions are worth pursuing. The central question, of course, was whether there is an autonomous parser that obeys the minimal attachment principle. In our theory, this question is no longer the focus because whether or not the interpretation described as "minimal attachment" is preferred depends on other factors. These factors become the new focus of attention. In closing, we mention some directions for future research.

Parsing Without a Parser

We have suggested that the arena for syntactic processing is the lexicon, in that syntactic structure is built through links between individual lexical items. This approach retains the idea that syntactic structure is computed during comprehension but abandons the parser, a modular, special-purpose processor that combines knowledge of grammar with special-purpose algorithms such as minimal attachment. Having pursued the lexical approach this far, a question naturally arises: Can all syntactic knowledge be represented entirely within the lexicon or is some represented at a more abstract, supralexical level that may influence lexical processing? The first alternative, with syntactic constraints only in the lexicon, is equivalent to the claim that syntactic constraints on well-formedness are local (i.e., specifiable in terms of links between lexical items). The alternative is that some nonlocal syntactic constraints exist and must be represented independently of the lexicon. Our approach does not demand that all syntax be lexically represented; however, it is important to determine whether there are domains in which nonlocal constraints are implicated. We briefly consider two such domains.

"Late closure" ambiguities. The garden path model posits a second heuristic, called *late closure* (Frazier, 1979; Frazier & Rayner, 1982), to handle a variety of ambiguities in which the alternative structures do not involve differences in complexity, so that minimal attachment does not apply. In 8a, *yesterday* can attach to (modify) either *noticed* or *saw,* but it is typically interpreted as modifying *saw.* In 8b, the PP *near the wall* can modify either *the book* or *the table,* but in both cases, modification of *the table* is preferred. Late closure specifies that attachment should occur to the most recent possible site, which is *saw* in 8a and *the table* in 8b, so it makes the correct predictions.

8a. Mary noticed that Bill saw Sue yesterday.
8b. The book on the table near the wall belonged to John.

The existence of such interpretation preferences is relatively uncontroversial, at least in English (e.g., Gibson, Pearlmutter, Canseco-Gonzalez, & Hickok, 1994, and the references therein), but their existence need not implicate the late closure principle. In our framework, the ambiguity in 8b is just another type of PP attachment ambiguity; it differs from the cases described earlier only in that both possible attachment sites are nouns instead of one being a noun and the other a verb. Thus, we would predict that the lexical frequency preferences for *book* and for *table* to take a PP assigning a location role would interact to determine the attachment preference. Lexical frequency explanations have not been tested for these ambiguities, but evidence from corpus analyses suggests that lexical preferences can predict attachment preferences (e.g., Whittemore et al., 1990) and in some cases may limit the effects of a general

preference for recent attachment (Gibson & Pearlmutter, in press).

Other late closure ambiguities, however, are not so easily handled by lexical frequencies. For example, comparing 8a with the same example but with the verbs switched—*Mary saw that Bill noticed Sue yesterday*—reveals a preference to attach to the more recent site in both cases; attachment preferences of the verbs seem to have little effect. However, another aspect of our proposal does capture these effects, because attachment sites (X-bar structures) are located in the lexicon and therefore subject to constraints on activation. In particular, a common assumption in interactive-activation models is that activation levels decay over time (e.g., McClelland & Rumelhart, 1981). In the case of X-bar structures, less recent sites will be less highly activated than more recent sites, and as a result, less recent sites will be more difficult to reaccess for additional attachments. Gibson et al. (1994) provided evidence that the degree to which a more recent site is preferred over a less recent site decreases with distance, consistent with this view.

Long-distance dependencies. The second challenge for local syntactic constraints comes from long-distance dependencies. The sentences in 9a–9d are examples of perhaps the best known and most studied type of long-distance dependency, the "filler-gap" construction (Fodor, 1978).

9a. Which boy did John know ____?
9b. Which boy did John know that Mary kissed ____?
9c. Which doorway did John see through ____?
9d. Which doorway did John see ____ through the window?

In Example 9, the blanks correspond to missing phrases, or gaps. In 9a, know is missing a direct object, as is *kissed* in 9b and *see* in 9d. In 9c, the gap is the object of *through* (cf. *John saw through the doorway*). In each of these sentences, the missing phrase (*which boy or which doorway*), called a *filler,* appears earlier in the sentence. Understanding how such dependencies are formed and constrained has been a major focus of research in virtually all syntactic theories (e.g., Bresnan, 1982; Chomsky, 1981, 1986, 1992; Gazdar et al., 1985).

Within our framework, the existence of such dependencies raises two issues: First, gap identification is another form of syntactic ambiguity resolution. For example, in 9c–9d, the gap is not unambiguously identifiable until nearly the end of each sentence, where the absence (9c) or presence (9d) of an overt object for the preposition *through* determines the gap's location. One view is that gap detection involves additional parsing heuristics (e.g., the active filler strategy of Frazier & Flores d'Arcais, 1989); alternatively, it could be subject to the same lexical and contextual constraints as the other ambiguities. This issue has been investigated extensively, in a debate similar to that concerning the MV/RR ambiguity (e.g., Boland & Tanenhaus, 1991; Frazier & Clifton, 1989). Under at least some circumstances, lexical frequencies do seem to determine whether a gap is postulated (Garnsey, Tanenhaus, & Chapman, 1989).

The second issue for our view is whether the syntactic constraints on long-distance dependencies can be stated strictly locally. These dependencies are "long distance" exactly because they can occur over potentially unbounded distances within a sentence. The difference between 9a and 9b is that in the latter, the gap is one clause farther away from the filler, and this embedding process can be continued indefinitely (e.g., *Which boy did John know that Bill understood that Susan noted that Mary kissed ____?*). During comprehension, the processor must somehow keep track of a filler and match it with an appropriate gap location over a potentially long distance. However, although the relationship between a filler and its gap is potentially unbounded, linguistic theories have consistently analyzed the relationship as a series of smaller relations (e.g., Chomsky, 1986; Gazdar et al., 1985), ranging in size from a single clause down to individual nodes in a syntactic tree. These smaller units are represented in the lexicon on our account; thus, there may be a processing mechanism consistent with the linguistic analysis of these constructions. This is an important issue to be addressed in future research.

What Kinds of Frequency Information Do People Keep Track of?

The frequencies of alternatives at different levels of representation play an important role in our theory. Understanding the kinds of frequency information that are encoded and used in comprehension is necessary not only for a more complete account of ambiguity resolution; it also contributes to understanding the architecture of the language processing system, specifically the kinds of information that are represented. We have assumed that all types of information in the lexicon are frequency coded, and a strong claim from this hypothesis is that all probabilistic effects in language comprehension can be traced to frequency information at the level of individual lexical items. However, it may be that frequency effects occur for some relatively subtle aspects of linguistic structure that go beyond individual words. Such effects may prove to be especially relevant to the locality of syntactic constraints and the late closure and long-distance dependency ambiguities discussed earlier. We briefly consider two examples.

Frequency of a lexical interpretation in a syntactic environment. In their investigation of the word *that,* Juliano and Tanenhaus (1993) noted that it was ambiguous over several different lexical categories but that some of these alternative interpretations were strongly associated with particular syntactic positions. For example, *that* at the beginning of a sentence is almost always a determiner (*That guy is*) and almost never a complementizer (*That the proposal is flawed is*). When *that* follows a verb, however, the opposite probabilities obtain—*that* is more often a complementizer than a determiner. Juliano and Tanenhaus found that comprehenders were acutely sensitive to these contingent frequency effects. Such effects may sometimes be more prominent than the simple effect of the frequency of alternative lexical interpretations (e.g., whether *that* is more frequent as a determiner, a complementizer, a relative pronoun, etc.).

MacDonald (1993) found a similar contextual effect in resolution of noun–verb ambiguities such as *fires.* One factor predicting comprehenders' difficulty on these ambiguities was the frequency with which the word preceding the noun–verb ambiguity occurred as the head of an NP versus as a modifier within an NP. In a sequence like *The warehouse fires,* for example, *warehouse* could be taken as the head of an NP, in which case *fires* would have to be a verb and the sentence would probably

continue with a direct object (*a few employees every year*). However, if *warehouse* were treated as a modifier, then the processor would still need a head for the NP, *fires* will be a likely candidate, and thus the sentence could be expected to continue with a main verb (*damaged a lot of merchandise*). MacDonald found that head versus modifier frequency was a reliable predictor of the interpretation of the ambiguity.

There is no obvious aspect of the lexical representations we have discussed that would encode this head–modifier information, nor is there any straightforward way for the contingent frequency effects that Juliano and Tanenhaus (1993) noted to be encoded within the lexical representation of *that*. A third example that is even more difficult to encode lexically is discussed in Tabossi et al. (1994): Reduced relative constructions are rarer in the first verb of the sentence than in later verbs. Why particular types of complex frequencies tend to be encoded and how they are represented remain to be determined.

Word co-occurrences. An alternative interpretation of Juliano and Tanenhaus's (1993), MacDonald's (1993), and the Tabossi et al. (1994) results is that comprehenders are not keeping track of word frequency in syntactic environments such as "beginning of sentence" or "head of NP" but are instead keeping track of the frequencies with which words co-occur. This interpretation may be seen as consistent with instance-based theories of memory (e.g., Jacoby & Brooks, 1984). Neither the Juliano and Tanenhaus nor the MacDonald study was designed to distinguish between contingent frequency effects that are based on syntactic environments versus word co-occurrences, but other results implicate co-occurrence information in ambiguity resolution. Recall that Trueswell et al. (1993) found that different verbs were followed by the optional *that* in S-complement constructions such as *John knew* (*that*) *Mary had left* with different frequencies. Thus, knowledge about the co-occurrence of a verb and *that* was guiding ambiguity resolution. Because this result depends on the individual verbs rather than a syntactic environment, it points to the importance of word co-occurrences as an important source of probabilistic information available to the comprehender (see also McKoon & Ratcliff, 1992). In future research it will be important to determine the extent to which people can and cannot encode contingent probabilities of this sort, the extent to which such probabilities can be used in comprehension, and their relationship to frequency information for individual words.

What Kinds of Contextual Information Are Relevant?

The theory we have proposed incorporates the familiar idea that contexts provide information that facilitates ambiguity resolution. The important question for this approach has always been whether there can be a general theory of contextual information in language processing. We have proposed that part of the function of context is to provide information that is relevant to resolving ambiguities over the different levels of lexical representation that we have analyzed. Moreover, we have discussed individual studies that are consistent with this view. However, our understanding of contextual effects is still limited. For example, we have noted some types of information that appear to underlie decisions about whether a noun is a likely agent or theme, as in the *John cooked* example, and we have discussed the importance of such computations in MV/RR ambiguity resolution, but no detailed account is available concerning exactly which kinds of information can and cannot be used in making such decisions. A similar question concerns the kinds of information that allow people to distinguish between alternate meanings of words. Tabossi (1988) has made an important step toward answering this question, proposing that contexts are relevant insofar as they relate to semantic features associated with a component meaning. However, the process by which contexts exert this effect is not well understood, nor is it clear whether this account can be extended to the other types of ambiguities.

What Are the Dynamics of Processing?

We have laid out a theory that specifies some of the complex interactions among different types of information in ambiguity resolution. In effect, processing routinely involves many-way interactions among factors. Keeping track of these interactions demands a computational modeling approach. This would also facilitate making behavioral predictions about on-line processing. There have already been some attempts to develop models that establish the relevance of constraint satisfaction mechanisms to sentence processing (e.g., St. John & McClelland, 1990). However, there is a need for models that implement exactly the kinds of lexical and probabilistic information that we have described. One example of this type of modeling approach is provided by Pearlmutter, Daugherty, MacDonald, and Seidenberg (in press), who describe a connectionist model of thematic role assignment based on interactions among several factors, including verb argument structure frequency and noun animacy. This model is limited in its scope, and much more research of this sort will be needed in order to assess the validity of the account that we have begun to sketch here.

Are There Individual Differences in the Use of Probabilistic Constraints?

A comprehender's knowledge of probabilistic constraints emerges from experience with the language, and so it stands to reason that different linguistic experiences, and different capacities to learn from experience, could yield different frequency and context effects across individuals. There is some support for this view (e.g., Mitchell, Cuetos, & Corley, 1992), but in most cases it is impossible to determine whether the individual differences that have been found should be attributed to comprehenders' different linguistic experiences, different linguistic abilities, or some combination of the two. For example, a number of studies have shown that individual differences in linguistic working memory capacity, as measured by Daneman and Carpenter's (1980) reading span task, result in different patterns of language comprehension, particularly lexical and syntactic processing and ambiguity resolution (Carpenter & Daneman, 1981; Just & Carpenter, 1992; MacDonald et al., 1992; Miyake, Just, & Carpenter, 1994). Several studies have traced differences in ambiguity resolution patterns to the ability to use probabilistic constraints: Participants with high reading spans are more able to use probabilistic information in ambiguity resolution than are low-span subjects (Just & Carpenter, 1992; Pearlmutter & MacDonald, 1994). Still, the basis of these differences is un-

clear. One explanation is that whereas high-span subjects have sufficient working memory capacity to compute these constraints, low-span subjects cannot and therefore tend to pursue a simple or high-frequency structure, independent of context. Alternatively, high-span subjects may have much more experience with reading and language than low-span subjects; thus, their superior ability to use constraints could result from a better representation of frequency information rather than additional computational capacity. A better understanding of these effects awaits additional research on many of the issues discussed earlier, particularly the kinds of frequency information that comprehenders encode and the relation between frequency and context effects.

Conclusions

The garden path theory developed out of a desire for a theory that identified general principles of language processing. Principles such as minimal attachment were thought to reveal characteristics of the parser, a part of the human language faculty. Our analyses now suggest that the minimal attachment phenomena have a different basis than the garden path theory suggested. What, then, happens to the goal of identifying general parsing principles?

Our approach points to a somewhat different direction in which to look for general principles. Comprehension involves the use of different types of information; linguistic theory provides an account of what those types of information are (see also Fodor, Bever, & Garrett, 1974). Processing involves factors such as the frequencies of occurrence and co-occurrence of different types of information and the weighing of probabilistic and grammatical constraints. A processing theory should explain the principles that govern the acquisition of this information, its representation in memory, and its use in on-line language processing. The garden path theory suggests that there are both forms of knowledge representation and processing principles that are specific to the language faculty, and even specific to the parser within the language faculty. Our approach has strongly questioned the special status of the parser within the language processor and has suggested that syntactic parsing, including ambiguity resolution, can be seen as a lexical process. More radically, our approach suggests that whereas there may be distinctly linguistic forms of *representation*, the *processing* principles that account for language comprehension and ambiguity resolution are not specific to language at all. Rather, they seem to reflect general properties of memory, perception, and learning, properties that are involved in nonlinguistic domains as disparate as concept learning, pattern recognition, and decision making. The identification of general principles in these domains would therefore shed considerable light on the problem of language comprehension.

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