Having Your Cake and Eating It Too: Autonomy and Interaction in a Model of Sentence Processing

Kurt P. Eiselt*
College of Computing
Georgia Institute of Technology
Atlanta, Georgia 30332-0280
eiselt@cc.gatech.edu

Kavi Mahesh*
College of Computing
Georgia Institute of Technology
Atlanta, Georgia 30332-0280
mahesh@cc.gatech.edu

Jennifer K. Holbrook
Department of Psychology
Albion College
Albion, Michigan 49224
jen@cedar.cic.net

Abstract

Is the human language understander a collection of modular processes operating with relative autonomy, or is it a single integrated process? This ongoing debate has polarized the language processing community, with two fundamentally different types of model posited, and with each camp concluding that the other is wrong. One camp puts forth a model with separate processors and distinct knowledge sources to explain one body of data, and the other proposes a model with a single processor and a homogeneous, monolithic knowledge source to explain the other body of data. In this paper we argue that a hybrid approach which combines a unified processor with separate knowledge sources provides an explanation of both bodies of data, and we demonstrate the feasibility of this approach with the computational model called COMPERE. We believe that this approach brings the language processing community significantly closer to offering human-like language processing systems.

The Big Questions

Years of research by linguists, psychologists, and artificial intelligence specialists have provided significant insight into the workings of the human language processor. Still, fundamental questions remain unanswered. In particular, the debate over modular processing versus integrated processing rages on, and experimental data and computational models exist to support both positions. Furthermore, if the integrated processing position is correct, just what exactly is integrated? And if the modular position is the right one, what are the different modules? Do they interact, and if so, to what extent and when? Or are those modules entirely autonomous?

Wrestling with these questions induces considerable frustration in researchers. This frustration stems not only from the research community's apparent inability to answer them satisfactorily, but also from the overwhelming importance of the answers themselves—these answers, once uncovered, undoubtedly will impact thinking in all areas of artificial intelligence and cognitive science research, including visual processing, reasoning, and problem solving, to name just a few. In this paper, we intend to provide the reader with answers to some of these questions—answers based on nearly ten years of our own interdisciplinary research in sentence processing, and built upon the work of many others who went before us. In brief, we propose a model of language understanding (or, more specifically, sentence processing) in which all linguistic processing is performed by a single unified process, but the different types of linguistic knowledge necessary for processing are separate and distinct. This model accounts for conflicting experimental data, some of which suggests an autonomous, modular approach to language processing, and some of which indicates an integrated approach. Because it is a closer fit to the experimental data than any model which has gone before, this model consequently points the way to more human-like performance from language processing systems.

Background

Our new model of sentence processing has its roots in work begun nearly ten years ago. That research effort started as an attempt to explain how the human language understander selected the most context-appropriate meaning of an ambiguous word, and then was able to correct both the choice of word meaning and the surrounding sentence interpretation, without reprocessing the input, when later processing showed that the initial choice of word meaning was erroneous.

The resulting computational model, ATLAST (Eiselt, 1987; Eiselt, 1989), resolved word sense ambiguities by activating multiple word meanings in parallel, selecting the meaning which matched the previous context, and deactivating but retaining the unchosen meanings for as long as resources were available for retaining them. If later context proved the initial decision to be incorrect, the retained meanings could be reactivated without reaccessing the lexicon or reprocessing the text. ATLAST proved to have great psychological validity for lexical processing—its use of multiple access was well grounded in the psychological literature (e.g., Seidenberg, Tanenhaus, Leiman, & Bienkowski, 1982), and, more importantly, it made psychological predictions about the retention of unselected meanings that were

*During the course of this work, these authors were supported in part by a research grant from Northern Telecom.

experimentally validated (Eiselt & Holbrook, 1991; Holbrook, 1989). ATLAST provided an architecture of sentence processing which was also used to explain recovery from erroneous decisions in making pragmatic inferences as well as explaining individual differences in pragmatic inferences (Eiselt, 1989; cf. Granger, Eiselt, & Holbrook, 1983).

Error recovery in semantic processing had occasionally aroused the attention of researchers in conceptually-based natural language understanding, but the questions that arose were usually dismissed as unimportant or something which could be resolved as an afterthought (Birnbaum & Selfridge, 1981; Lebowitz, 1980; Lytinen, 1984). These researchers were content to assume that the first inference decision made was the correct one. Meanwhile, other researchers investigating syntactically-based approaches had long since concluded that the means by which erroneous syntactic decisions were accommodated had a dramatic impact on the architecture of the syntactic processor being proposed. For example, the backtracking models embodied the theory that only a single syntactic interpretation need be maintained at any given time, so long as the processor could keep track of its decisions, undo them when an erroneous decision was discovered, and then reinterpret the input (e.g., Woods, 1973). The lookahead parsers tried to sidestep the problems inherent in backtracking by postponing any decision until enough input had been processed to guarantee a correct decision, thereby avoiding erroneous decisions to some extent (e.g., Marcus, 1980). Another approach to avoiding erroneous decisions was offered by parallel parsers which maintained all plausible syntactic interpretations at the same time (Kurtzman, 1985). ATLAST, however, was a model of semantic processing and did not address the issue of recovery from erroneous syntactic decisions, nor did it substantially address the issue of syntactic processing at all.

Recently, Stowe (1991) presented experimental evidence showing that in dealing with syntactic ambiguity, the sentence processor accesses all possible syntactic structures simultaneously and, if the structure preferred for syntactic reasons conflicts with the structure favored by the current semantic bias, the competing structures are maintained and the decision is delayed. Furthermore, the work suggests an interaction of the various knowledge types, as in some cases semantic information influences structure assignment or triggers reactivation of unselected structures. This model of limited delayed decision in syntactic ambiguity resolution had much in common with the ATLAST model of semantic ambiguity resolution. Both models proposed an early commitment where possible. Both models had the capability to pursue multiple interpretations in parallel when ambiguity made it necessary. Both models explained error recovery as an operation of switching to another interpretation maintained in parallel by the sentence processor. Finally, both models made decisions by integrating the preferences from syntax and semantics.

One explanation for this high degree of similarity between the syntactic and semantic error recovery mechanisms is that there are two separate processors, one for syntax and one for semantics, each with its corresponding source of linguistic knowledge, and each doing exactly the same thing. A more economical explanation, however, is that there is only one process which deals with syntactic and semantic information in the same manner. We have chosen to explore the latter explanation, as others have done, but we have also chosen to maintain the separate knowledge sources for reasons which will be explained below. (See also Holbrook, Eiselt, & Mahesh, 1992.)

Overview of COMPERE

Our new model of sentence processing, called COMPERE (Cognitive Model of Parsing and Error Recovery), consists of a single unified process operating on independent sources of syntactic and semantic knowledge. This is made possible by a uniform representation of both types of knowledge. The unified process applies the same operations to the different types of knowledge, and has a single control structure which performs the operations on syntactic and semantic knowledge in tandem. This permits a rich interaction between the two sources of knowledge, both through transfer of control and through a shared representation of the interpretations of the input text being built by the unified process.

An advantage of representing the different kinds of knowledge in the same form is that the boundaries between the different types of knowledge can be ill-defined. Often it is difficult to classify a piece of knowledge as belonging to a particular class such as syntactic or semantic. With a uniform representation, such knowledge lies in between and can be treated as belonging to either class.

Syntactic and semantic knowledge are represented in separate networks in which each node is a structured representation of all the information pertaining to a syntactic or semantic category or concept. A link, represented as a slot-filler pair in the node, specifies a parent category or concept of which the node can be a part, together with the conditions under which it can be bound to the parent, and the expectations that are certain to be fulfilled should the node be bound to the parent. In addition, nodes in either network are linked to corresponding nodes in the other network so that the unified process can build on-line interpretations of the input sentence in which each syntactic unit has a corresponding representation of its thematic role and its meaning. In addition, there is a lexicon as well as certain other minor heuristic and control knowledge that is part of the process. (COMPERE's architecture and knowledge representation are displayed graphically in Figures 1 and 2.)

The unified process is a bottom-up, early-commitment parsing mechanism integrated with top-down guidance through expectations. The operators and the control structure that constitute the unified process are described briefly in the algorithm shown in Figure 3.

The COMPERE prototype has been implemented in Common LISP on a Symbolics LISP Machine. At this time, its unified process can perform on-line interpretations of its input, and can recover from erroneous syntactic decisions when necessary. COMPERE is able to process relatively complex syntactic structures, including relative clauses, and

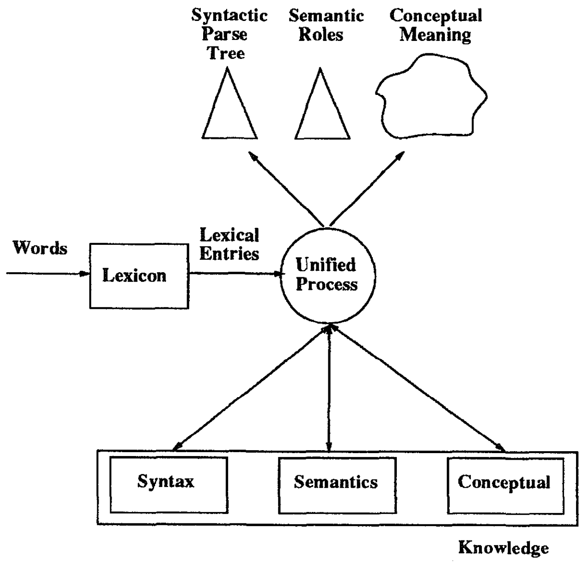

Figure 1: Architecture of COMPERE.

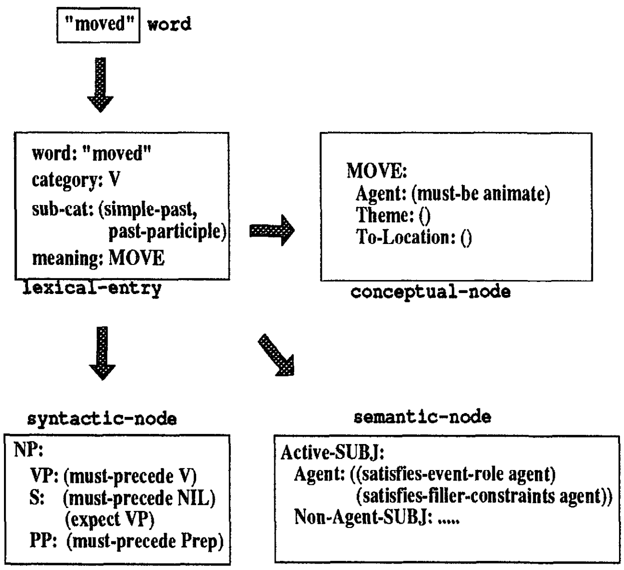

Figure 2: Knowledge Representation in COMPERE.[1]

---

1. Access lexical entries of next word.
2. Create instance nodes for syntactic category, meaning, and (primitive) thematic role.
3. Compute feasible bindings to parents for syntactic instance node and role instance node. (This operation checks any conditions to be satisfied to make the binding feasible; it also takes existing expectations into account.)
4. Rank syntactic and semantic feasible bindings by their respective preference criteria.
Combine feasible bindings and select the most preferred binding.
5. Make the binding by creating parent node instances and appropriate links, and generating any expectations. Create links between corresponding instances in syntax and their thematic roles and meanings.
6. Retain alternative bindings for possible error recovery.
7. If there is no feasible binding for a node, explore previously retained alternatives to recover from errors.
8. Continue to bind the parent nodes to nodes further up as far as possible (such as until the S node in syntax or the Event node in semantics).

Figure 3: Unified Process: Algorithm.

can resolve the associated structural ambiguities.

Autonomy and interaction effects from one process

COMPERE is able to exhibit seemingly modular processing behavior that matches the results of experiments showing the autonomy of different levels of language processing (e.g., Forster, 1979; Frazier, 1987). It is also able to display seemingly integrated behavior that matches the results of experiments showing semantic influences on syntactic structure assignment (e.g., Crain & Steedman, 1985; Tyler & Marslen-Wilson, 1977). For example, consider the processing of the following sentence:

(1) *The bugs moved into the new lounge were found quickly.*

This sentence has a lexical semantic ambiguity at the subject noun *bugs* that could mean either insects or electronic microphones. In addition, it is also syntactically ambiguous locally at the verb *moved* since there is no distinction between its past-tense form and its past-participle form. In the simple past reading of *moved*, it would be the main verb with the corresponding interpretation that "the bugs moved themselves into the new lounge." On the other hand, if *moved* is read as a verb in its past-participle form, it would be the verb in a reduced relative clause corresponding to the meaning "the bugs which were moved by somebody else into the new lounge...." Parse trees for the two structural interpretations and the corresponding thematic-role assign-

[1]The arrows in Figure 2 simply indicate which types of knowledge point to which other types; they do not mean that the specific nodes shown point to the other nodes.

ments are shown in Figures 4 and 5.[2]

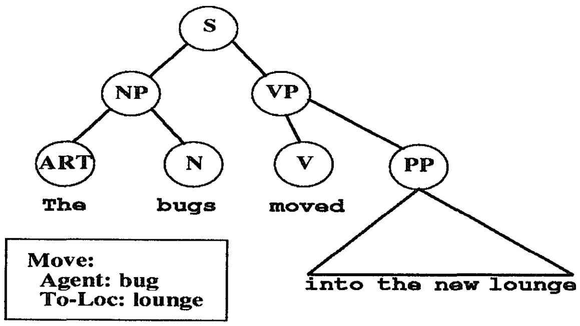

Figure 4: Garden Path: Main-Clause Interpretation.

Null Context: When sentence (1) is presented to COMPERE in a null semantic context, one where there is no bias for either meaning of the noun *bugs*, COMPERE reads ahead without resolving the lexical ambiguity at the word *bugs*. When it encounters the structural ambiguity at the verb *moved*, COMPERE does not have the necessary information to decide which of the two structures in Figures 4 and 5 is the appropriate one to pursue.

However, COMPERE has a syntactic preference for the main-verb interpretation over the relative clause one. Though this preference can be explained by the minimal attachment principle (Frazier, 1987), COMPERE offers a more general explanation. Extrapolating from Stowe's model, we have endowed COMPERE with the pervasive goal of completing an incomplete item at any level of processing. In syntactic processing, it has a goal to complete the syntactic structure of a unit such as a phrase, clause, or a sentence. COMPERE prefers the alternative which helps complete the current structure (called the Syntactic Default) over one that adds an optional constituent leaving the incompleteness intact. For instance, in (1), a VP is required to complete the sentence after seeing *The bugs*. Since the main-clause interpretation helps complete this requirement and the relative-clause interpretation does not, the main-clause structure gets selected. In other words, COMPERE would rather use the verb to begin the VP that is required to complete the sentence structure than treat it as the verb in a reduced relative clause which would leave the expectation of the VP unsatisfied. This behavior is the same as the one explained by the "first analysis" models of Frazier and colleagues (Frazier, 1987) using a minimal-attachment preference. COMPERE can produce this behavior by applying structural preferences independently since it maintains separate representations of syntactic and semantic knowledge.

As a consequence of choosing the main-clause interpretation, the lexical ambiguity is also resolved. The electronic bug meaning is now ruled out since there is a selectional restriction on the verb *moved* that is not satisfied by electronic bugs (namely, they cannot move by themselves).[3]

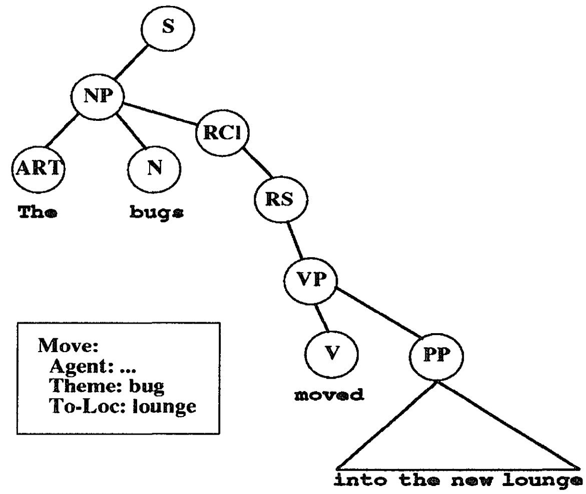

Figure 5: Garden-Path: Reduced Relative Clause.

Thus, until seeing the word *were*, the verb *moved* is treated as the main verb since it satisfies the expectation of a VP that is required to complete the sentence. However, at this point, the structure is incompatible with the remaining input. COMPERE recognizes the error and now tries the alternative of attaching the VP as a reduced relative clause so that there is still a place for a main verb. This results in a garden-path effect upon reading this sentence. That is, the sentence processor is led up a garden path and has to backtrack when later information shows that it was the wrong path to take. This behavior is not influenced by semantic or conceptual preferences and can be perceived as a modular behavior. COMPERE's error recovery method was first developed in the ATLAST model (Eiselt, 1987). It was also experimentally validated (Eiselt & Holbrook, 1991).

As a consequence of switching to the new syntactic interpretation, COMPERE makes corresponding changes to thematic role assignments and also "unresolves" the lexical ambiguity. There is no longer any reason to eliminate the electronic bug meaning since either kind of bugs can be moved by others.

Semantically Biasing Context: Now consider sentence (1) in a semantically biasing context such as the one in (2).[4]

[2]For simplicity, these figures show the parse trees and the thematic roles separate from each other. In COMPERE's actual output, the parse trees and thematic roles are interlinked.

[3]COMPERE's program does not resolve lexical semantic ambiguities at this time. We are currently rectifying this by incorporating lexical ambiguity resolution strategies from our earlier model ATLAST (Eiselt, 1989) in COMPERE.

[4]At present, COMPERE is not capable of using context effects in its ambiguity resolution process. However, its architecture supports the inclusion of such effects and we are working on providing context information to the unified process.

(2) *The Americans built a new wing to the embassy. The Russian spies quickly transferred the microphones to the new wing. The bugs moved into the new lounge were found quickly.*

The semantic context in (2) resolves the lexical ambiguity by choosing the electronic bug meaning. This decision helps COMPERE resolve the structural ambiguity at the verb *moved*. Using its conceptual knowledge, represented as a selectional restriction, that only animate agents can move by themselves, COMPERE decides that *moved* cannot be a main verb and goes directly to the reduced relative clause interpretation (Fig. 5), thereby avoiding the garden path. This shows how the same unified process that previously exhibited modular processing behavior can also produce interactive processing behavior when semantic information is available. Syntax and semantics interact in COMPERE to help resolve ambiguities in each other.

COMPERE can also use independent syntactic preferences in other types of sentences such as those with prepositional attachment ambiguities. The COMPERE prototype thus demonstrates that the range of behaviors that the interactive models account for (Crain & Steedman, 1985; Tyler & Marslen-Wilson, 1977), and the behaviors that the "first analysis" models account for (Frazier, 1987), can be explained by a unified model with a single processor operating on multiple independent sources of knowledge.

Comparative evaluation

There is certainly nothing unique about a unified process model of language understanding—the integrated processing hypothesis has been visited and revisited many times, for good reason, and with significant results (e.g., Jurafsky, 1992; Lebowitz, 1980; Riesbeck & Martin, 1986). Yet each of these models labors under the assumption that the integration of processing necessarily goes hand in hand with the integration of the knowledge sources. While this design decision may make construction of the corresponding computational model easier, it also makes the model incapable of easily explaining the autonomy effects demonstrated by Forster (1979), Frazier (1987), and others. As shown above, COMPERE's unified processing mechanism combined with its separate sources of linguistic knowledge offers an explanation for observed autonomy effects as well as the interaction effects reported by Marslen-Wilson and Tyler (Tyler & Marslen-Wilson, 1977). Furthermore, the integrated models noted above cannot capture syntactic generalizations.

Another form of the modularity debate concerns the effect of context on syntactic decisions—does context affect structure assignment, or are context effects absent until later in language processing (Taraban & McClelland, 1985)? Though we do not have a model of context effects in COMPERE, we believe that contextual information can be incorporated as an additional source of preferences in COMPERE's architecture.

An added benefit of COMPERE's sentence processing architecture is that it offers an explanation for the effects of linguistic aphasias. In reviewing the aphasia literature, Caramazza and Berndt (1978) concluded that the evidence pointed strongly to the functional independence of syntactic and semantic processing. COMPERE suggests an alternate explanation—the different aphasic behaviors are not due to damage to the individual processors, but are instead due to damage to the individual knowledge sources or, perhaps, to the communications pathways between the knowledge sources and the unified processor.

We believe that COMPERE's architecture accounts for the wide variety of seemingly conflicting data on linguistic behavior better than any previously proposed model of sentence processing. Yet COMPERE is not the first sentence processing model to be configured as a single process interacting with independent knowledge sources. The localist or punctate connectionist models of Pollack (1987; Waltz and Pollack, 1985) and Cottrell (1985; Cottrell and Small, 1983) resemble COMPERE at a gross architectural level, but these models did not offer the range of explanation of different behaviors that COMPERE does; for example, these models do not recover from errors, nor can they deal with complex syntactic structures such as relative clauses.

Despite all its theoretical advantages over other models, the prototype implementation of COMPERE is not yet fully developed and suffers from some weaknesses. Its role knowledge is fairly limited, and its conceptual knowledge is even more so. Also, the implementation currently diverges slightly from theory. The divergence appears in the process itself: the theoretical model has a single unified process, while the prototype computational model consists of two nearly-identical processes—one for syntax and one for semantics. These two processes share identical control structures, but they are duplicated because we have not yet completed the task of representing the different types of information in a uniform format. Some readers may take this as an indication that we are doomed to failure, but the connectionist models mentioned earlier serve as existence proofs that finding a uniform format for representing different types of linguistic knowledge is by no means an impossible task.

Conclusion

Is the human language understander a collection of modular processes operating with relative autonomy, or is it a single integrated process? This ongoing debate has polarized the language processing community, with two fundamentally different types of model posited, and with each camp concluding that the other is wrong. One camp puts forth a model with separate processors and distinct knowledge sources to explain one body of data, and the other proposes a model with a single processor and a homogeneous, monolithic knowledge source to explain the other body of data. In this paper we have argued that a hybrid approach which combines a unified processor with separate knowledge sources provides an explanation of both bodies of data, and we have demonstrated the feasibility of this approach with the computational model called COMPERE. We believe that this approach brings the language processing community significantly closer to offering human-like language processing systems.

Acknowledgement: We would like to thank Justin Peterson for his comments on this work and his help in finding good examples.

References

Birnbaum, L., and Selfridge, M. 1981. Conceptual analysis of natural language. In Schank, R. C., and Riesbeck, C. K. eds. Inside computer understanding: Five programs plus miniatures, 318-353. Hillsdale, NJ: Lawrence Erlbaum.

Caramazza, A., and Berndt, R. S. 1978. Semantic and syntactic processes in aphasia: A review of the literature. *Psychological Bulletin* 85:898-918.

Cottrell, G. W. 1985. A connectionist approach to word sense disambiguation, Technical Report, 154, Computer Science Department, University of Rochester.

Cottrell, G. W., and Small, S. L. 1983. A connectionist scheme for modelling word sense disambiguation. *Cognition and Brain Theory* 6:89-120.

Crain, S., and Steedman, M. 1985. On not being led up the garden path: The use of context by the psychological syntax processor. In Dowty, D. R., Kartunnen, L., and Zwicky, A. M. eds. Natural language parsing: Psychological, computational, and theoretical perspectives, 320-358. Cambridge, England: Cambridge University Press.

Eiselt, K. P. 1987. Recovering from erroneous inferences. In Proc. AAAI-87 Sixth National Conference on Artificial Intelligence, 540-544. San Mateo, CA: Morgan Kaufmann.

Eiselt, K. P. 1989. Inference processing and error recovery in sentence understanding, Technical Report, 89-24, Ph.D. diss., Dept. of Computer Science, University of California, Irvine.

Eiselt, K. P., and Holbrook, J. K. 1991. Toward a unified theory of lexical error recovery. In Proc. of the Thirteenth Annual Conference of the Cognitive Science Society, 239-244. Hillsdale, NJ: Lawrence Erlbaum.

Forster, K. I. 1979. Levels of processing and the structure of the language processor. In Cooper, W. E., and Walker, E. C. T. eds. Sentence processing: Psycholinguistic studies presented to Merrill Garrett, 27-85. Hillsdale, NJ: Lawrence Erlbaum.

Frazier, L. 1987. Theories of sentence processing. In Garfield, J. L. ed. Modularity in knowledge representation and natural-language understanding. Cambridge, MA: MIT Press.

Granger, R. H., Eiselt, K. P., and Holbrook, J. K. 1983. STRATEGIST: A program that models strategy-driven and content-driven inference behavior. In Proc. of the National Conference on Artificial Intelligence, 139-147. San Mateo, CA: Morgan Kaufmann.

Holbrook, J. K. 1989. Studies of inference retention in lexical ambiguity resolution. Ph.D. diss., School of Social Sciences, University of California, Irvine.

Holbrook, J. K., Eiselt, K. P., and Mahesh, K. 1992. A unified process model of syntactic and semantic error recovery in sentence understanding. In Proc. of the Fourteenth Annual Conference of the Cognitive Science Society, 195-200. Hillsdale, NJ: Lawrence Erlbaum.

Jurafsky, D. 1992. An on-line computational model of human sentence interpretation. In Proc. of the Tenth National Conference on Artificial Intelligence, 302-308. San Mateo, CA: Morgan Kaufmann.

Kurtzman, H. S. 1985. Studies in syntactic ambiguity resolution. Ph.D. diss., Dept. of Psychology, Massachusetts Institute of Technology.

Lebowitz, M. 1980. Generalization and memory in an integrated understanding system, Research Report, 186, Dept. of Computer Science, Yale University.

Lytinen, S. L. 1984. The organization of knowledge in a multi-lingual, integrated parser, Research Report, YALEU/CSD/RR 340, Dept. of Computer Science, Yale University.

Marcus, M. P. 1980. *A theory of syntactic recognition for natural language.* Cambridge, MA: MIT Press.

Pollack, J. B. 1987. On connectionist models of natural language processing, Technical Report, MCCS-87-100, Computing Research Laboratory, New Mexico State University.

Riesbeck, C. K., and Martin, C. E. 1986. Towards completely integrated parsing and inferencing. In Proc. of the Eighth Annual Conference of the Cognitive Science Society, 381-387. Hillsdale, NJ: Lawrence Erlbaum.

Seidenberg, M. S., Tanenhaus, M. K., Leiman, J. M., and Bienkowski, M. 1982. Automatic access of the meanings of ambiguous words in context: Some limitations of knowledge-based processing. *Cognitive Psychology* 14:489-537.

Stowe, L. A. 1991. Ambiguity resolution: Behavioral evidence for a delay. In Proc. of the Thirteenth Annual Conference of the Cognitive Science Society, 257-262. Hillsdale, NJ: Lawrence Erlbaum.

Taraban, R., and McClelland, J. L. 1988. Constituent attachment and thematic role assignment in sentence processing: Influences of content-based expectations. *Journal of Memory and Language* 27:597-632.

Tyler, L. K., and Marslen-Wilson, W. D. 1977. The on-line effects of semantic context on syntactic processing. *Journal of Verbal Learning and Verbal Behavior* 16:683-692.

Waltz, D. L., and Pollack, J. B. 1985. Massively parallel parsing: A strongly interactive model of natural language interpretation. *Cognitive Science* 9:51-74.

Woods, W. A. 1973. An experimental parsing system for transition network grammars. In Rustin, R. ed. Natural language processing. New York: Algorithmics Press.