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Abstract

The development of models of human sentence processing has traditionally followed one of two paths. Either the model posited a sequence of processing modules, each with its own task-specific knowledge (e.g., syntax and semantics), or it posited a single processor utilizing different types of knowledge inextricably integrated into a monolithic knowledge base. Our previous work in modeling the sentence processor resulted in a model in which different processing modules used separate knowledge sources but operated in parallel to arrive at the interpretation of a sentence. One highlight of this model is that it offered an explanation of how the sentence processor might recover from an error in choosing the meaning of an ambiguous word: the semantic processor briefly pursued the different interpretations associated with the different meanings of the word in question until additional text confirmed one of them, or until processing limitations were exceeded. Errors in syntactic ambiguity resolution were assumed to be handled in some other way by a separate syntactic module.

Recent experimental work by Laurie Stowe strongly suggests that the human sentence processor deals with syntactic error recovery using a mechanism very much like that proposed by our model of semantic error recovery. Another way to interpret Stowe's finding that two significantly different kinds of errors are handled in the same way is this: the human sentence processor consists of a single unified processing module utilizing multiple independent knowledge sources in parallel. A sentence processor built upon this architecture should at times exhibit behavior associated with modular approaches, and at other times act like an integrated system. In this paper we explore some of these ideas via a prototype computational model of sentence processing called COMPERE, and propose a set of psychological experiments for testing our theories.

Overview

Most models of human language processing enforce a separation of language levels either through an assumption of individual modules each devoted to a different level of language or, de facto, by focusing on only one aspect of language processing (e.g., lexical disambiguation, theta-role assignment, or syntactic structure building). In contrast, our ongoing research has focused on finding ways to integrate language processing using as few assumptions of separate processes as possible. However, we have always been cognizant of the fact that theories of modular processes have support in the literature, and we have found it convenient in our own work to focus on lexical and pragmatic disambiguation during sentence processing in a modular fashion.

Our current work represents a meeting of theoretical intent with computational instantiation. In this new model, a unified processor is able to generate multiple inferences and make decisions among these inferences at all levels of language processing. Currently, our model encompasses lexical, syntactic, semantic, and pragmatic processes. The model is also able to make the kinds of inferential errors that people do and to recover from them automatically, as people do. Finally, this model, although a single processor, unites two schools of thought regarding the modularity of language. Our model is able to exhibit seemingly modular processing behavior that matches the results of experiments showing different levels of language processing (e.g., Forster, 1979; Frazier, 1987) but is also able to display seemingly integrated processing behavior that matches the results of experiments showing semantic influences on syntactic structure assignment (e.g., Crain & Steedman, 1985; Tyler & Marslen-Wilson, 1977).

Background

ATLAST (Eiselt, 1989) was a model of unified lexical and pragmatic disambiguation and error recovery. The model included lexical and world knowledge; it also included some amount of syntactic knowledge. The syntactic information was processed separately, using an ATN parser. The model achieved disambiguation using multiple access of meanings for lexical items and pragmatic situations, choosing the meaning that matched previous context, and deactivating but retaining all other meanings. If later context proved the initial disambiguation decision incorrect, the retained meanings could be reactivated without reaccessing the lexicon or world knowledge. ATLAST proved to have great psychological validity for lexical and pragmatic processing—its use of multiple access was well grounded in psychological literature (e.g., Tanenhaus, Leiman, & Seidenberg, 1979), and, more importantly, it made psychological predictions about the retention of unselected meanings that were experimentally validated (Eiselt & Holbrook, 1991; Holbrook, 1989).

ATLAST was not intended to model syntactic disambiguation and error recovery, but we believed that the principles embodied in the model should extend to syntactic knowledge as well (Granger, Eiselt, & Holbrook, 1984): that syntactic disambiguation and error recovery would follow the same pattern of multiple access, selection based on previous context, deactivation and retention of unselected structures, and reactivation of unselected structures should an error be discovered. At last year's meeting of the Cognitive Science Society, Stowe presented the finding that syntactic information and semantic information interact as the knowledge structure is built. Stowe's work (1991; Holmes, Stowe & Cupples, 1989) has lent credence to the prediction that syntactic knowledge is processed just like other language knowledge sources. Particularly relevant to the work presented herein is Stowe's conclusion that in cases of 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. The new psychological evidence inspired us to extend ATLAST to include syntactic knowledge as an integral part of a unified language processor.

The New Theoretical Model

We propose that the human sentence processor can best be described as a single unified language processor which operates on distinct knowledge sources. These knowledge sources correspond to what are typically labeled *syntax* and *semantics*. While these sources contain different types of knowledge, the same process is used to manipulate and integrate each type of information into a coherent and plausible interpretation. The single processor allows inferences about the interpretation to be generated uniformly, regardless of the type of inference that must be made. Thus, an ambiguous word, an ambiguous parse tree, an ambiguous thematic role assignment, and an ambiguous semantic representation are all disambiguated by the processor in the same way.

This model of sentence processing attempts to explain several different phenomena. For example, lexical/semantic disambiguation and error recovery are accounted for by the approach first postulated in the ATLAST sentence processing model. Since we are using a single processor for all processing in our new model, the approach used by ATLAST is now applied to syntactic disambiguation and error recovery. As a result, we have a plausible process account of Stowe's (1991) findings.

Additionally, because the knowledge sources are modular while the processing is unified, we predict that this new model will sometimes exhibit ambiguity resolution behavior like that expected from a strong modular, autonomous process approach to sentence processing (e.g., Forster, 1979), and at other times it will exhibit behavior more like that expected from a strong interactive approach (e.g., Tyler & Marslen-Wilson, 1977). These differences in behavior will depend on whether the information available from the different knowledge sources is sufficient to resolve the specific ambiguities at hand at any given time. In short, this model should account for the wide range of data accumulated by the opposing camps in this ongoing debate.

Implementation

To explore how well ATLAST's approach to lexical/semantic disambiguation and error recovery would actually work when applied to the resolution of syntactic ambiguity, we constructed a prototype computational model called COMPERE (Cognitive Model of Parsing and Error Recovery) to serve as a testbed. This computational model follows closely the spirit of the theoretical model described above, but diverges slightly in actual implementation. The divergence appears in the processor itself: the theoretical model has a single processor, while the prototype computational model has two nearly-identical processors—one for syntax and one for semantics—which share identical control structures but are duplicated for convenience because each processor must work with information encoded in slightly different formats. Because we intended only to explore syntactic ambiguity and error recovery with this initial computational model, the distinction between two identical processors and one unified processor is unimportant. As we expand the scope of our investigations, however, we will need to unify the two processing components completely.

Both types of knowledge are represented as networks of structures. Syntactic knowledge is represented as a network in which each node holds all the knowledge about a particular syntactic category necessary for parsing a sentence into its surface structure. A node in the network representing semantic knowledge stands for a concept. The structure of the node (i.e., its slots) represents the relationships between the node and other concepts. These relationships can include world knowledge in the form of selectional restrictions.

In addition to syntactic and semantic knowledge, COMPERE has a lexicon which provides

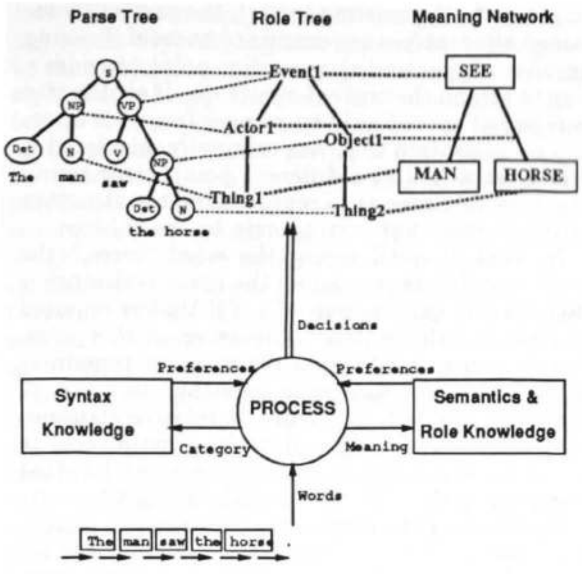

Figure 1: Architecture of COMPERE

the syntactic categories and subcategories of words as well as the meanings of words represented as pointers to nodes in the semantic network. The semantic component also has knowledge of thematic roles which helps bridge syntax and semantics. For instance, it knows that a noun phrase has a primitive role called **THING** which can evolve *in context* to an **ACTOR** or an **OBJECT** role. The representations of the different bodies of knowledge and the flow of information between them is shown in Figure 1.

The Process

Words are read from left to right, and their lexical entries are retrieved. The syntactic categories are passed to the syntax processor; at the same time, the pointers to corresponding meanings are passed to the semantic processor. The semantic processor builds a tree of thematic roles, as well as a network of instances of meaning structures.

As explained above, the control structures of the syntax and semantic processors are identical, though they process different kinds of knowledge. The processors interact many times in processing each word as they build the trees. The syntax processor first builds the basic node for the category of the word which will be a leaf of the parse tree. The semantic processor builds a node for the primitive role the word plays (if any) and also instantiates the meaning structure for the word. For instance, on reading the verb "saw," the syntax processor builds a verb node (V) to be added to the parse tree of the current sentence. The semantic processor builds nodes for an **EVENT** role and an instance of the **SEE** structure. These structures must be connected to other role and meaning structures already built for the sentence. The processors now try to connect the new nodes with the partial trees built earlier. When the syntactic structure of a sentence is successfully parsed, the meaning of the sentence is available as the meaning attached to the root node (S) of the parse tree.

Whenever the syntactic processor connects a node to its parent, it communicates with the semantic processor. The semantic processor tries to find corresponding relationships in the meanings associated with the two nodes by way of connecting their roles in the role tree. Thus the meanings associated with the nodes move up along the syntactic structure. When they meet at a common node, the semantic processor tries to bind them together through their roles. For example, consider the following sentence:

Text 1: The man saw the horse.

The structures that exist after reading "The man saw" are shown in Figure 2.

Figure 2: COMPERE's output for "The man saw."

Now, after reading "the horse," the system creates a noun phrase (NP) node to be connected to the above parse tree, a **THING** role to be connected to the above role tree, and a **HORSE1** structure to be connected to the meaning structures above. Syntactic processing could propose a connection from the new NP to the verb phrase (VP) in the tree, making "the horse" the syntactic object. The semantic processor finds corresponding links between the **HORSE1** node and the **SEE1** node through its **OBJECT** slot. This results from specializing the **THING** role of "the horse" to an **OBJECT** role which can now be connected to the **EVENT1** role. This process can be viewed as the meaning of "horse" propagating up the parse tree to meet the meaning of "see" at the VP node where the corresponding semantic connections are found. The structures built at the end of the sentence are shown in Figure 3.

Though the syntactic and semantic processors interact with each other, they are functionally independent; each can do its job should the other fail. If the syntactic processor fails to build a parse structure for a sentence, the semantic processor connects the primitive role for a word with the role tree (or a set of subtrees) built thus far. The processor can make decisions based on preferences coming only from one source of knowledge (such as syntax or semantics) if other sources fail to provide any preferences. Such a failure of the other sources could be either due to a lack of

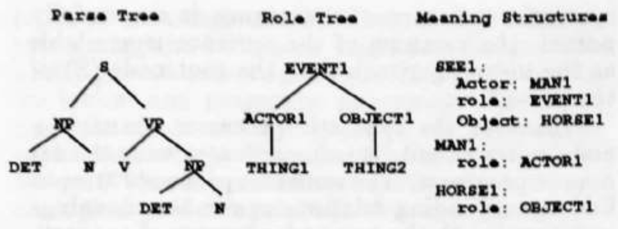

Figure 3: COMPERE's output for Text 1.

knowledge or due to a lesion in the communication pathways. Functionally independent behavior of this kind would not have been possible if the system had a single integrated source of knowledge together with a unified processor as seen in other models (e.g., Jurafsky, 1991; Lebowitz, 1983).

Ambiguity Resolution

Structural ambiguities in a sentence can be resolved through semantic or syntactic processing. For instance, if Text 1 were changed to:

> **Text 2:** The man saw the woman with the horse.

there would be at least two possible interpretations from a syntactic point of view—attaching the prepositional phrase (PP) to the VP or to the object NP—but only one of them is supported by semantics. The NP-attachment interpretation with its "woman together with the horse" meaning is acceptable whereas the VP-attachment interpretation with its "saw using the horse as an instrument" is not acceptable since it violates the constraint that the **INSTRUMENT** slot of the event **SEE** must be filled by an optical instrument.

On the other hand, consider the following sentence:

> **Text 3:** The officers taught at the military academy were very demanding.

The verb "taught" is interpreted as the main verb of the sentence since that would satisfy the expectation of a VP at that point in processing. In other words, we would rather use the verb to begin the VP that is required to complete the sentence structure, instead of treating it as the verb in a reduced relative clause which would have left the expectation of a 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.

Error Recovery

When choices are made to resolve structural ambiguities, the alternatives that were not selected are retained for possible recovery from erroneous decisions. When it is not possible to attach a structure to the existing tree(s), the previously retained alternatives are examined to see if choosing another alternative at an earlier point provides a way to attach the current structure. If so, the tree is repaired accordingly to recover from the error. Since the subtree that was originally misplaced is merely attached at a different point, error recovery does not amount to reprocessing the structure of the phrase that corresponds to the subtree.

In Text 3, until seeing the word "were," the verb "taught" 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. The processor now tries the other way of attaching the VP as a reduced relative clause so that there will still be a place for a main verb. In doing so, it did not have to process the PP that was part of the VP for the verb "taught."

In resolving the structural ambiguity in Text 3, semantic preferences did not play a significant role. In other situations, semantic preferences could influence the decisions that the processor makes in resolving syntactic ambiguities. Such behavior would be the same as the ones explained by models which argue for the early effects of semantic and contextual information in syntactic processing (e.g., Crain & Steedman, 1985; Tyler & Marslen-Wilson, 1977). COMPERE is intended to demonstrate that the range of behaviors that these models account for, and the behaviors that the "first analysis" models (e.g., Frazier, 1987) account for, can be explained by a unified model with a single processor operating on multiple independent sources of knowledge.

COMPERE has been implemented on a Symbolics workstation in the Common Lisp language with the Common Lisp Object System. It can process both the syntax and semantics of simple sentences (including all examples used in this paper) and uses semantic information in resolving structural ambiguity. Recovery from errors in resolving structural ambiguity has been implemented in the syntax processor alone; recovery from lexical/semantic errors has not yet been implemented in this model, but it will require very little effort to adapt the mechanism already used successfully by the ATLAST (Eiselt, 1989) system.

Proposed Psychological Studies

To test the validity of our psychological claims, we must answer the following questions: (1) How do we show that there is a single processing architecture which applies to multiple knowledge sources to make language decision, as opposed to multiple, non-identical processors? (2) How can we show error recovery occurring automatically and on-line for lexical, syntactic, semantic and other types of errors?

Answering Question 1

Recent experiments (e.g., Holmes, Stowe, & Cupples, 1989) have focussed on manipulating the information processed, but not the act of processing itself. By varying the type of task assigned to the subject, we can manipulate the processing style that is being executed. We have created materials that make processing more (or less) syntactic or semantic, by giving a task that biases the processor toward any given level. In one experiment, we are using two sets of materials, one semantically weighted and the other syntactically weighted. We have manipulated the level of processing by changing the task that subjects must perform. We are comparing the time it takes for subjects to make word-by-word completion decisions: either a decision on whether a sentence can still be completed grammatically, or whether a sentence can still be completed semantically. We are looking at the kinds of comprehension errors that are made for syntactically versus semantically weighted sentences, as well as at how the reaction time curve changes for the stimuli depending on the level of processing. Thus, in this experiment, we are able to assess the separate effects of the processor and the type of information processed on parsing decisions. Both processing models make empirical predictions. The single-processor model predicts uniform processing errors when we manipulate the processing environment but not the information processed. The multiple processor model predicts that processing errors will be different when we manipulate the processing environment.

A second point of comparison between single and multiple processor models is that the single processor model assumes interaction between lexical information and syntax and semantics, while the multiple processor model assumes that these would be separable. One point at which the information sources may interact is when lexical items are recognized. Some words are syntactically ambiguous, such that more than one part of speech (and probably meaning as well) must be called up.

Seidenberg, Tanenhaus, Leiman, and Bienkowski (1982) looked at ambiguous words that each had a meaning which lexically subcategorized as a noun and a meaning which lexically subcategorized as a verb. Their results showed that even when subcategorization information is available, it does not immediately restrict the processor from viewing all possible meanings of a word any more than other aspects of the word's meaning do. This is evidence that, at the place where meaning and structure are first constructed, the information is extracted in the same manner. We are conducting a similar experiment to that of Seidenberg et al., the main difference being that in our study, the ambiguous word is embedded within the sentence instead of at the end. This is because active suppression of alternate meanings is more likely to occur at the end of materials than within them (Holbrook, 1989). Seidenberg et al.'s results suggest support for the single processor model over the multiple processor model, but only at 0 msec. We are testing to see the time course of disambiguation due to subcategorization information, and the extent to which subcategorization information is relied upon exclusively for disambiguation. If the single processor model is correct, the subcategorization information should be useful but not always deterministic. A multiple processor model would predict that the subcategorization information will be an early and unassailable determiner of meaning choice.

Answering Question 2

Error recovery ought to act differently for a single processor system than for a multiple processor system. A unified process ought to make the task easy, and multiple processes ought to make it hard. The single processor model predicts that error recovery is uniform, no matter at what level of processing the error occurs. The same elements will be brought to bear to fix the error at the lexical, syntactic, and semantic levels. Our previous experiments (e.g., Eiselt & Holbrook, 1991; Holbrook, 1989) have validated the mechanism for lexical ambiguity, but have not validated it for other types of errors. Evidence from similar experiments by Holmes, Stowe and Cupples (1989) showed similar findings for syntactic subcategorization: as in our experiments, one interpretation was chosen and then discarded when later information negated this decision. To tie these two sets of experiments together, we are running the variations on the Holmes et al. experiments described above. To look at error recovery, we will look for priming effects for both meanings of the ambiguous word and for evidence of re-instantiation of a discarded structure.

Conclusion

A model that unifies separate processing mechanisms can only be considered successful if it is able to explain apparently different types of output, such as syntactic and semantic output. In this paper we have developed a model that is able to do so by uniformly processing different types of information. The advantages to this model are that processing errors are usually avoided; many of the processing errors that still occur can be corrected immediately and unconsciously, so that processing can remain automatic and unconscious. The emphasis on different information types allows our model to remain consistent with work that suggests modularity at various levels of processing; the modularity lies in the division of the information types. However, the single processor simplifies the task of building compatible syntactic and semantic structures and allows for their interaction as the meaning of the text is evolved from the separate types of information. Hence, we can explain apparently anomalous psychological findings (e.g, Frazier, 1987; Tyler & Marslen-Wilson, 1977) within a single perspective.

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