Resolution of Structural Ambiguities in Sentence Comprehension: On-line Analysis of syntactic, lexical, and semantic effects[1]

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Temporal onset and relative strength of effects of lexical preference and world knowledge were analyzed in relation to syntactic preferences in a series of experiments on the interpretation of sentences that contained structurally ambiguous prepositional phrases. We found a significant effect of lexical preference (i.e., of main verb subcategorization) that was established before a decisive influence of world knowledge. Since the sentences were in German, transforming them into the "Perfekt" (present perfect) tense allowed for studying the relative effects of those factors in head-final verb phrases. Under these conditions, world knowledge suppressed the influence of lexical preference, which nevertheless affected decision times. In all cases, a slight bias in favor of early closure was found. The results are discussed with respect to contrasting theories of psychological principles in sentence parsing.

To assess how different sources of knowledge, like syntactic, semantic or lexical, and world knowledge, influence the way we process natural language, constitutes one of the main goals for psycholinguistic studies (e.g., Bever, 1970, Crain & Steedman, 1985, Flores d'Arcais, 1982, Ford, 1986, Frazier, 1987, Strube, Hemforth & Wrobel, 1990). We believe that language understanding entails the incremental construction of a mental model (Johnson-Laird, 1983, van Dijk & Kintsch, 1983), making use of those sources of knowledge interactively. Sentences with global structural ambiguities are optimally suited for studies of the relative effects of those sources of knowledge.

The materials used in our experiments consists of sentences of the following kind:

(a)   *Susanne verzierte die Torte mit der süßen Sahne.*
           (Susan garnished the fancy cake with the sweet cream.)

Here we get two possible readings:

(a1)   *instrumental:*   *garnished ... with the sweet cream*
(a2)   *attributive:*   *the fancy cake with the sweet cream*

The structural interpretations (a1) and (a2) differ with respect to the attachment of the prepositional phrase (PP). In (a1), the PP would be attached as an instrument to the verb, in (a2), it would serve as a specification of the second noun phrase (NP "the fancy cake"), and would be integrated into a complex NP.

Three kinds of linguistic hypotheses have been stated regarding the processing of structural ambiguities: (1) purely syntactic principles (Frazier, 1987, Kimball, 1973), (2) lexical preferences (Ford, 1983, 1986, Ford, Kaplan & Bresnan, 1982, Mitchell & Zagar, 1986), (3) hypotheses concerning dominant influences of pragmatic constraints and general world knowledge (Altmann, 1988, Altmann & Steedman, 1988, Crain & Steedman, 1985, Johnson-Laird, 1983).

A well-known syntactic principle is minimal attachment (Frazier & Fodor, 1978). In essence, it postulates that the reading containing the least number of precategorial nodes in the phrase-structure tree is the preferred one. Other sources of knowledge, i.e., lexical and semantic preferences, come in later, operating as a kind of filter (Frazier, 1987). In contrast, Lexical Functional Grammar calls for direct inclusion of lexical knowledge in the process of sentence parsing and interpretation (Ford, Bresnan & Kaplan, 1982). Based on the LFG framework, although not strictly dependent on it, Ford (1986) developed four parsing guidelines, or syntactic closure principles. The central principle of lexical preference states that whenever the lexicon contains several possible subcategorization frames for the same verb, they will be ordered according to lexical preference, and this order will affect how a sentence is parsed. With respect to our example sentence (a), this amounts to the following prediction: If a three-slot frame (subject, object, oblique instrument) is prioritized for the verb "to garnish", (a1) will be chosen as the preferred reading. If otherwise, i.e., the two-slot frame (subject, object) having priority, parsing of (a) would be subjected to Ford's final argument principle: when the last slot has been filled and the sentence still continues, the object NP is not closed before the sentence has been parsed completely, resulting in the construction of a complex NP, or reading (a2).

The above theories of psychological parsing rely on grammatical knowledge, i.e., on language-specific knowledge as contrasted to general world knowledge (Felix, Kanngießer & Rickheit, 1986). They cannot explain the principles that guide the analysis of a sentence like

(b)　　Susanne verzierte die Torte mit dem delikaten Mokkageschmack.
　　　　(Susan garnished the fancy cake with the delicious mocca flavor.)

Obviously, knowledge is needed about possible or probable pairings between entities and suitable attributes, or between verbs and instruments (or ornatives). In (b), a mocca flavor is hardly a possible instrument for decorating a cake, nor a decoration in itself. Crain and Steedman (1985) express this line of reasoning through their principle of a priori plausibility: Other things being equal, that reading of a sentence will be preferred which appears more plausible in the face of general or domain-specific world knowledge, or the current discourse. This is in turn explained by a principle of parsimony: The more plausible an interpretation, the less presuppositions, or changes to the mental model currently held, are needed to understand the sentence.

In the following, two experiments from a larger series are reported in which we studied the processing of sentences with structurally ambiguous prepositional phrases (all of them using the German preposition "mit", i.e., "with"). Lexical preference and world knowledge were varied in both experiments. Due to a variation of tense (which put the main verb at the end of the sentence according to German grammar), these sources of knowledge could be applied at different times in the two experiments. Experiment 1 used German "Imperfekt", with head-initial position of the verb like (a) or (b), whereas the "Perfekt" sentences of Experiment 2, like (c), are characterized by head-final position of the verb (in the form of the participle). Thus lexical preference comes into play before world knowledge in Experiment 1, but only at the end of the sentence in Experiment 2.

(c)　　Susanne hat die　Torte　　mit　der süßen Sahne　verziert.
　　　　(Susan　has the fancy cake with　the　sweet cream　garnished.)

Experimental design

Lexical preference (L) and world knowledge (W) were included as factors in the design. Lexical preference had the following values:

　　　　L1　preferred subcategorization frame with 3 slots (subject, object, oblique instrument or ornative)(3-slot verbs),
　　　　L2　preferred subcategorization frame with 2 slots (subject, object)(2-slot verbs),
　　　　L3　no clear preference of either the 2-slot or 3-slot frame (neutral verbs).

World knowledge also entered the design in three categories:

W1 preferred verb-modifying (e.g., instrumental) interpretation,
W2 preferred object-specifying interpretation,
W3 ambiguous, both readings possible with respect to general knowledge.

Here are some examples of the resulting combinations:

L1 W1 *Susan garnished the cake with the small icing funnel.*
    W2 *Susan garnished the cake with the delicious mocca flavor.*
    W3 *Susan garnished the cake with the sweet cream.*

L2 W1 *Laura ordered the document with the short phone call.*
    W2 *Laura ordered the document with the black binding.*
    W3 *Laura ordered the document with the yellow form.*

L3 W1 *Bill frightened the child with the old ghost story.*
    W2 *Bill frightened the child with the little snub-nose.*
    W3 *Bill frightened the child with the small toy pistol.*

Construction of materials

In order to construct sentences according to the nine conditions, we had to conduce some extensive pre-tests. Following a linguistically founded preselection of verbs with the help of a pertinent dictionary (Ballmer & Brennenstuhl, 1986), we ascertained the verbs' lexical preference with several sentence completion tasks. For each of the classified verbs, we then built three sentences according to the three world knowledge conditions. This classification was verified with another pre-test in which subjects' comprehension of structurally disambiguated versions of the sentences were recorded.

Experimental Technique

In both experiments, we used the technique of a continuous semantic decision task which we developed in the context of previous project work on the comprehension of temporal clauses. According to this technique, subjects read sentences on a computer screen word by word. By pressing one of two buttons, the subject indicates her comprehension of the sentence and at the same time controls the speed of the presentation. As soon as the button is pressed, the actual word disappears from the computer screen and the next word appears.

This procedure combines a method first used by Aaronson (1976) – the recording of word reading times during RSVP (rapid serial visual presentation) of the sentence material – with the method of continuous reaction which was developed by Wickelgren, Corbett & Dosher (1980) and improved by Schmalhofer (1986).

Experiment 1

Method

Procedure: 21 subjects (students of the Ruhr-University of Bochum with German mother-tongue; no students of psychology) participated in the experiment. Subjects were run individually in half an hour sessions. They were paid for their efforts. The continuous semantic decision task mentioned above was realized in the following way: word by word, subjects had to decide or hypothesize, respectively, whether the prepositional phrase of the actual sentence was more likely to modify the verb (left button), or the object (right button). After the end of the sentence, a question mark appeared on the computer screen. Now the subjects had to indicate their decision again. To make sure that they considered the whole sentence, subjects were asked an additional question about the actual sentence's semantic content. For warming up, seven filler sentences were presented in the beginning of the experiment.

We recorded the following dependent variables:
(a)   on-line decisions about the attachment of the prepositional phrase for each word and after the end of the sentence
(b)   inspection times for each word and for the decisions after the sentence, i.e the time interval between the appearance of a word on the computer screen and the moment when the button is pressed

Hypotheses

Assuming that both sources of information, world knowledge and lexical knowledge, guide processing immediately, as soon as the corresponding informations are available, the following course of decisions should be found: the verb should deliver the preferred subcategorization frame, so that from the second position onwards significant main effects should be found. For two-slot frames only few decisions should be made in favor of the "verb-modifying" interpretation, whereas this interpretation should be strongly preferred for three-slot frames. No preferences are expected for neutral verbs. In the unambiguous world knowledge conditions decisions should definitely be influenced, as soon as the noun in the prepositional phrase is processed. Since the semantic analysis of some adjectives constrains the choice of following nouns (the girl with the blond ...), at this position (position 7) first effects of world knowledge may be found.

Facilitiation effects should be demonstrable for decisions as well as inspection times, when informations from both sources are congruent, whereas incongruent informations should complicate processing. From earlier experiments with different materials we expect that world knowledge dominates the final interpretation, so that lexical preferences can only influence final interpretations of semantically ambiguous sentences.

Statistical Methods

For both experiments, decisions were statistically analyzed by stepwise adaptations of hierarchical loglinear models with lexical preference and world knowledge as independent variables.
Inspection times were tested by within subject analyses of variance with the same independent variables. The word length, operationalized as the number of letters for each word, was included as covariate, if needed.

Results

Decisions:

As shown in figure 1, there is a significant main effect of lexical preference from position 4 to position 7 (from the noun of the simple object NP to the adjective in the PP). The significant effects are due to the fact that at these positions sentences are judged more often in favor of a verb-modifying interpretation, if the sentence contains a three-slot verb. Neutral and two-slot verbs do not differ significantly. There is a weak tendency (p < .11) for the main effect at position 3 (the article of the simple object NP).
Contrary to our hypothesis, the main effect does not show up at position 2 and can no longer be found at the end of the sentence even for semantically ambiguous sentences.

As expected, sentences were judged according to the world knowledge conditions from the adjective of the PP onwards (see figure 2). In semantically ambiguous sentences PPs were more often interpreted as verb-modifying (60.5%).

Inspection times

No significant differences between the three lexical conditions were found. At the end of the sentence (position 8), there is a significant main effect due to world knowledge. The unambiguous conditions are processed faster (verb-mod. vs ambig.: $F=3.95$, $df=1,19$, $p<.07$; obj.-mod. vs ambig.: $F=21.03$, $df=1,19$, $p<.001$).
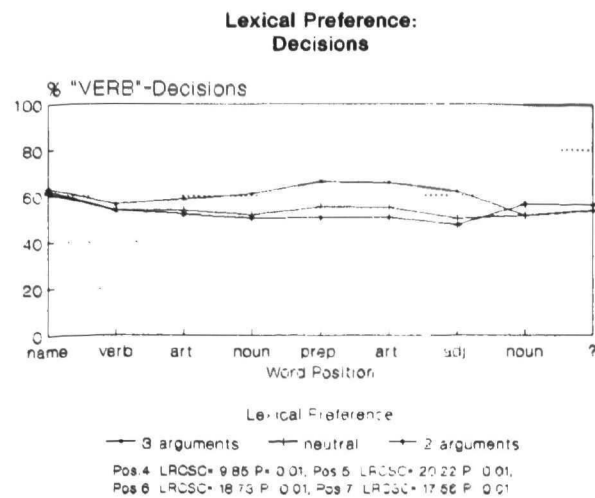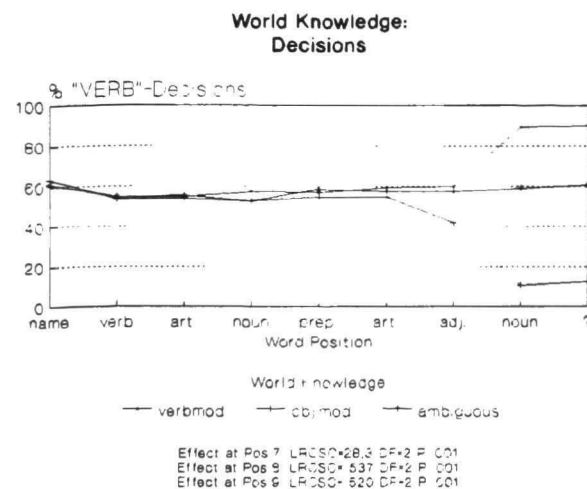
Figure 1.

Lexical Preference:
Decisions

% "VERB"-Decisions

Lexical Preference

←— 3 arguments —+— neutral —*— 2 arguments

Pos.4 LRCSC= 9.85 P= 0.01, Pos.5 LRCSC= 20.22 P 0.01,
Pos.6 LRCSC= 18.73 P 0.01, Pos.7 LRCSC= 17.56 P 0.01

Figure 2.

World Knowledge:
Decisions

% "VERB"-Decisions

World Knowledge

←— verbmod —+— objmod —*— ambiguous

Effect at Pos.7 LRCSC=28.3 DF=2 P .001
Effect at Pos.9 LRCSC= 5.37 DF=2 P .001
Effect at Pos.9 LRCSC= 5.20 DF=2 P .001

Congruent informations from both sources (world knowledge and lexical preference) lead to significantly shorter inspection times than incongruent informations (verb-mod./verb.-mod.: mean= 2729 msec, obj.-mod./obj.-mod.: mean=2525 msec, verb.-mod./obj.-mod.: mean=3638 msec, obj.-mod./verb-mod.: mean=3375 msec; F= 4.43;DF=2,40;p < .02).

Experiment 2

Method

Because of the head-final position of the main verb in German perfect tense sentences the availability of world knowledge and lexical preference is reversed. For our second experiment only the tense of the sentences was changed from "Imperfekt" (past tense) to "Perfekt" (present perfect). Method and experimental design, and consequently dependent and independent variables were identical to those of Experiment 1.

562

Hypotheses

As in the first experiment we expect that world knowledge is used for disambiguation immediately, i.e. as soon as the corresponding informations are available. According to this hypothesis the course of decisions should develop in the following way: When the adjective and the noun of the prepositional phrase are processed there is enough information to decide whether the prepositional phrase can be attached to the simple object NP. If attachment is possible subjects should prefer the object modifying interpretation, otherwise they should decide that the prepositional phrase will modify the verb. The attachment to the simple object NP implies that the new information (PP) can be combined with an already established entity in the mental model of the sentence. This integration should be less effortful, i.e. less time-consuming than the establishment of a new entity in the verb modifying case. If world knowledge supports the verb modifying interpretation the prepositional phrase delivers information about possible verbs. So the main verb should be processed faster in this condition.
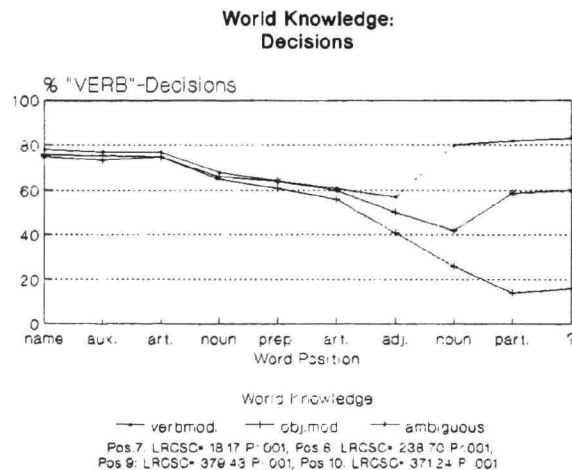
In our first experiment we did not find any effects of lexical preference on decisions as soon as world knowledge information was fully available. Because of the head-final position of the verb we do not expect any effects of lexical preference in this experiment. The interaction of world knowledge and lexical preference concerning inspection times should still be demonstrable.

Results

Decisions

No effects of lecical preference were found. The expected main effect of world knowledge is already to be found at the seventh position (adjective) and stays significant up to the decision after the end of the sentence. Decisions were made according to the world knowledge conditions (see figure 3).

Figure 3.

World Knowledge:
Decisions

% "VERB"-Decisions

World Knowledge

—•— verbmod.   —+— obj.mod   —*— ambiguous
Pos.7. LRCSC= 18.17 P .001, Pos 8 LRCSC= 238.70 P .001,
Pos 9: LRCSC= 379.43 P .001, Pos 10. LRCSC= 371.24 P .001

Inspection times

There were no significant effects of lexical preference. As shown in figure 4, a significant main effect of world knowledge is present from position 7 (adjective of the PP) on. As expected, inspection times for positions 7 and 8 (adjective and noun of the PP) were shorter

563

if world knowledge supported the object-modifying interpretation (position 7: F=6.00, df=1,19, p < .03, position 8: F=3.74, df=1,19, p < .07). At position 9 (main verb participle) the order of means is reversed (F=12.6, df=1,19, p < .01), again as expected. This results in a significant interaction between world knowledge and position (F=12.88, df=2,37, p < .001). Unambiguous world knowledge leads to significantly shorter inspection times at the end of the sentence (position 9; verb-mod. vs amb.: F=19.14, df=1,19, p < .001; obj.-mod. vs amb.: F=14.02, df=1,19, p < .01).

Figure 4.

World Knowledge:
Inspection Times
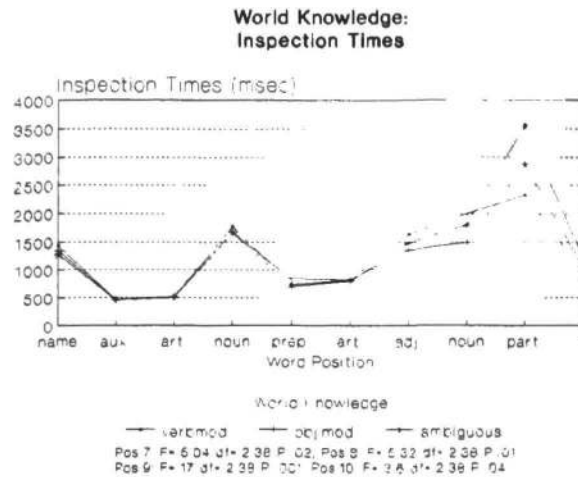
As in Experiment 1, a significant interaction between lexical preference and world knowledge was found at the end of the sentence(F=4.83, df=2,37, p < .02). The effect is confined to 3-slot verbs where congruent informations from both sources lead to shorter inspection times than incongruent informations (verb-mod.: mean=2107 msec; obj.-mod.: mean =3167 msec; F=14.37, df=1,20, p < .01).

Discussion

Summing up, the results of our experiments show that both sources of knowledge are drawn upon during sentence processing, and that they are used on-line, i.e., human parsing proceeds incrementally. The various sources of knowledge are, however, not equally important in determining the interpretation of a sentence.

(1) An effect of lexical preference could be demonstrated in Experiment 1, although it did not quite conform to expectations. For one, availability of lexical information (contingent on the verb) does not show an effect immediately, but only builds up a significant difference from the noun of the object NP onward. This testifies against immediate **full** processing, suggesting gradual processing of lexical information. Most important, lexical effects are present before the PP is processed. Therefore we conclude that lexical preference operates as a source of information guiding further syntactic analysis (lexical guidance, Ford, 1986, Holmes, 1987) rather than a filter applied to the result of autonomous syntactic analysis (Frazier, 1987).

Verb frames for verbs with preferred 2-slot readings (without an oblique instrument) and for verbs without a clear preference do not give rise to statistically significant differences during sentence processing. In other words, preferredly 2-slot subcategorization frames do not generate a specific expectation. Even at the end of a sentence, no effect shows up, and world knowledge alone

determines the interpretation.

(2)   World knowledge comes into play as soon as possible, i.e., when reading the adjective of the PP. Inspection times show that unambiguous world knowledge facilitates processing.

In head-final sentences (German present perfect) integrating the PP is easier if it can be integrated with the object into a complex NP. On the other hand, the predictive value of the instrument/ornative noun of the PP facilitates processing of the main verb participle.

(3)   For both experiments, congruent information at the end of the sentence (i.e., both world knowledge and lexical preference in concordance) leads to shorter processing times. (In Experiment 2, this effect is confined to 3-slot verb frames.)

(4)   World knowledge and lexical preference show two major differences. While world knowledge dominates the interpretation and is processed immediately, the effects of lexical preference take some time to build up, are generally much weaker, and disappear toward the end of a sentence.

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