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Processing Syntactically Ambiguous Sentences: Evidence from Semantic Priming

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In this paper, we report the results of a study which investigates the processing of syntactically ambiguous sentences. We examined the processing of sentences in which an embedded clause is interpretable as either a complement clause or as a relative clause, as in, for example, "The receptionist informed the doctor that the journalist had phoned about the events." *The embedded clause in such sentences is typically analyzed as a complement to the verb* informed, *rather than as a relative clause modifying* the doctor. *A number of models parsing predict this is the only analysis ever considered, while others predict that both interpretations are computed in parallel. Using a cross-model semantic priming technique, we probed for activation of* doctor *just after the embedded verb. Since only the relative clause analysis contains a connection between* the doctor *and the embedded verb, we expected reactivation of* doctor *at that point only if the relative clause analysis were a viable option. Our results suggest that this is the case: Compared to priming in an ambiguous control sentence, a significant reactivation effect was obtained. These results are argued to support a model of parsing in which attachment of a clause may be delayed.*

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INTRODUCTION

A central question in the study of sentence comprehension is how the parser copes with syntactic ambiguity. That is, how does the parser behave when confronted with an input which is compatible with two (or more) different syntactic analyses? It is possible that the parser selects one analysis, in which case, it risks the possibility of error. Alternatively, it could pursue both analyses in parallel, or it could delay making a decision, either of which could be computationally demanding. These different solutions to the problem are compatible with fundamentally different processing systems. Discovering how the parser processes syntactic ambiguity helps us to illuminate the architecture of the sentence processing system.

In this paper, we focus on the processing of sentences in which the ambiguity concerns the attachment of a *that* clause, as exemplified by (1):

(1) The receptionist informed the doctor that the journalist had phoned about the events.

This sentence can have either (a) a complement clause interpretation, in which *the receptionist* informed *the doctor* about a particular thing, i.e., *that the journalist had phoned about the events*, or (b) a relative clause interpretation, in which *the receptionist* informed a particular *doctor* (namely, the doctor that the journalist had phoned) *about the events*. According to syntactic theories in which phrase structure plays a central role, the syntactic representations associated with these two interpretations differ in the attachment site of the embedded clause. Attaching this clause to the verb phrase (VP) satisfies the verb's ability to take a sentential complement, and doing so yields the complement clause reading. Attaching the clause to the noun phrase (NP) object the *doctor* gives rise to the relative clause reading, in which the relative clause modifies the NP to which it is attached. Alternative syntactic accounts encode the basic difference that the embedded clause is associated with the verb *informed* on the complement clause reading, but with *the doctor* on the relative clause reading.

Most theories of parsing acknowledge the fact that sentences such as (1) (at least when presented in isolation) are most commonly inter-

preted with the complement clause analysis; indeed, it is not uncommon to find that listeners or readers have great difficulty recovering the relative clause analysis at all, even when they are alerted to the fact that such sentences are ambiguous. That is, there seems to be a preference for the complement clause interpretation. The question which needs to be addressed, and the issue which divides the different models of parsing, is whether preferences of this type are reflected in the *initial* parse of sentences such as (1), or whether such preferences play a later role in processing.

We consider four approaches to this question. These are reviewed in the next section.

THEORIES OF SENTENCE PARSING

Serial, Strategy-Driven Parser

Proponents of serial models hold the view that the sentence parser constructs, in time with the input, a single phrase marker. At a point of ambiguity, where there is more than one legitimate attachment which could be made, the attachment decision is guided by parsing principles. Typically, such principles make exclusive reference to aspects of the syntax, independent of semantics or pragmatics. Frazier's formulation of Minimal Attachment, for example, dictates that incoming material be attached to the current parse tree "using the fewest nodes consistent with the well-formedness rules of the language" (Frazier & Rayner, 1982, p. 181). Another example is Abney's (1989) principle "attach to a θ-assigner", which makes reference to the capacity of a constituent to assign thematic roles.

The virtue of such models is that the parser, in computing a single phrase structure, need not require the computational or memory resources that might be required by the other approaches we will be describing. The disadvantage of serial systems, however, is that they are error-prone. Since such parsers cannot wait for possibly disambiguating input, and since they immediately commit to one parse, they will often "be led down the garden path." Proponents of such models argue that, of course, this is precisely what the human parser does, and this family of models has been dubbed "the garden-path model."

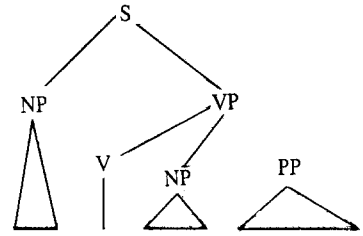
The evidence for this position comes from a substantial number of experiments (e.g., Clifton & Ferreira, 1989; Ferreira & Clifton, 1986; Frazier, 1979; Frazier & Rayner, 1982; Rayner, Carlson, & Frazier,

1983; Rayner & Frazier, 1987). For example, in the research reported by Rayner et al., subjects read sentences such as (2) and (3):

(2) The spy saw the cop with binoculars, but the cop didn't see him.
(3) The spy saw the cop with a revolver, but the cop didn't see him.

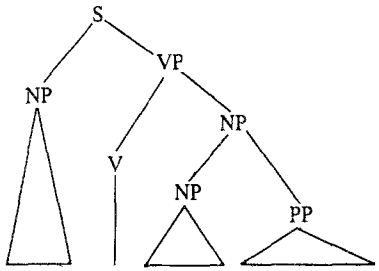
These sentences are ambiguous with respect to the attachment of the prepositional phrase containing *with;* according to Rayner et al., (1983), when this preposition appears, a decision must be made whether to attach it to the verb phrase node or to the noun phrase node. As shown by the tree structures associated with these sentences [(4) and (5), from Rayner et al., p. 368], the attachment of the prepositional phrase into the VP does not require the construction of new nodes. Associating the PP with the NP object of the verb, however, does demand that an additional node be created. Thus, attachment into the VP produces the syntactically simpler structure.[5]

(4)



[5] On more recent analyses of phrase structure, which do not allow trinary branching trees [as in (4)], it is still the case that the simpler structure is the one in which there has been attachment to the VP, but *only* when the PP is a complement to the verb and an adjunct to the noun. This is because attachment of an adjunct into *either* a VP or NP is taken to involve the creation of an additional node, whereas attachment of a complement (into either type of phrase) does not (see Radford, 1988, for basic exposition of these notions). This treatment of phrase structure complicates the minimal attachment strategy, because the garden-path model requires that attachment occur before the PP is interpreted, and there would be no grounds for the parser to assume that the PP is a complement of the verb. See Abney (1989) for similar, and additional, criticisms.

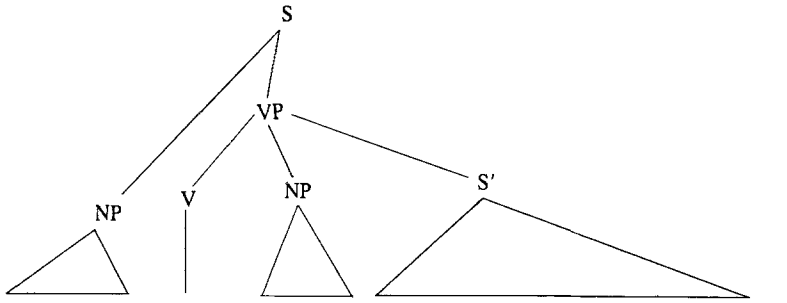
(5)



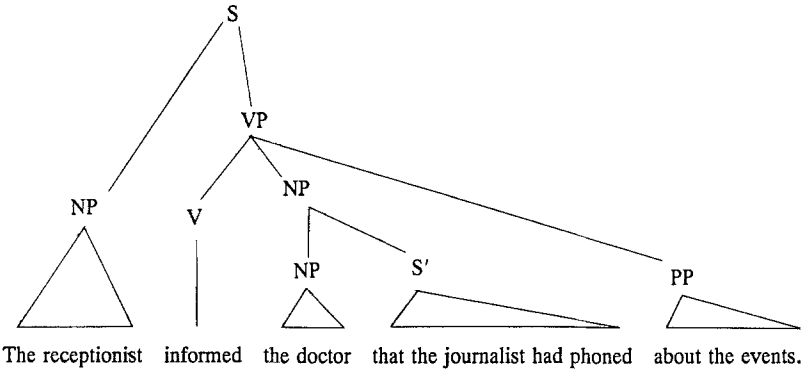
These sentences were presented on a CRT and subjects' eye movements were monitored and recorded. Rayner et al. (1983) reasoned that if the minimal attachment strategy is invoked during processing, it will result in attachment of the PP to the VP in both sentence versions. In only version (2), however, did minimal attachment produce a sentence which was pragmatically coherent: If the phrase *with binoculars* was attached to the VP (that is, if it *modifies* the verb), the result was a sensible sentence (e.g., *the spy uses binoculars to see the cop).* In (3), however, minimal attachment produced a sentence which was implausible (e.g., *the spy uses a revolver to see the cop*). Once the implausibility was registered, they argued, reanalysis automatically ensued. They assumed that detecting an error and reanalyzing the clause should cause longer reading latencies. Hence, reading times for (3) should be longer than for (2). This is exactly what they found.

Extrapolating to the sentence types of interest in this paper, the minimal attachment strategy would cause the *that* clause to be attached to the VP, since this attachment requires the construction of fewer nodes than would attachment to the NP *the doctor.* This is illustrated in (6) and (7).

(6) Complement clause analysis:



(7) Relative clause analysis:



In these sentences, the application of minimal attachment creates a structure in which the *that* clause is a complement clause, rather than a relative clause.[6] This accords with the general preference for the complement clause reading of such sentences. Note that the non-minimal attachment reading is never considered in sentences such as this, which contain no information which would be inconsistent with the initial parse. Once a commitment to the complement clause reading is made, the sentence continues to be both grammatical and plausible on this reading.

[6] Note that other serial models also predict, via different constraints, that the *that* clause will be construed as a complement to the verb. See, for example, Gorrell (1992), Pritchett (1992), and Weinberg (1992).

Weakly Interactive Parallel Parser

Crain and Steedman (1985), Altmann and Steedman (1988), and Steedman and Altmann (1989) (henceforth, where appropriate, referred to as ACS) propose a model which is similar to the garden-path model in that a commitment to a single analysis is made early, but different from this model in terms of its decision strategies; specifically, semantic information may be used to select a syntactic analysis. When an input has two different attachment possibilities, ACS assume that these are computed in parallel. These analyses are semantically interpreted, and evaluated with respect to the preceding discourse context, and the most contextually compatible analysis is selected. Any other analyses are immediately discarded.

In support of this view, Altmann & Steedman (1988) bring to bear a number of experiment results, such as that by Crain (1980), in which subjects were asked to judge the grammaticality of sentences similar to (8) and (9) below:

(8) The psychologist told the woman that he was having trouble with to leave her husband.
(9) The psychologist told the woman that he was having trouble with her husband.

These sentences were preceded by one or other of the following context sentences:

(10) A psychologist was counseling two women. He was worried about one of them but not about the other.
(11) A psychologist was counseling a man and a woman. He was worried about one of them but not about the other.

Each context sentence was paired with each target sentence. Target sentence (8) is more compatible with context sentence (10) than context sentence (11), whereas (9) is more compatible with (11) than (10). This is because the object of *told* is the complex NP *the woman that he was having trouble with* in (8), but the simple NP *the woman* in (9). Sentence (8) is compatible with the context sentence (10) because the restrictive relative clause picks out a particular woman from the set of women described in the context sentence, whereas (9) is compatible with the context sentence (11) because the simple NP *the woman* refers to the one woman mentioned in the context. Crain found that the target sentences were judged to be grammatical faster and more consistently when

preceded by their compatible context sentences. He concluded that both analyses of the ambiguous string were computed in parallel and that the analysis which was maintained was that one that was compatible with the preceding context. If the sentence turned out to be incompatible with the context, then, either reanalysis occurred, which explains the longer RTs, or the sentence was simply judged to be ungrammatical. Similar effects have been found with other methodologies, such as self-paced reading (Altmann 1988; Altmann & Steedman, 1988).

The notion of "compatibility with preceding context" has been elaborated by Altmann and Steedman (1988) in terms of a "principle of referential support," under which an NP analysis which has all its referential presuppositions satisfied by the context will be favored over one which does not. Hence, the simple NP presupposes mention of a particular women in the prior context, whereas the complex NP presupposes mention of more than one woman.[7] This principle is applied during processing of the fragment *...the woman that...*; hence, commitment to one analysis occurs very early on in processing.

On their model, the complement clause reading should be adopted for ambiguous sentences such as (1) (repeated here as 12), when presented in isolation:

(12) The receptionist informed the doctor that the journalist had phoned about the events.

In this case, neither the simple NP nor the complex NP analysis is referentially supported, because the use of the definite article presupposes reference to a particular individual already mentioned in the discourse. They assume that, *in addition*, the relative clause interpretation presupposes previous mention of more than one entity. Hence, the simple NP interpretation requires fewer unsupported presuppositions than the complex NP interpretation does.

Note that once a commitment to the complement clause reading is made in sentences like (12), it is maintained throughout, and the relative clause analysis is never reconsidered.

Extended Parallel Parser

Extended parallel parsers may process more than one analysis of a string at the same time. Attachments may be computed immediately, as

[7] Altmann & Steedman's interpretation ignores certain possibilities; for instance it is felicitous to say, "*the woman that I just mentioned. . .*", even in a context in which there is only one woman.

in the case of the serial processor. Each analysis constructed by a parallel processor is equivalent to the complete analysis constructed by a serial processor.

In principle, parallel models may differ in a number of ways, such as how many analyses may be computed, and how long parallelism may be maintained. In addition, they may differ according to their decision strategies: Ultimately, a single interpretation of a sentence is adopted, and so a parallel processing theory must have a mechanism for choosing one analysis and discarding any others. Clearly, parallel parsers need to be constrained to account for the behavioral data which suggest that (1) certain interpretations are preferred, and (2) nonpreferred interpretations may be more difficult to process.

Let us consider, as one example, the extended parallel account proposed by Gorrell (1987, 1989). Following Kurtzman (1985), he assumes that all possible analyses are computed in parallel and maintained for the duration of the ambiguity. On Gorrell's account, these analyses are ranked on the basis of structural criteria similar to minimal attachment; the parser favors structurally simpler analyses.

Gorrell (1987) examined the processing of sentence fragments such as the following:

(13) It's obvious that Holmes suspected the son of the banker...

After subjects read such fragments, a target word appeared for lexical decision. The target, which was typically an auxiliary verb, constituted either a syntactically well-formed continuation or not. Gorrell (1987) exploited the "syntactic priming" phenomenon reported by Wright and Garrett (1984), who showed that lexical decision responses were faster to words which form grammatical continuations than to the same words when they form ungrammatical continuations.

By showing that syntactic priming is obtained for a target which constitutes a good continuation of the *nonpreferred parse*, Gorrell (1987) inferred that the nonpreferred parse is indeed computed. To show that the preferred structure is also being computed, Gorrell also used a speeded grammaticality judgment task with similar materials and found that the judgments corresponded to the minimal attachment reading. Putting the results of the two tasks together, Gorrell concluded that the sentence parser computes multiple analyses in parallel and maintains them throughout the ambiguous region. By the end of the sentence, however, one interpretation is selected, even in sentences such as (12), which do not contain

disambiguating input. The analysis which is ultimately selected would be, on this model, the highest-ranked analysis; here, the highest-ranked analysis is the structurally simpler one, the sentence containing the complement clause.

In contrast to the models described above, according to the extended parallelism model, parallel analyses of an ambiguous structure are computed and maintained.

Delay Models

The parallel and serial models described above share the property that the attachment of a constituent is carried out immediately. Delay models, on the other hand, allow the parser to wait before incorporating new material. For example, the structure of a phrase may be computed, but the attachment of this phrase to the other constituents within the sentence may be delayed.

There are, in theory, a number of parameters on which delay models may differ. One is the depth of analysis assigned to an unattached input. that is, prior to attachment, a phrase or constituent may be stored as simply a series of words, or it may be assigned a syntactic analysis so that it becomes a single "chunk" (or series of syntactic chunks). The length of unattached input—in terms of either words or constituents—may also vary from model to model. Finally, it is possible that delaying attachment is a specific device employed to cope with syntactic ambiguity, or that it is part of the parsers' normal routine. This will be raised again in the Discussion section.

The notion of "attachment" may be viewed as a set of statements about the relation between constituents. In this case, "delayed attachment" can simply mean the later addition of new statements. Gorrell (1992), following Marcus, Hindle, and Fleck (1983) and Weinberg (1992), has recently argued that, in response to an input, a "minimal" structure is computed. As a sentence proceeds, further structure may be added. This minimal structure consists of statements about dominance and precedence relations. That is, certain syntactic relations, such as "VP dominates NP" are computed without delay. However, the exact relation, such as whether or not the VP *directly* dominates the NP, may be computed after additional information appears. Although this kind of model could, in principle, predict that the attachment options in sentences like (1) remain open for some period of time, in fact, Gorrell's model dictates

that the complement clause analysis is the only one considered, and that this analysis is fixed at the point of the ambiguity.[8]

By contrast, Kennedy, Murray, Jennings, and Reid (1989) suggested that the attachment of entire constituents may be delayed. They found, in an eye-movement study, that reading times for an ambiguous sentence like (14) patterned with those for the unambiguous counterparts, like (15):

(14) The workers considered the last offer from the management was an insult.
(15) The workers considered that the last offer from the management was an insult.

They pointed out that the application of a strategy like minimal attachment would force the (ultimately erroneous) attachment of the postverbal NP to the VP in (14); sentences like (15), which contain the complementizer *that* would, of course, be exempt from this strategy. Therefore, the garden-path model would predict that reading latencies for (14) should be significantly longer than those for (15). But that's not what was found; Kennedy et al. (1989) found that sentences like (14) and (15) elicit *equivalent* reading times. Although Kennedy et al. do not provide a detailed parsing model, it is clear that this result is compatible with a delay model, and incompatible with early commitment models.[9]

CROSS-MODAL LEXICAL PRIMING

Each of the models just described receive empirical support from a number of experimental studies. In general, these studies have used reading time differences as the primary index of processing difficulty, which was, in turn, taken to reflect either reanalysis, or the adoption of a nonpreferred structure. Gorrell's technique (1987), by contrast, used lexical decision times as a measure syntactic congruity, which were, in turn, assumed to reflect which structures had been computed. We would like

[8] This is because Gorrell (1992) endowed his model with both the requirement that lexical items be "attached" on a word-by-word basis, and a preference for simpler structures (i.e., structures that involve fewer dominance and precedence statements).

[9] The results of this study are in direct conflict with those reported by Rayner and Frazier, 1987. See Kennedy et al. (1989) for discussion of this discrepancy.

to add to the range of methodologies considered by using a semantic priming technique to examine the connections that listeners make during sentence processing, which should, in turn, allow us to determine which analyses are computed.

In this procedure, subjects listen to words or sentences, while simultaneously performing a lexical decision task. It has been well established that lexical decision on a word is faster if a strong associate of the word is presented immediately before as a priming stimulus (Meyer & Schvaneveldt, 1971). This technique has been used extensively to examine lexical processing within sentences (Swinney 1979; Tanenhaus, Leiman, & Seidenberg, 1979). More recently it has been used to examine the establishment of syntactic/semantic associations between elements in a sentence [Fodor, Swinney, & McKinnon, 1991 (reported by Fodor, in press); Nicol and Swinney, 1989; Shillcock, 1982; Swinney, Ford, & Bresnan, 1989]. The research has shown that the formation of an association between two elements within a sentence—such as between a pronoun and its antecedent, or between the head of a relative clause and the embedded verb—will cause the semantic properties of the earlier of the two elements to be refreshed, or reactivated.

For example, Swinney et al. (1989) examined the processing of relative clauses in sentences such as the following:

(16) The policeman saw the boy that the crowd at the party accused of the crime.

In this sentence, there is an association between *the boy*, which functions as the head of the relative clause, and *accused*, the verb in the embedded clause, because *the boy* serves as the object of *accused*. Swinney et al. (1989) found the lexical decision to *girl*, a strong associate of *boy*, was faster than to a control word when the probe appeared at the offset of the verb *accused*, but there was no difference when *girl* was presented immediately before *accused*. Also, there was no similar effect with associates of *policeman* or *crowd*.

This study suggests that the connection between the head of the relative clause and the embedded verb is registered in the vicinity of the verb, and that it is the establishment of this association which causes *boy* to be reactivated. The lack of priming at a point before *accused* suggests that the priming effect is due to *reactivation*, not simply residual activation of the first presentation of *boy*. Further, because no effect was found with associates of the other nouns in the sentence, we can be

confident that the activation was closely tied to the formation of a linguistically real association, presumably the association often called an "unbounded dependency." This finding has been replicated by Nicol and Osterhout (reported in Nicol, 1989, and Swinney, 1991), and with an all-visual version of the technique by Hickok (1993).

This finding of priming for the head of the relative in the vicinity of the embedded verb may be used to examine low ambiguous sentences such as (1) [repeated here as (17)] are interpreted:

(17) The receptionist informed the doctor that the journalist had phoned about the events.

As we observed above, the embedded clause in this sentence may be construed either as a sentential complement or a relative clause. If the relative clause analysis is represented at the offset of *phoned*, then it should be possible to observe priming of the head of the relative, *doctor*, at this point. If the relative clause interpretation is *not* represented at this point, then we predict no priming. This is because there is no reason to assume a syntactic association between *phoned* and *physician* on the complement clause reading. Sentences such as (17) may be contrasted with sentences like (18):

(18) The receptionist informed the doctor why the journalist had phoned about the events.

Since these sentences are unambiguous—the complementizer forces the complement clause analysis—there should be no evidence of reactivation of *doctor*. Hence, such sentences serve as cases against which to compare the ambiguous sentences.

Let us review the four approaches to parsing and the predictions they make about priming:

1. Garden-Path Parsers. Any approach in which there is an early commitment (prior to the embedded verb) to the complement clause reading predicts no priming. This includes the garden-path model, which requires that the complement clause reading is chosen immediately on the basis of minimal attachment.

2. Weakly Interactive Parsers. Again, if there is early commitment to the complement clause reading, no priming is predicted. This is the case with Crain and Steedman (1985) and Altmann and Steedman (1988), where the complement clause reading is chosen by the time that the complementizer is reached on the basis of its contextual appropriateness.

3. Extended Parallel Parsers. Priming is consistent with extended parallel models as long as the relative clause analysis remains active at least until the embedded verb is reached. This is the case with Gorrell's (1989) model.

4. Delayed Commitment Parsers. Priming is expected as long as the parser has not committed itself to a complement clause reading.

CROSS-MODAL EXPERIMENT

Method

Subjects

One hundred and eight subjects participated in this experiment for course credit. All had normal hearing and normal or corrected-to-normal vision.

Design and Materials

Eighteen experimental sentences of the same form as in (17) above were constructed in triplets. Each triplet contained two versions of the ambiguous sentence, one produced with an intonation which favored the complement clause reading, and one which favored the relative-clause intonation. These two different versions were included not because we expected them to produce different results, but rather because we wanted to be able to compare our results to those obtained in experiments which require subjects to read sentences (i.e., most of the experiments on parsing). Since we do not know what intonation pattern, if any, a subject typically imposes on a *visually presented* input, we felt it was important to present the two versions. The third member of the triplet was the unambiguous version of the sentence as in (18); in these versions, the complementizer was changed from *that* to *how* or *why*. They were included to provide a control condition for the ambiguous sentence versions. If priming of the head of the relative is observed in the ambiguous sentences, it is critical to determine that we do *not* observe priming in comparable sentences where there is no relative clause reading: It must be clear that priming in the ambiguous sentences is associated with the availability of a relative clause interpretation, rather than, for example, residual activation of the head of the relative.

Each sentence was paired with a target item (which was to be pre-

sented visually for lexical decision). In the critical cases, the target was always a real word of English, and was either a strong semantic associate of the head of the relative clause (in this case, *jury*), or was an unrelated word. In both semantically related and semantically unrelated conditions, the same set of target words was used, but paired with two different sentences; a target which was semantically related to the head in one sentence served as an unrelated target in a different sentence. Hence, both the related and unrelated conditions contained the same set of targets. (All experimental stimuli are given in the appendix.)

Six presentation lists were created. Lists 1 and 2 contained the ambiguous versions of the experimental sentences produced with relative clause intonation, lists 3 and 4 contained the ambiguous sentences with complement clause intonation, and lists 5 and 6 contained the unambiguous versions. Targets were counterbalanced such that each list contained nine targets related to the head of the relative clause and nine unrelated targets. Target lists 1, 3, and 5 were identical, as were lists 2, 4, and 6. Any given subject was presented with only of the lists.

In addition to the 18 experimental sentences in each presentation condition, 82 filler sentences were included. Of these, 18 were pseudoexperimental; they were of the same syntactic and intonational types as the experimental sentences; six unambiguous, six ambiguous with complement clause intonation, and six ambiguous with relative clause intonation. These were paired with nonwords, and therefore served to prevent subjects from being able to ascertain that sentences of the experimental type would always warrant a *yes* response. The other 64 filler sentences were in the form of questions (these made up a separate, unrelated experiment); half of these were paired with real word targets and half with nonword targets. In addition, there were 10 practice sentences. In all, each subject heard 110 sentences.

Sentences were recorded onto a Technics DAT player by a female speaker, who read the sentences at a normal rate of speech. The sentences were all read with the intonational pattern appropriate for expressing the meaning of the sentences. The intonational pattern was the same for both the unambiguous and ambiguous complement clause sentences. By contrast, the ambiguous relative clause sentences were read with a distinct intonational pattern. The differences in intonation begin at *doctor*; this difference is extremely subtle, and involves, in the complement clause sentence, a slight fall in pitch, followed by a very short pause. The most salient differences occurred several words downstream. In the relative clause sentence, the embedded subject was stressed, the following verb

received a falling pitch, and this verb was followed by a relatively long pause.[10] The different sentence types were recorded in blocks in order to ensure that the intonational pattern was uniform across all tokens of a particular type.

All sentences were digitized at a sampling frequency of 16K, and a waveform editing system was used to locate and label the point in the sentence that was to coincide with the presentation of the visual stimulus. In the experimental and pseudoexperimental sentences, the label was placed at the offset of the verb in the lower clause. These labels were converted to pulses, and stored in a separate file. The digital files containing sentences and pulses were then recorded simultaneously onto an audio tape in a pseudorandom order, with the sentences on the right channel and the pulses on the left.

Sentences were presented to subjects auditorily. Subjects heard the sentences binaurally over headphones. The left track, which contained only the pulses, was connected to a voice trigger, which signaled the experimental program—the DMASTR system[11]—to start a timer, and to display (for 400 msec) the appropriate visual target on a computer screen that was positioned in front of the subject. Subjects made a lexical decision on the target item as quickly as possible, by pressing either a button labeled "YES" or one labeled "NO." The button-press stopped the timer, and the response time was automatically recorded.

At predetermined points throughout the experiment, subjects were cured by the sound of a bell to paraphrase the immediately prior sentence.

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[10] This pattern was established by asking six linguistically sophisticated speakers to read a subset of the sentences (five in all) to convey the relative clause meaning. This was done in the following way. Subjects were asked to silentlyn read about a particular scenario, and to read aloud the sentence indicated with a mark. Here is an example intended to bias subjects toward the relative clause reading: "There are several doctors. A receptionist informed one of the doctors about the events. Which doctor was informed? "The receptionist informed the doctor that the journalist had phoned about the events' " (last sentence read aloud). Here is an example of a scenario meant to bias readers toward a complement clause analysis: "There is a doctor and a receptionist. The receptionist informed the doctor about something. What did the receptionist tell the doctor? "The receptionist informed the doctor that the journalist had phoned about the events' " (last sentence read aloud). These utterances were recorded and presented to the speaker who was to record the full set of sentences. The intonational pattern used by five out of six of the speakers conformed with our speaker's own preferred intonation for expressing the relative clause reading. As a result, the sentences sounded fluent and natural.

[11] DMASTR was developed by Kenneth Forster, Rod Dickinson, and others at Monash University, and modified at the University of Arizona by Jonathan Forster.

These occurred at varying intervals and were included only to keep subjects attending to the sentences. Roughly 6% of the sentences were tested in this way (7/110).

Results

Prior to analysis, the data were treated in the following way. Data from subjects whose mean reaction times were over 1300 msec, or who made greater than 15% errors, were rejected; 12 subjects were rejected on these grounds. All response times that exceeded a value greater than 2 standard deviations from the subject's mean were replaced by the value *equal* to 2 standard deviations from the mean. Erroneous responses were omitted from the analysis. In addition, data for one of the sentences in the relative clause intonation condition were excluded from analysis after it was discovered that this sentence contained the wrong intonation pattern.[12]

Mean reaction times and error percentages, collapsed across subjects and items, are shown in Table I.

Analyses of variance which included all three sentence types showed an interaction of sentence type with target which was robustly significant by subjects, $F_1(2, 90) = 7.07$, $p = .0014$, and weakly significant by

Table I. Mean Reaction Times (msec); Mean Percentage of Errors for Each Relevant Condition Shown in Parentheses

	Sentence type		
Target type	Ambiguous—relative clause intonation	Ambiguous—complement clause intonation	Unambiguous
Related	693 (1.81)	689 (2.92)	781 (4.71)
Unrelated	728 (1.83)	705 (4.77)	752 (2.92)
Magnitude of priming	35 (0.02)	16 (1.85)	−29 (−1.97)

[12] In fact, this sentence was inadvertently taken from the set of sentences designed to have a neutral intonation contour.

items, F_2 (2, 32) = 3.20, $p = .0542$).[13] ANOVAs in which sentence types are compared in pairwise fashion are given below.

1. Comparison of Ambiguous Structure with Relative Clause Intonation vs. Unambiguous Version

Analyses of variance on the response time data revealed no main effects of target. The interaction of interest—Sentence type × Target Type—was found to be significant on an analysis of variance with both subjects as a random variable (F_1) and with items as a random variable (F_2):$F_1(1, 60) = 11.05$, $p = .00152$; $F_2(1, 16) = 8.23$, $p = .0111$. There were no other significant effects. Taken individually, the results for each sentence condition were marginally significant. The difference between the related and unrelated targets for the ambiguous relative clause sentences was significant on the subjects analysis only [$t_1(30) = 2.73$, $p = 0.0105$; $t_2(16) = 1.70$, $p = .108$]. For the unambiguous complement clause sentences, the difference is also significant only by subject [$t_1(30) = 2.01$, $p = .052$; $t_2(16) = 1.62$, $p = .124$]. This inhibition effect in the unambiguous sentences is noteworthy in that it suggests *suppression* of items mentioned in the matrix clause. It is not immediately obvious to us why there should be inhibition in *any* sentence context, yet we do find it, both here and in experiments which have recently been conducted in our lab. We also note that Hickok (1993) found inhibition in his control cases. Clearly, further investigation is needed in order to identify the circumstances under which inhibition takes place.

Error data were also subjected to analyses of variance. The error rate was very low in general, and especially so in the ambiguous relative clause condition. The error percentages mirrored the response time data

[13] The main effect of sentence type, significantly only by items [$F_1(2, 90) = 1.38$, $p = .257$; $F_2(2, 32) = 16.98$, $p = .00009$] is uninterpretable, due to the fact that sentence type is a between-subjects factor, and hence, confounded with different subject groups. We shall therefore omit discussion of this effect in further analyses. We also note here that the longer reaction times and greater percentage of errors in the *unambiguous* sentence condition (which might suggest that these sentences are more difficult for subjects) is likely to be due to differences between the groups of subjects; that is, the group that heard the unambiguous sentences may have been slower to respond in general. In fact, this appears to be so: This group also showed slower reaction times (and a greater number of errors) for the *nonword targets* as well as the real word targets. (For the nonword targets, the group in the unambiguous sentence condition had a mean RT of 904 msec, with 6.63% errors, while the group in the ambiguous relative clause sentence condition had a mean response time of 855 msec, with 5.4% errors, and the group in the ambiguous complement clause condition had a mean RT of 856 msec, with 4.68% errors.)

only in the unambiguous sentence condition (i.e., here, the condition with the higher mean RT is associated with a greater number of errors); the interaction of Sentence Type × Target type was nonsignificant. The only significant effect was the interaction of presentation list (our counterbalancing factor) with target [significant by subjects: $F_1(1, 60) = 4.21; p = .045$].

2. Comparison of Ambiguous Structure with Complement Clause Intonation vs. Unambiguous Version

Analyses of variance show the relevant interaction (Sentence Type × Target) to be significant by subjects only [$F_1(1, 60) = 6.40, p = .0141$; $F_2(1, 16) = 2.71, p = .119$]. There were no other significant effects or interactions.

Error data were similarly analyzed. The sentence type by target interaction was nearly significant on both analyses [$F_1(1, 60) = 2.94$, $p = .0915$; $F_2(1, 16) = 3.90, p = .0657$]. No other effects or interactions approached significance.

3. Comparison of Ambiguous Relative Clause vs. Ambiguous Complement Clause

The comparison of the two ambiguous sentence conditions revealed the interaction of Sentence Type × Target to be nonsignificant ($p_1 > .17$, $p_2 > .59$). The only significant effect in the entire set of analyses was a main effect of target on response time, and only by subjects [$F_1(1, 60) = 9.77, p = .0027$; $F_2(1, 16) = 1.56, p = .229$]. The analysis of error rate showed no significant main effects or interactions.

DISCUSSION

Problems for Garden-Path and Weakly Interactive Models

Our clearest result is the significant reactivation effect found in the ambiguous relative clause sentences (compared to the unambiguous sentences). This finding suggests that, well downstream from the point of ambiguity, the relative clause reading is available in these sentences. That is, in our example, the relative clause analysis is still a viable option at the point of the embedded verb *phoned*:

(19) The receptionist informed the doctor that the journalist had *phoned* about the events.

This finding is clearly incompatible with both the garden-path model and the weakly interactive parallel model. The garden-path model assumes that the relative clause reading is never even considered on the first pass, while the weakly interactive model assumes that both analyses are active momentarily, but that, without discourse support, the relative clause reading is rapidly rejected. Hence, both accounts would predict that, by the point at which the embedded verb is encountered, the complement clause analysis is the only one still under consideration.

But what if the complement clause analysis was *not* the analysis that the processor pursued? After all, our sentences were deliberately intoned in such a way as to favor the relative clause analysis. Could intonation come into play at the point of ambiguity to force the relative clause reading? We think this is unlikely, for the following reasons.

Recall that the differences in intonation are extremely subtle at the point when these models predict a choice should be made—the point of ambiguity (i.e., in the vicinity of *that*). It seems improbable that intonation would have a disambiguating effect at this point in the sentence. Note that the most salient differences in intonation occur after *that*: within the following NP and VP. Hence, the intonation contour becomes more distinct as the NP and VP are processed, and it is really only at the postverbal pause (our probe point) that the relative clause contour is clearly apparent. Further, intonation is only probabilistic; any one pattern is only *likely* to convey a particular interpretation; there is no *one* intonation pattern which corresponds to either the relative clause or the complement clause construction. And clearly, the fewer the cues, the greater the uncertainty. Hence, it is unlikely that the particular pattern of (a) pitch on *doctor*, (b) pause length prior to the onset of the *that* clause, and (c) pitch and intensity of the word *that* would be sufficient to override either the normal attachment mechanisms or the normal selection process based on presuppositional simplicity.

If, at the point of ambiguity, intonational cues are not used to select the relative clause analysis, there is still a way to rescue the garden-path and weakly interactive parallel models. Suppose that the complement clause analysis is initially pursued, but that, as intonational evidence favoring the relative clause reading is accrued, the complement clause analysis is abandoned, and the sentence reanalyzed. That is, the complement clause reading would be pursued until the point where the intonation becomes clearly incompatible with the current parse, and reanalysis

would ensue. The subsequent computation of a single relative clause analysis would then give rise to our reactivation effect.[14]

However, there are two additional findings that are incompatible with the reanalysis account. One is our near-significant priming effect in ambiguous complement clause sentences. Both the garden-path model and the weakly interactive parallel model would predict that, in terms of priming, these sentences should pattern with the unambiguous complement clause sentences. But this is not what we found. In fact, they are nearly significantly different from the unambiguous sentences, and indeed, pattern more closely with the ambiguous relative clause sentences. The other finding is the result reported by Hickok (1993), who found priming in sentences that were structurally identical to our ambiguous ones, *even though* his sentences were presented *visually*.[15] Hence, when sentences are presented without intonation, there is still a reactivation effect.

In sum, the garden-path and weakly interactive parallel parsers, because they require such early commitment, are simply incompatible with the lexical priming results.

Extended Parallel Models

The priming effect found in the ambiguous condition with relative clause intonation (compared to the unambiguous condition) is straightforwardly compatible with an extended parallel model such as that proposed by Gorrell (1987, 1989). An extended parallel model would predict that, at our probe point, *both* the relative clause analysis and the complement clause analysis would be represented; the computation of the relative clause structure would trigger reactivation of the head.

While this model is compatible with our daa, we are reluctant to embrace it, for a number of reasons. First, a number of eye movement

[14] We should point out the difficulty in describing the mechanisms that would need to come into play during such a process. One would need to argue that the syntactic analysis is constantly being evaluated with respect to the incoming prosodic cues and that the degree of compatibility is somehow computed. One would also need to specify a threshold; if incongruity were too great, reanalysis would ensue. In this context, we reiterate the point raised above that the intonational cues signaling the relative clause analysis are only probabilistic. Therefore, one would need to argue that such cues nevertheless *override* the normal mechanisms dictating attachment.

[15] Greg Hickok conducted his experiment simultaneously with ours, and his results are clearly relevant to the work reported here. However, since his paper appears in this issue, and given space limitations, we have refrained from discussing the account he provides—which is different from ours—and refer the reader to his article.

experiments suggest that there are regressions back to the point of ambiguity in cases when the nonpreferred reading turns out to be the correct one. Frazier and Rayner (1982), for example, found that subjects usually regressed to *a mile* or to the beginning of the sentence after being garden-pathed by *seems* in the example below[16]:

(20) Since Jay always jogs a mile and a half seems like a short distance to him.

But a parser which has constructed parallel representations need only discard the preferred analysis and choose the secondary analysis instead. This is could be accomplished without referring back to an earlier point in the sentence.

Second, there is no evidence of a processing load increase during the ambiguous region in an ambiguous structure compared with an equivalent unambiguous structure, even though one might predict that additional analyses are likely to increase processing load. For example, Kennedy et al. (1989) found that processing time on the region *the last offer from the management* was no different in the ambiguous and unambiguous versions of their sentence:

(21) The workers considered (that) the last offer from the management was an insult.

Similar findings are reported by Holmes, Kennedy, and Murray (1987).

Third, it is possible to produce sentences with an arbitrarily large number of analyses which can be maintained as viable analyses for an arbitrarily long time. In the simplest extended parallel model, all structures would be represented in parallel. In order to prevent processing overload, it would be necessary to restrict the extent of parallelism available to the processor, but this is only possible by adding otherwise unmotivated complexities to the theory.

Finally, such models require a great deal of redundant information to be computed and maintained. For example, in (1), both complement

[16] The explanation for the garden path is that the processor has analyzed the NP *a mile and a half* as the object of *jogs* and had done so by the time the verb *seems* is reached. The garden-path parser does not consider the possibility that *a mile and a half* is the subject of a main clause, and hence, has to backtrack in order to recompute this analysis.

and relative clause analyses have *the receptionist* as the subject of *informed* and *the journalist* as the subject of *had phoned*, but this common information simply has to be represented twice.

A Delay Model (with Limited Parallelism)

The observed results are consistent with certain models which allow delayed attachment. The results do not directly support any of the models discussed above; therefore, in this section, we shall describe the type of model which could account for our findings.

We assume, first, that attachment is delayed until the embedded verb and not beyond this point. This is because our reactivation effect suggests that attachment has not occurred prior to this point, since we assume that early attachment would only be compatible with a complement clause analysis (as we discussed above, at an early point, the processor does not have sufficient intonational evidence that the clause is a relative clause). In addition, attachment is not likely to be delayed beyond the probe point. This follows from the assumption that reactivation of the head of the relative clause requires that a fully elaborated relative clause be computed; if attachment of the embedded clause were delayed beyond the probe point, then reactivation would not be triggered. Hence, it is reasonable to assume that attachment of the *that* clause occurs once the embedded verb is processed.

The question to be addressed, then, is why the embedded verb is so critical. One reason that attachment would be delayed until the embedded verb is that this verb constitutes the first point at which the embedded clause has all of its necessary constituents. This fact may be captured in different ways by different syntactic theories, and although the explanation given below is cast in terms of GB theory, the basic idea could readily be reformulated in other terms.

Within a phrase-structure framework, such as Government Binding theory (Chomsky, 1981), the explanation is as follows: Attachment of the S′ [*the* node dominating both the complementizer (COMP) and sentence (S)] may be delayed until the first point at which each of the major constituents of S have been encountered—that is, at the first point at which the postulation of the S node is licensed. This point is precisely at the embedded verb. It is at this point that a verb phrase may be projected, under the reasonable assumption that the postulation of a lexical phrase is licensed upon encountering a lexical head. Given COMP (e.g., *that*), a subsequent NP (*the journalist*), and a verb (*phoned*) (and

its maximal projection), the S node can be licensed.[17] Once this is done, the two different attachments may be attempted in parallel and evaluated according to some metric, and the less-preferred analysis may then be abandoned. In fact, this account is like that proposed by ACS, the difference being that attachment of the complementizer and subsequent S waits for the input.

Note that this view gives an asymmetric characterization to the point at which lexical (NP, VP, PP, AP) and functional (S and S′) projections are attached. Lexical projections may be postulated immediately upon encountering a lexical head and attached to the current parse tree; functional projections may be postulated and attached only upon encountering the string of phrases which constitute them (COMP and S for S′; NP, INFL, and VP for S). This is not an unreasonable asymmetry, since there is a cardinal difference between lexical heads, which carry subcategorization and theta-marking information, and functional heads, which do not.

Such a description is compatible with the notion that the delay in the attachment of the *that* clause is not a specific response to structural ambiguity. That is, we consider it plausible that a similar delay in attaching the embedded clause occurs in sentences such as our *unambiguous* constructions. This should be testable: Assuming that parallel attachments and their subsequent evaluation are not cost-free, one could use a secondary load task to determine whether, at the embedded verb, processing load increases in the structurally ambiguous sentences but not in the unambiguous versions.

We have so far made no claim about what causes one analysis to be selected at the point at which the two options are available. Selection could be based on a number of criteria: structural simplicity, compatibility with preceding discourse, simplicity in terms of number of unsatisfied presuppositions. Since the results of experiments which addresses these questions are conflicting, and since our experiment did not address this particular issue, we make no claims about this.

Our study did include a source of information which could well be used in the selection process: intonation. As we emphasized above, the cues provided by intonation are relatively weak early in the structure, and are therefore unlikely to be sufficient to force a relative clause analysis at the point of ambiguity. We also pointed out that the two patterns of intonation are most distinct in the vicinity of the embedded verb.

[17] This view is captured in large part by the "No Incomplete Nodes" principle proposed in Frazier and Fodor (1978).

Could intonation be used to select one analysis? In principle, this seems possible. Unfortunately, the results of this experiment are unrevealing. This is because we did not directly ask subjects to tell us their interpretations. In fact, this turns out to be extremely difficult to do, and our attempts at finding out how to test which analysis subjects ultimately computed were largely unsuccessful. According to a number of introspective reports, the sentences themselves were not so difficult to understand, but the process of being asked about a sentence interfered with the subject's recollection of the sentence.[18]

Tied to the question of what role is played by intonation is the question of whether our two versions of the ambiguous sentences—which differ in intonation—are actually processed differently. We argued at the beginning of the Discussion section that intonational cues are unlikely to be powerful enough to exert an influence at the point of ambiguity. Above, we suggested that intonation might be used to select one of two analyses. That is, once the essential daughters of the S′ have been encountered, both attachments of this S′ are attempted, and evaluated. The processes are ordered in this way: Attach, assess, then select. Since attachment occurs—*must* occur—prior to the evaluation of the attachment options, and since attachment which yields a relative clause triggers reactivation, we should observe equivalent priming for both versions of the ambiguous sentence. Recall, however, that in comparing the complement clause intonation sentences with the unambiguous versions, we found only a trend; the interaction was not statistically significant, as we would predict. One reason for this might be that, in the complement clause intonation sentences, subjects may be uncertain about how to parse the verb phrase. This is because the embedded clause contains a sequence such as *see about*; with no pause between these two words, this sequence may be ambiguous between a verb-plus-preposition and a verb-plus-particle. Clearly, additional testing is needed to clarify this question.

Our account of the results of this study involves delaying attachment of the embedded clause until the necessary constituents of that clause have been encountered. Are we suggesting that the processor systemat-

[18] The tasks we used to try to determine subjects' final interpretations included having subjects answer yes/no questions and verify whether a given statement, which subjects read prior to the presentation of the sentence, was true of the sentence. For instance, given either the ambiguous or unambiguous version of our example sentence, subjects might be asked, "Did the journalist phone the doctor? or "Did the journalist phone about the events?" Or subjects might be asked whether the proposition *The journalist phoned the doctor* was true of the experimental sentence. Subjects performed poorly, responding with roughly 50% accuracy.

ically delays attachment? Not necessarily. *If* the delay relates to the fact that the attachment of an S′ depends on the projection of certain lexical phrases, then a similar delay may not be apparent in examples such as the following:

(22) The spy saw the cop with binoculars, but the cop didn't see him.
(23) Susan gave the director the newspaper discussed a call.

In sentences like (22), which have been studied experimentally by a number of investigators, including Rayner et al. (1983) and Altmann & Steedman (1988), the ambiguity centers on whether the PP is to be attached directly into the VP or as an adjunct to the object NP. In (23) the ambiguity concerns the attachment of the NP *the newspaper* either to the VP as the object of the verb, or as the subject of a clause modifying the NP *the director*. During the processing of the NP, the question is how to attach the NP, not how to attach a potential S.

Although our account may not predict delayed attachment in (22) and (23), it *does* suggest, however, that words are not automatically attached as they are input. We argue, for example, that functional elements like *the* and *that* are not attached into the parse tree immediately, but rather, are only attached once they are incorporated into lexically headed phrases.

CONCLUSION

The experiment reported here examined the processing of sentences which were ambiguous with respect to the attachment of an embedded clause. Our results favor a model with, at least, the following properties: (1) Attachment of lexical items does not proceed word by word, but rather, awaits lexical heads; (2) at points of ambiguity, multiple attachments may be attempted and evaluated. Further research is required to clarify which types of information are used during the evaluation process, including a potentially very useful one: intonation.

APPENDIX: STIMULUS MATERIALS

In the following, the target words (for lexical decision) appear in uppercase letters. Each target is followed by the two sentences with which it was paired. In the first, the target is semantically related (R) to

the matrix object (shown in italics); in the second, it is unrelated (U). Each sentence is given with both types of complementizer, the ambiguous complementizer *that*, and the unambiguous *why* or *how*. The probe point is indicated with #.

1. JURY
   (R) The man told the *judge* that/why the young secretary had seen # about the business.
   (U) The receptionist informed the *doctor* that/why the enthusiastic journalist had phoned # about the events.

2. CLEAN
   (R) The child reminded the *janitor* that/why the tall salesman had phoned # about the equipment.
   (U) The general told the *king* that/how the enemy spy had heard # about the plans.

3. CAR
   (R) The manager reminded the *chauffeur* that/why the anxious guest had called # about the arrangements.
   (U) The lecturer taught the *nephew* that/why the state senator had known # about the judgment.

4. SONG
   (R) The woman whispered to the *singer* that/why the tired attendant had forgotten # about the details.
   (U) The man told the *judge* that/why the young secretary had seen # about the business.

5. TOOTH
   (R) The actor told the *dentist* that/why the important actress had phoned # about the visit.
   (U) The manager reminded the *chauffeur* that/why the anxious guest had called # about the arrangements.

6. PRAY
   (R) The gardener explained to the *nun* that/how the new helper had known # about the intruder.
   (U) The child reminded the *janitor* that/why the tall salesman had phoned # about the equipment.

7. NIECE
   (R) The lecturer traught the *nephew* that/why the state senator had known # about the judgment.
   (U) The woman whispered to the *singer* that/why the tired attendant had forgotten # about the details.

8. MONEY
   (R) The architect confessed to the *banker* that/how the new trainee had remembered # about the affair.
   (U) The mechanic told the *baker* that/why the old lady had phoned # about the preparations.

9. CAKE
   (R) The mechanic told the *baker* that/why the old lady had phoned # about the preparations.
   (U) The customer explained to the *accountant* that/why the new shopkeepers had phoned # about the arrangement.

10. PAINT
   (R) The people reminded the *artist* that/why the rich benefactor had called # about the meeting.
   (U) The architect confessed to the *banker* that/how the new trainee had remembered # about the affair.

11. SUIT
   (R) The visitor whispered to the *tailor* that/why the traveling saleslady had remembered # about the delivery.
   (U) The lawyer confessed to the *butcher* that/why the other partners had forgotten # about the agreement.

12. STEAL
   (R) The landlord whispered to the *burglar* that/how the three tenants had heard # about the offer.
   (U) The visitor whispered to the *tailor* that/why the traveling saleslady had remembered # about the delivery.

13. DUCHESS
   (R) The servant informed the *duke* that/why the strong workman had seen # about the damage.
   (U) The teacher taught the *boy* that/why the two politicians had forgotten # about the regulations.

14. MEAT
   (R) The lawyer confessed to the *butcher* that/why the other partners had forgotten # about the agreement.
   (U) The servant informed the *duke* that/why the strong workman had seen # about the damage.

15. TAX
   (R) The customer explained to the *accountant* that/why the new shopkeepers had phoned # about the arrangement.
   (U) The people reminded the *artist* that/why the rich benefactor had called # about the meeting.

16. QUEEN
   (R) The general told the *king* that/how the enemy spy had heard # about the plans.
   (U) The actor told the *dentist* that/why the important actress had phoned # about the visit.

17. GIRL
   (R) The teacher taught the *boy* that/why the two politicians had forgotten # about the regulations.
   (U) The landlord whispered to the *burglar* that/how the three tenants had heard # about the offer.

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