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Meaning, Memory and Modularity*

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1. Introduction

Given that meaning in language is conveyed by sequences of words occurring one at a time, questions of timing in studies of sentence processing are inescapable. The modularity hypothesis (Fodor, 1983) generates predictions regarding the relative timing of the availability and use of various sources of information in the resolution of structural ambiguities. A fundamental tenet of the modularity hypothesis is that plausibility considerations do not influence the structure-building operations of the parser. The operating characteristics of several parsing models are consistent with this assumption. In this paper, we test the implications of one such model, the referential theory (Crain & Steedman, 1985; Altmann & Steedman, 1988; Ni, Crain, & Shankweiler, in press).

Here are the basic assumptions of the referential theory:

A. The language faculty is composed of sub-modules: the lexicon, the phonology, syntax and semantics. Our focus is on syntax and semantics. Syntactic processing is highly automatic for most linguistic constructions (see, e.g., Chomsky, 1965). Semantic principles (such as compositionality) and certain principles of discourse representation also reside within the language faculty. Collectively, the latter are instantiated as the semantic/referential component.

B. When an ambiguous phrase or sentence fragment is encountered, (partial) structural analyses are generated in parallel within the syntactic component. The alternative analyses are shunted to the semantic/referential processor, which attempts to choose among them. Many parsing decisions can be made effectively and immediately on the basis of semantic/referential principles (e.g., Ni et al., in press).

C. Operations within the language faculty are not guided by real world knowledge (beliefs, desires, expectations, etc.). Because the language faculty is insulated from the influence of background beliefs, the parser can recognize sentences that are false. For example, the sentence *Mice chase cats* is judged false on the basis of its syntactic/semantic analyses, rather than being assigned alternative analyses that would make it true (*Cats chase mice*). As Fodor (1984) puts it, this is "one of the reasons why encapsulated perceptual modules might be a good thing for an organism to have: background beliefs, and the expectations that they engender, from

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time to time prove *not to be true*." For our purposes, the relevant point is that background beliefs may be queried in making decisions about how to interpret sentences only *after* syntactic and semantic/referential analyses have been pursued.

D. Both syntactic and semantic/referential information is used on-line by the parser. The structure-building operations of the syntactic component are largely automatic and, therefore, conserving of processing resources. Evidence for this will be presented in the first experiment reported in this paper (Experiment 1). In contrast to the syntactic component, the operations of the semantic/referential component are sometimes consuming of processing resources (see both Experiments 1 and 2). Because extralinguistic knowledge is accessed only after the syntactic and semantic/referential analyses have been constructed, processing resources may already be exhausted before this source of information can be used (see Experiment 2).

E. The verbal working memory system is the glue that holds the language apparatus together. The design features of the language apparatus lead us to expect that the ability to access and use world knowledge should co-vary with individual differences in memory capacity, but the use of syntactic and semantic/referential information should not be affected by memory. In the present paper, we exploit individual differences in verbal working memory as a litmus test of the predictions of the referential theory. It is important, therefore, to state our conception of the verbal working memory system.

2. Working Memory

As we see it, the verbal working memory system has two parts. First, there is a storage component, which retains the phonological units of the input. This component resembles what others refer to as 'short-term' memory. The second component of verbal working memory is a control mechanism. The primary function of the control mechanism is to transfer information between levels of linguistic representation (the phonology, the syntax, and the semantic/referential component) as they are computed within the language apparatus. At each of these levels, the parser computes all possible analyses of ambiguities in parallel, rather than serially. Given the limited capacity of the phonological storage buffer, however, only limited stretches of unstructured linguistic input can be held in the buffer. The linguistic input must immediately be recoded into a more durable form, and passed from lower to higher levels of representation, in order for the parser to keep up with the input. Once structural representations are formed at any level of representation, the information on which these representations are based can be discarded, permitting additional material to be analyzed at that level. The control mechanism ensures that the results of computations at lower levels of representation are transferred upwards through the system quickly enough to promote on-line extraction of meaning.[1]

When structural ambiguity is encountered, the control mechanism relays partial structural descriptions of each of the alternative analyses in parallel, for evaluation and resolution by the semantic/referential component. The analysis that best fits (the perceiver's mental model of) the discourse context is the one that is selected (Crain & Steedman, 1985). In an extension of the theory, Ni et al. (in press) offer the proviso that for ambiguity resolution, semantic/referential principles are available and used on-line, pre-emptively, before world knowledge (e.g.,

[1] To evaluate this conception of the verbal working memory system, we have conducted a number of studies investigating the kinds of unambiguous sentences that are costly of memory resources, and those sentence types that pose lesser demands on memory resources. Space does not permit us to review the relevant literature here. For discussion and empirical research on the effects of working memory differences on processing, see Crain, Shankweiler, Macaruso and Bar-Shalom (1990), Bar-Shalom, Crain and Shankweiler (1993), Ni, Shankweiler and Crain (1995), and Shankweiler and Crain (1986).

plausibility) is brought into play. Although information governing plausibility may be available at the same time as information pertaining to syntactic and semantic/referential principles, general knowledge of the world cannot guide syntactic or semantic/referential processes; appeals to world knowledge are made only after syntactic and semantic/referential analyses have been computed (see Fodor, Ni, Crain, & Shankweiler, 1996).

The modularity perspective implies that knowledge of the world is queried only whenever a decision cannot be reached among alternative analyses within the modular language processing system. In addition, an appeal to world knowledge may be necessary if an analysis must be rejected because it proves incompatible with subsequent input, resulting in a so-called garden path effect. Extralinguistic knowledge is ordinarily not invoked in processing unambiguous sentences (Ni, Shankweiler, & Crain, 1995; 1996). Parsing strategies become operative only if there is structural ambiguity. Without ambiguity, such strategies hold no sway on parsing. Whatever explains the strong preference to avoid the reduced relative clause analysis of the classic garden path sentence *The horse raced past the barn fell* does not deter that analysis in the unambiguous sentence *The horse ridden past the barn fell.*

3. Experiments

Exploiting the technique of monitoring subjects' eye movements during reading (Rayner, 1993), two experiments were conducted to assess the predictions of the referential theory. In particular, the experiments sought to test the role of working memory in the resolution of local ambiguities. The experiments had several features in common. Both experiments manipulated the semantic/referential properties of the test sentences by alternating the prenominal modifier of one of the NPs; one set of sentences contained the definite determiner, *the*, and another set contained the focus operator, *only*. Both experiments used a fully-crossed design, with disambiguating information confirming each of the alternative structural analyses on half of the test trials, and disconfirming it on the other half of the trials. Finally, the subjects of both experiments were assessed for verbal working memory capacity, using a test of memory span adapted from Daneman and Carpenter (1980).

The experiments contrasted two types of ambiguity. The first experiment tested the processing of locally ambiguous sentences involving the main-clause/reduced-relative-clause ambiguity characteristic of the classic garden path sentence *The horse raced past the barn fell.* The second experiment tested sentences involving ambiguities in the site of attachment of a prepositional phrase. The most important difference between the experiments concerned the type of information supplied for the purpose of disambiguating the test sentences. In the first experiment, the parser could, in principle, detect a misanalysis on the basis of structural information, as in the classic garden path example. In the second experiment, a misanalysis was signaled by a semantic anomaly, i.e., the subject's general knowledge of the world was required to detect and recover from a misanalysis. For example, many people find the following sentence to be semantically anomalous, at least temporarily: *The police officer captured the man with a fish.* Real-world knowledge tells us that fish aren't used by the police as a means of capturing people.

According to the referential theory, as noted earlier, syntactic and semantic/referential processing is accomplished on-line, whereas world knowledge exerts its influence later in the time course of sentence processing, and only if an ambiguity has not been resolved within the language faculty. These properties of the language processing system lead us to expect that the ability to access and use world knowledge will co-vary with individual differences in memory capacity, but that the access and use of structural information will be relatively unaffected by memory. If this is right, then individual differences in memory span should be a relevant factor in the results of the second experiment, but not those of the first experiment.

3.1 Procedures

The same procedures were used in each experiment. Subjects' eye movements were recorded using an IRIS infrared light eye movement system, a differential reflection method of eye-movement recording which allows eye positions to be tracked continuously while the subject reads sentences from a computer screen. Comprehension was checked by a YES/NO question that followed some of the filler trials. Analysis of the data was based on two measures: 1) First pass reading times, which is the total duration of all first-pass fixations on each predetermined region of a sentence; and 2) Incidence of regressive eye movements, which is the percent of first pass eye fixations that are immediately followed by a backward glance from each region. It is our working hypothesis that first pass reading times reflect on-line processes; that is, they reflect the influence of information that is immediately assimilated by the reader. Regressions testify to the readers' inability to use certain critical information for sentence interpretation; regressions also indicate difficulties that readers encountered during their first pass of the sentence.

The eye-movement data were analyzed using memory span as an independent variable. For the analyses, subjects were partitioned into two groups, according to their performance on a memory span test adapted from Daneman and Carpenter (1980). In this test, subjects listened to recorded material over headphones and indicated after every sentence whether or not that sentence was "true." In addition, the subjects' task was to report the last word of each sentence in a set of sentences. Set size varied from two to five sentences. Accuracy in recalling the last words from a set of sentences was taken to be an indicator of verbal working memory capacity. Based on span length, subjects were divided into two groups by a median split, so that High Span versus Low Span could be treated as a separate factor in the statistical analyses. The span lengths of subjects were similar across experiments. In Experiment 1, the mean span length for the high-span group was 35.5 (range: 32-40); for the low-span group, the mean was 26.63 (range: 18-31). In Experiment 2, the means were 36.25 (range: 33-40) and 27.88 (range: 18-32) respectively.

3.2 Experiment 1: The Resolution of Main-Verb / Reduced-Relative Clause Ambiguities

The first experiment examined eye movement patterns in processing sentences containing main-clause/reduced-relative-clause ambiguities. The critical comparison involved pairs of sentences that differed only in the first word. Sentences with a prenominal *only* were contrasted with sentences containing the determiner *the*. Test sentences also varied in a second way; namely, by the presence or absence of the word *but*. A complete paradigm is as follows:

(1) The horses raced past the barn were unable to clear the jump cleanly.
(2) Only horses raced past the barn were unable to clear the jump cleanly.
(3) The horses raced past the barn but were unable to clear the jump cleanly.
(4) Only horses raced past the barn but were unable to clear the jump cleanly.

The semantic/referential properties of the test sentences were manipulated by alternating the focus operator ONLY and the definite determiner *the*. According to the referential theory, the presence of the focus operator *only* should either deter or induce garden path effects, but the pattern of garden path effects for sentences with *only* should be the mirror image of that for those with the definite determiner. That is, whereas a garden path effect should occur in sentences like (1), there should not be garden path effects for sentences like (2) (see Ni et al., in press). This finding would support the referential theory, which supposes that ONLY+NP creates a contrast set at the point of ambiguity (*raced*) and prompts the parser to pursue the otherwise dispreferred reduced relative clause reading, thereby avoiding a potential garden path.

Here is the reason. The semantic representation of sentences with the focus operator *only* can be partitioned into three parts. One part represents *background information*, the second

represents *the element in focus*, and the third represents *a contrast set* -- the alternatives to the focus element. The contrast set is not mentioned explicitly in the sentence; instead, it is presupposed to exist. Two conditions must be met for sentences with *only* to be true. First, the information in the background must apply to the element in focus. Second, the background information must *not* apply to any members of the contrast set. That is, the background must apply *uniquely* to the focus element. See the appendix for a more formal description of the semantic properties of the focus operator *only*.

Based on the semantic properties of *only*, the referential theory predicts that sentences like (2), repeated below, will not evoke garden path effects, but that ones like (1) will.

(1) The horses raced past the barn were unable to clear the jump cleanly.
(2) Only horses raced past the barn were unable to clear the jump cleanly.

These differences are expected despite the fact that (1) and (2) are minimal pairs, i.e., they are identical following the initial noun phrase; specifically, the sentences are identical at the point of disambiguation. According to the referential theory, the subject NP *only horses* in (2) causes the parser to establish a discourse representation (a mental model) of the conversational context in which a set of horses is represented. The pre-nominal modifier *only* in the initial NP prompts the parser to search for a contrast set. Since a contrast set has not been previously established in the discourse, the parser has two options. First, it could attempt to construct a contrast set from scratch. That is, the parser could conjure up some set of entities to be contrasted with the horses already introduced into the mental model, or the parser could contrast the set of horses with everything else in the domain of discourse. Pursuing these options requires the parser to add new entities to the mental model, or to shoulder commitments that might have to be retracted later.

There is another option, however. Since the verb *raced* is ambiguous, the parser could choose to satisfy the presupposition associated with *only* by adopting the reduced relative clause analysis of the verb phrase. Pursuing this option simply requires the parser to partition the set of horses already admitted into the mental model. A set of horses being raced can be contrasted with another set of horses that are not being raced. If the decision is made to analyze the ambiguous fragment as a reduced relative clause, no garden path effect will occur when the main verb (*were able*) is encountered.

The referential theory predicts a reversal in the pattern of results for sentences like (3) and (4), repeated here.

(3) The horses raced past the barn but were unable to clear the jump cleanly.
(4) Only horses raced past the barn but were unable to clear the jump cleanly.

If the reduced relative clause reading is adopted in sentence (4), a garden path effect will be witnessed at the new clause beginning *but were*, because these elements indicate that *raced* should have been analyzed as a main verb. No corresponding garden path effect should occur for (3), however, since the main verb analysis of *raced* should have originally been pursued.

Based on our conception of the role of verbal working memory in sentence processing, we did not expect differences associated with memory capacity to affect the results of the present experiment. Because the disambiguating information is structural in nature, recovery from misanalyses takes place within the language faculty according to the referential theory.[2] Repairs that can be made within the language faculty are relatively conserving of processing resources.

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[2] It is worth pointing out that Waters and Caplan (in press) also report that individual differences in memory span did not result in differences in processing sentences containing main verb/reduced relative clause ambiguities.

In this connection, we note that the critical information for choosing one analysis over another, which is contributed by the focus operator *only*, is expected to be used on-line because the referential theory maintains that semantic/referential principles guide parsing decisions within the language faculty. This expectation also applies to the second experiment.

Thirty-two undergraduate students participated in the first experiment. They were randomly assigned one of the four stimulus lists. Twenty-four sets of test items were generated, each consisted of the four types illustrated by (1)-(4). A fully-crossed design was used so that six tokens of each of the four types appeared in each of the four stimulus list. Each list contained the 24 test sentences dispersed among 58 fillers. Sentence type was a within-subject factor: no subject read more than one type of a particular sentence, but every subject was presented with representatives of all four types. There were 12 warm-up sentences preceding the test materials. Thirty-two of the filler sentences were followed by a comprehension question.

For data analysis, the test sentences were divided into six regions. Region 1 was the subject NP, which contained either *the* or *only*. Region 2 was the first verb, which was morphologically ambiguous. Region 3 was the remainder of the first verb phrase. Region 4 was the disambiguating region. This region either contained the main verb phrase, e.g., *were unable,* or the conjunction, *but*, followed by the verb phrase in the (subjectless) new clause, e.g., *but were unable*. We will refer to the former as the main verb continuation (MV), and the latter as the new clause continuation (NC). Region 5 contained the two words after the disambiguating region, and Region 6 contained the remainder of the sentence. Residual reading times were used as the dependent measure because the critical Region 4 contained material that differed in length. The measure statistically removed length as a factor (see Trueswell, Tanenhaus, & Garnsey, 1994, for a detailed discussion of this measure). A full factorial 2 by 2 analysis of variance for repeated measures was performed which included the factors THE/ONLY and type of continuation MV/NC.

Figure 1 depicts the first pass reading time profile of the four types of test sentences over the 6 regions.

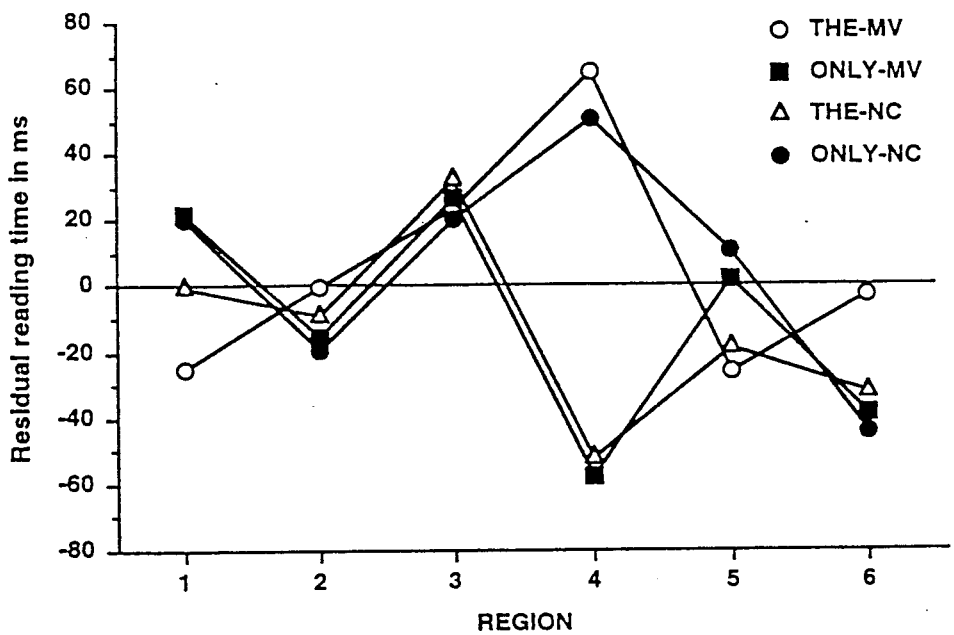

Figure 1: Mean first pass residual reading time at each region

The first region in Figure 1 presents the reading times for the subject NP. In this region, subjects took longer to read NPs containing *only* than ones containing *the*. At Region 4 (the disambiguating region), there was a significant interaction of THE/ONLY by type of continuation (MV/NC): $F_1(1,31) = 85.549$ $p < .0001$; $F_2(1,23) = 86.369$, $p < .0001$. That is, for the main verb continuation (the classic garden path construction, as in 1 and 2), reading times were longer for sentences with *the* than for ones with *only*; but for the new clause continuation (with *but,* as in 3 and 4), reading times were longer for sentences with *only* than for ones with *the*. This is exactly the pattern of results predicted by the referential theory, based on the semantic/referential properties of these sentences.

Individual differences in working memory did not interact with patterns of eye-fixation duration. Both high-span and low-span subjects displayed the same reading time profile at the disambiguating region 4, as illustrated in Figure 2 (for ease of comparison, the figure has been adjusted by adding 100 to each of the values).

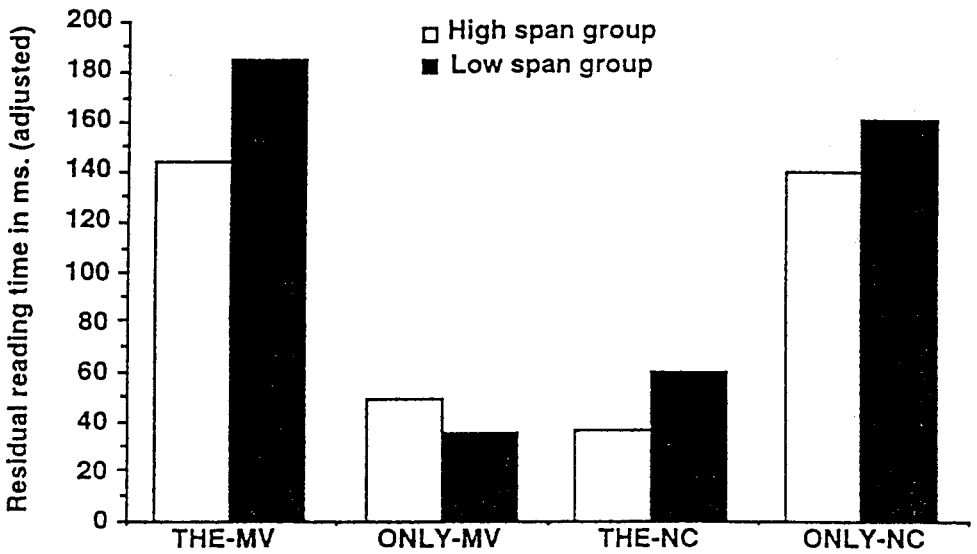

Figure 2: Mean first pass residual reading time at Region 4 by subject group

ANOVAs were performed separately for each subject group. There was a significant interaction of THE/ONLY by type of continuation (main verb or new clause) for both the high-span group ($F_1(1,15) = 46.899$ $p = .0001$; $F_2(1,23) = 44.580$, $p = .0001$) and the low-span group ($F_1(1,15) = 39.725$ $p = .0001$; $F_2(1,23) = 26.176$, $p = .0001$). Compared with their high-span counterparts, however, the low-span group displayed slightly longer reading times in processing the two types of sentences that induced garden path effects (THE-MV and ONLY-NC), although the difference between groups was not significant (cf. MacDonald, Just, & Carpenter, 1992; Pearlmutter & MacDonald, 1995). As for the regression data, there were no significant differences among the four types of sentences, nor were there differences between the subject groups.

The results are readily interpreted by the referential theory. Three predictions were upheld: (a) structural information was apparently used for disambiguation within the language faculty, (b) the semantic/referential properties of sentences were accessed and used on-line to decide among the competing analyses of ambiguous phrases, and (c) individual differences in memory capacity were not a factor.

Before proceeding to the second experiment, we would like to respond to two recent criticisms of our previous experimental investigations of the referential theory. The first criticism is by Frazier (1995), who contends that the study reported in Ni and Crain (1990) used "poor experimental design" because, she maintains, the test sentences containing *only* were consistently disambiguated in the same manner, in favor of the reduced relative clause reading. The problem, as Frazier sees it, is that "subjects are likely to catch on to the fact that, for example, every sentence beginning with *only* continues with a (reduced) relative clause structure." (p. 446).

This criticism is unwarranted, however. In the Ni and Crain study, half of the test sentences with *only* had an adjective intervening between the focus operator and the head noun, as illustrated in (5).

(5) Only white horses raced past the barn were unable to clear the jump cleanly.
Cf. Only horses raced past the barn were unable to clear the jump cleanly.

According to the referential theory, the presence of an adjective permits the parser to establish the requisite contrast set for the focus operator *before* the ambiguity is encountered. The phrase *white horses* in (5) satisfies the requirement of setting up a contrast set: a set of horses which are not white. Having established the contrast set in advance of the ambiguity, the main clause analysis is more highly favored. Adopting the main clause analysis results in a garden path effect, however, when the main verb continuation, *were able,* is encountered. As predicted, strong garden path effects occurred in the Ni and Crain study with sentences with *only* followed by an adjective, as in (5), but there was no evidence of garden path effects in sentences like (2), without an adjective. In sum, it is not the case that ambiguities in the test sentences were all resolved in the same way, as Frazier claimed.

Two additional precautions were taken in the present experiment, and in the Ni and Crain study, to avoid the criticism levied by Frazier. First, the 24 test sentences were camouflaged in the present experiment; they were interspersed among 48 filler trials. Second, the data were probed to determine whether or not subjects had detected recurrent patterns within the test sentences as the experiment progressed. For this purpose, data were analyzed separately for the first and second halves of the experimental trials. An effect of 'catching on,' if it exists, should surface only in the later trials. To determine whether or not subjects were detecting a pattern, we compared the results from the first and second halves of the experiment. In fact, there was a significant interaction of THE/ONLY by type of continuation for each half of the experimental materials considered separately, and the results were significant both by subjects and by items. The findings for the first half of the experimental sentences, which included six sentences with *only*, were as follows: $F_1(1,31) = 28.898$ $p = .0001$; $F_2(1,11) = 90.741$, $p = .0001$. The findings were comparable in the second half: $F_1(1,31) = 37.629$ $p = .0001$; $F_2(1,11) = 25.416$, $p = .0001$.

Another challenge to the referential theory is posed by Frazier and Clifton (1996), who offer the following putative counterexample:

(6) Only horses raced past the barn today.

Frazier and Clifton (1996) state that "garden pathing type phenomena should be observed in forms" such as (6) according to the referential theory, because the temporal modifier *today* should indicate that "the incorrect analysis" had been adopted (p. 20).

In fact, the temporal modifier can be readily incorporated into either structural analysis of the ambiguity. Suppose, for example, that the parser has opted for the reduced relative clause analysis. If so, the parser's analysis of (6) will be the same as that assigned to its unambiguous counterpart (7).

(7) Only horses ridden past the barn today.

As (7) shows, the presence of the temporal modifier does not inform the parser that an "incorrect analysis" has been pursued. The period following the temporal modifier informs the parser that it has constructed an incomplete, but well-formed structural representation. In our view, it is important to distinguish acceptable but incomplete linguistic material from true "garden pathing phenomena."

Frazier and Clifton's putative counterexample (6) points to a lack of familiarity with the referential theory. Like the prenominal modifier in (5), the presence of a temporal modifier in (6) would be expected to lead the parser to resolve the ambiguity by adopting the *main clause analysis*, rather than the reduced relative clause analysis. This follows from a basic principle of the referential theory, the principle of parsimony (Crain and Steedman, 1985). The principle of parsimony guides the on-line operation of the parser outside of context, instructing the parser to avoid unnecessary extensions to the mental model of the conversational context. Unnecessary extensions are avoided to minimize cognitive effort. As Crain, Ni, and Conway (1994) remark, "the advantage of such a "least effort" strategy for ambiguity resolution is to reduce the risk of making commitments that will need to be changed later" (p. 453). In short, the referential theory champions a minimal commitment parser.

With these observations in mind, we can take the sting out of Frazier and Clifton's apparent counterexample (6). By restricting the frame of reference, the temporal modifier *today* in (6), reduces the risk of making commitments that may later have to be retracted, as prescribed by the principle of parsimony. Navigating within a circumscribed domain of discourse -- i.e., events that took place today -- the parser can construct the requisite contrast set without extending the mental model at all; the contrast set can be everything in the domain except horses. Although this analysis of the initial NP would ordinarily run the risk of accruing commitments that might later have to be jettisoned, the temporal modifier decreases the peril. Therefore, sentence (6) should not pose processing difficulties except for individuals who resolve the ambiguity in favor of the reduced relative clause analysis *before* the temporal modifier is encountered; in that event, the example should be perceived to be well-formed but incomplete, as we saw.

Pursuing the point further, suppose that the temporal modifier appears *before* the initial NP, as in (8) and (9). In processing these sentences, the parser should establish the requisite contrast set *before* the ambiguity is encountered. (As before, the contrast set is everything in the domain of discourse except horses.) This leads to the prediction that sentences like (8), with a new clause continuation, should not pose processing difficulties (for the most part), whereas sentences like (9), with a main verb continuation, should induce garden path effects (at least some proportion of the time).[3]

(8) Today, only horses raced past the barn but they were unable to jump the fence cleanly.[4]
(9) Today, only horses raced past the barn were unable to jump the fence cleanly.

As these observations illustrate, seemingly subtle changes in form can have far-reaching consequences for the semantic/referential properties of sentences and, hence, for the analysis that is selected in cases of ambiguity.

[3] We are hedging here because we don't see any clear difference in the complexity of the discourse representations associated with the alternative structural analyses.

[4] The plural pronoun *they* is inserted in the example because no set of entities other than horses has been previously introduced into the mental model. Consequently, anaphoric relations are more felicitously established using an overt pronoun in the subordinate clause, rather than a covert pronominal NP.

As we saw in Experiment 1, the alternation of the focus operator *only* and the definite determiner *the* was enough to either avert or induce garden path effects when the disambiguating information was structural. In the next experiment, we ask whether similar results obtain when disambiguation hinges on general knowledge of the world.

3.2. Experiment 2: Ambiguities in Prepositional Phrase Attachment

The second experiment examines ambiguity resolution in cases that require the use of world knowledge. The referential theory anticipates that individual differences in memory span will often become relevant if world knowledge is required for resolving ambiguity. It is assumed that querying the extra-linguistic knowledge base taxes working memory when alternative analyses of an ambiguous phrase must be maintained in the buffer while the search is in progress. The present experiment investigates this prediction by comparing individuals who differ in memory capacity.

The test sentences contained a prepositional phrase *with...* which can attach either to a preceding noun, as in (10), or to a preceding verb, as in (11). We label the examples by referring to the analysis on which they make sense. So, (10) is called an NP-attachment sentence, and (11) is a VP-attachment sentence.

(10) The man painted the doors with large cracks before the festival. NP-attachment
(11) The man painted the doors with new brushes before the festival. VP-attachment

The NP-attachment sentence is temporarily anomalous at the words *large cracks*. This follows from a preference to attach the prepositional phrase in such sentences to the verb. Since it is implausible to use large cracks as tools for painting, this type of sentence is more difficult to process than the VP-attachment sentence (Altmann & Steedman, 1988; Britt, Perfetti, Garrod, & Rayner, 1992; Ferreira & Clifton, 1986; Perfetti, 1991; Rayner, Carlson, & Frazier, 1983; Rayner, Garrod, & Perfetti, 1992).

If the focus operator *only* is substituted for *the*, however, the preference for attachment of the prepositional phrase should be reversed, according to the referential theory. Specifically, the preference should be to attach the prepositional phrase to the preceding noun. This reversal in preference is expected to bring about an associated reversal in semantic anomaly judgments. For sentences with *the*, as we saw, the temporary anomaly is expected to result in the NP-attachment sentence (10), but not in the VP-attachment sentence (11). For sentences with *only*, by contrast, the preference for NP-attachment of the prepositional phrase should make the VP-attachment sentence with *only* (13) temporarily anomalous, but not the NP-attachment sentence (12).

(12) The man painted only doors with large cracks before the festival. NP-attachment
(13) The man painted only doors with new brushes before the festival. VP-attachment

The reasoning parallels that of the previous experiment. In the present examples, the noun *doors* is the focus element. Felicitous use of the focus operator *only* requires a set of entities which stand in contrast to the focus element within the mental model of the discourse context. The most parsimonious way to establish a contrast set for the focus element *doors* is to use the prepositional phrase that follows it as a modifier. Semantically, the set of doors previously introduced into the mental model is thereby partitioned into two subsets: *doors with...*, and *doors without...*. In the sentences with *only*, as in (12), this leads to a coherent set of entities, doors with large cracks; therefore, no processing difficulty is expected for these sentences. But processing difficulties are expected for sentences like (13), where a nonsensical set of entities, doors with new brushes, is the initial reading dictated by the semantic/referential properties of the sentence. To achieve a coherent interpretation for sentences like (13), the parser must not only revive the alternative structure for the ambiguous portion of the sentence, it must also pursue its other

options for constructing a contrast set -- making a specific contrast set up from scratch, or taking the contrast set to be everything, other than doors, in the domain of discourse. Not surprisingly, the combined effort of these computations is expected to create processing difficulties which can be highly demanding of memory resources.

Experiment 2 was designed to test these predictions of the referential theory. Thirty-two undergraduate students participated in the experiment, which used the eye-movement monitoring technique. Twenty test sentences were constructed, each with four versions, as illustrated above: (10) = THE-NP; (11) = THE-VP; (12) = ONLY-NP; (13) = ONLY-VP. A fully-crossed design was used, with five tokens of each version distributed in each of the four stimulus lists. Each list was administered to eight subjects, making a total of 32 subjects. There were forty fillers intermixed among the test items, and 8 warm-up sentences. One third of the fillers were followed by a comprehension question.

The data were analyzed using a full factorial 2 by 2 analysis of variance for repeated measures, with the factors THE/ONLY and type of attachment VP/NP. Test sentences were divided into five regions for analysis. Region 1 was the subject NP. Region 2 was the verb. Region 3 was the noun phrase that contained either *the* or *only*, and the preposition *with*. Region 4 was the disambiguating region, which contained the object NP of the preposition (e.g., *new brushes* or *large cracks*). Region 5 contained the remainder of the sentence. As in Experiment 1, residual reading times were used as the dependent measure because Regions 3 and 4 differed in length across sentence types.

The data were subjected to two analyses; once without regard to memory span, and once using memory span as a between-group factor. The eye-movement profiles from the first analysis are shown in Figure 3.

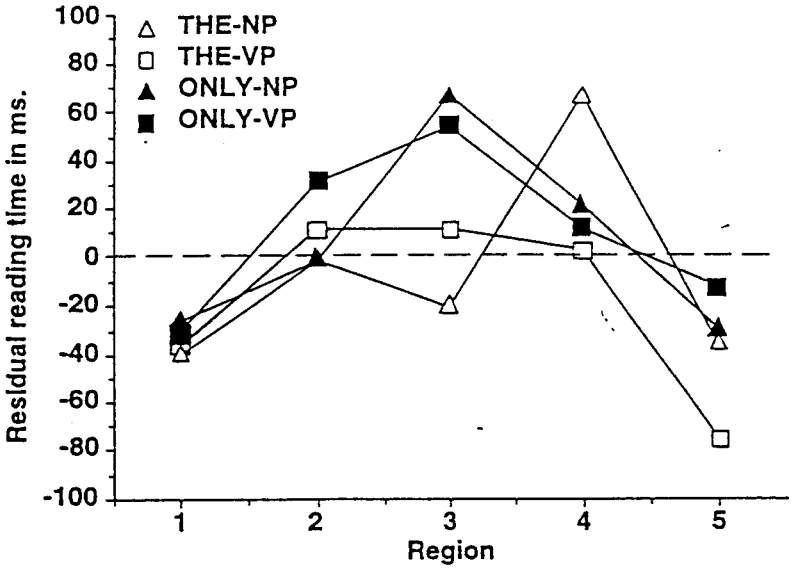

Figure 3: Mean residual reading times at each region

There were three significant findings. First, sentences with the focus operator *only* took longer to read than sentences with the definite determiner *the* in the region in which these words appeared, Region 3. This replicated one of the findings from Experiment 1. The second finding was that the NP-attachment sentences with *the* (THE-NP) registered longer reading times at the

disambiguating region, Region 4, than VP-attachment sentences with *the* (THE-VP): F_1 (1,31) = 10.01, $p < .01$; F_2 (1,19) = 7.39, $p < .02$. There was no corresponding difference in sentences with *only*, however. This is the third finding of importance.

To explain this last finding, we need to look at the second analyses of the data, which examined reading times and regressions separately for the two groups, divided according to memory span. Both groups took longer to read the NP-attachment sentences with *the* than they did the VP-attachment sentences with *the*. In sentences with *only*, by contrast, the processing patterns were different for the high-span and the low-span subjects. It was found that when the attachment of the prepositional phrase to the preceding NP led to an implausible interpretation, as in the case of ONLY-VP sentences, high-span subjects took longer to read the material in the disambiguating region, whereas low-span subjects made more regressive eye-movements. First pass reading times for high-span subjects were greater at the unexpected phrase *new brushes* in the ONLY-VP sentences than in the corresponding region in the ONLY-NP sentences, where the phrase *large cracks* makes sense; the difference approached significance in the analysis by subjects (F_1 (1,15) = 3.65, $p < .08$), but not in the analysis by items. The profile of responses by the low-span subjects was strikingly different. These subjects dwelled only briefly on the unexpected phrase *new brushes* in the ONLY-VP sentences. However, they registered a significantly greater number of regressions from that region, as compared to their regressions from the corresponding region of the ONLY-NP sentences: F_1 (1,15) = 26.42, $p < .01$; F_2 (1,19) = 11.34, $p < .01$. Profiles of reading times and regressions on the sentences with *only* are illustrated in Figures 4 and 5.

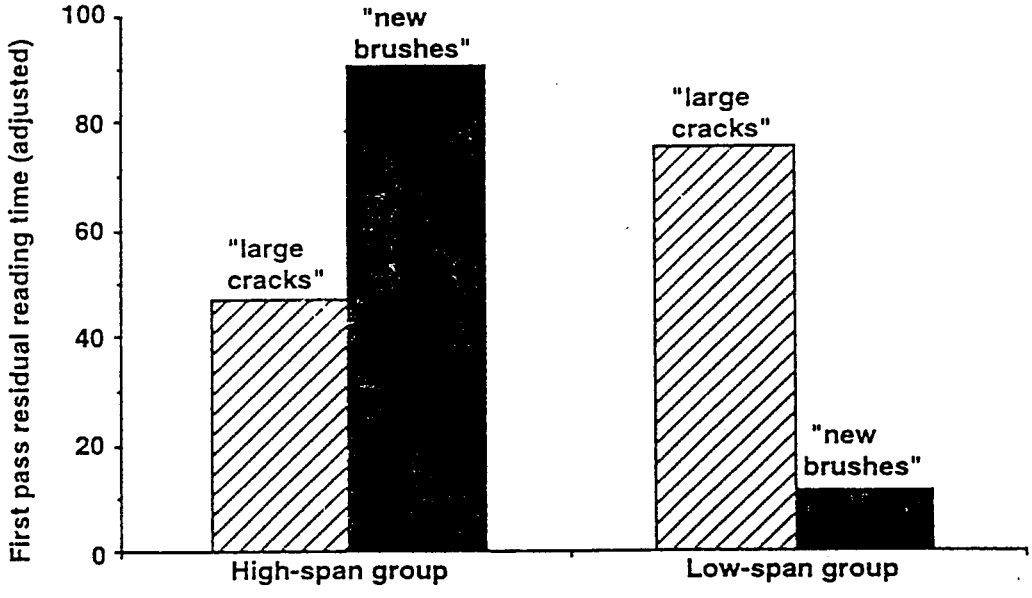

Figure 4: First pass residual reading times at Region 4 for sentences with ONLY

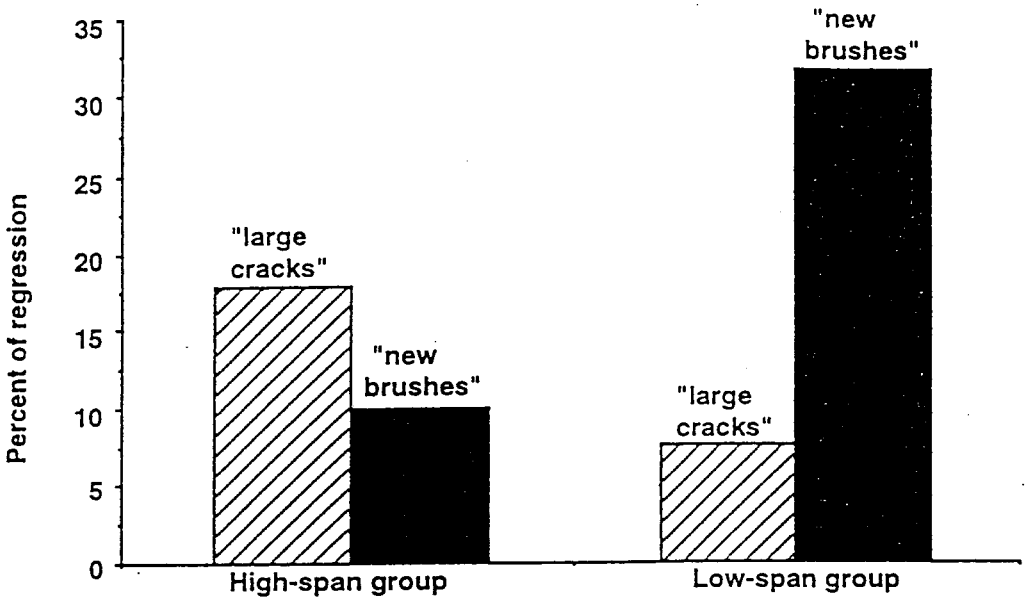

Figure 5: Percent of regressions from Region 4 for sentences with ONLY

Here is our interpretation of these findings. As expected on the referential theory, it turned out to be relatively easy for both high-span and low-span subjects to construct a mental representation for sentences with the definite determiner, *the*. It is apparent from the results of both Experiments 1 and 2 that NPs containing *only* are more difficult to process than ones containing *the*, even before the ambiguous region. This underscores our comment in the introduction -- that semantic/referential processes are sometimes consuming of memory resources. Having pursued the referentially simpler VP-attachment analysis for the THE-NP sentences, both high-span and low-span subjects detected the implausibility of the noun phrase *large cracks* as a modifier of the verb in these sentences. Reanalysis was therefore initiated, resulting in long first pass reading times in the disambiguating region, Region 4. That the relatively simple recovery process was generally accomplished on-line is also attested by the relatively low incidence of regressions by both high-span and low-span subjects.

In processing sentences with *only*, however, the eye-movement data differentiate the two subject groups. High-span subjects were able to recover on-line from the anomaly in ONLY-VP sentences, where the PP *with new brushes* was not a plausible modifier for the NP *doors*. These subjects were able to resolve the ambiguity on-line by using real-world knowledge, although the process led to inflated reading times. The long first pass reading times on ONLY-VP sentences by the high-span subjects, coupled with the absence of appreciable regressions from that region, indicated that these subjects successfully reanalyzed the sentence without frequently looking back to earlier regions.

Low-span subjects, by contrast, were largely unable to resolve ambiguities on a first pass reading of the sentences with *only*, when general world knowledge signaled that the wrong analysis had been selected by the semantic/referential processor. The coupling of results of relatively faster reading times with more regressions at the disambiguating region for low-span subjects suggests that these subjects had difficulties recovering on-line from an initial misanalysis. They were aware of the anomaly in the ONLY-VP sentences, but were unable to immediately use available plausibility information for on-line reanalysis. Hence, they were compelled to review material that they had read earlier.

The referential theory gives a parsimonious explanation of the complementary pattern of eye fixations and regressions for the two subject groups. The use of semantic/referential information (contributed by the focus operator *only*) made some demands on processing resources before the ambiguity was encountered. The presence of *only* also caused subjects to select the NP-attachment analysis of the ambiguity, and late-arriving plausibility information was needed to disconfirm the parsing decision. The memory resources of low-span subjects had apparently been exhausted, however, by the time the anomaly had been detected, so these subjects were forced to deal with the anomaly by returning to earlier portions of the sentence. In short, frequent regressions can be taken as evidence that low-span subjects were unable to use real-world knowledge as rapidly as high-span subjects in on-line recovery from a misanalysis.[5] High-span subjects were able to recover from the misanalysis within the disambiguating region, although this led to longer fixation times.

To summarize, Experiment 2 was designed to exploit the technique of eye movement recording to estimate the time at which plausibility information is used by the sentence processing system. Adopting a modular conception of the language apparatus, we anticipated that the use of plausibility information would be delayed, in contrast to the contribution of syntactic processes, and the influence of semantic/referential principles. Subjects were grouped according to their working memory span to see whether the resolution of ambiguities based on pragmatic plausibility would co-vary with individual differences in memory. The results indicated that the time course of the use of plausibility information did in fact co-vary with memory span. Plausibility information was used quickly by individuals who had relatively high memory spans, but its use was delayed in low-span individuals. These results provide evidence that the ability to use plausibility information is resource-dependent.

4. Conclusion

The experimental data reported in this paper lend support to the referential theory of sentence processing. The findings indicate that semantic/referential principles are applied on-line in ambiguity resolution. These principles are used to decide among available representations which are computed in parallel within the syntactic component.

A comparison across the experiments suggests, moreover, that the use of plausibility information depends upon the memory capacity of the individual. For subjects with relatively high memory spans, plausibility information seems to be used rapidly, whereas its use appears to be delayed for low-span subjects (Experiment 2). Differences in memory capacity are not instrumental in ambiguity resolution, by contrast, when disambiguation hinges on structural knowledge, rather than general knowledge about the world (Experiment 1).

These findings are interpreted as evidence favoring a modular conception of the language apparatus, according to which the construction of structural representations is not influenced by the perceiver's background beliefs about the world (Fodor, 1983; Crain & Steedman, 1985). Use of world knowledge appears to be available only after structure-building operations take place within the language module. How quickly background beliefs can be used depends on two factors. One factor is the memory capacity of the perceiver. The second factor concerns the time at which plausibility information is available. If information regarding plausibility is encountered before the point of ambiguity, then this information may be effective in resolving local ambiguities that are subsequently encountered (see Trueswell, et al. 1994). If information about

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[5] The alternative is to suppose that low-span subjects did not initially pursue the NP-attachment analysis of prepositional phrases in sentences with *only*. However, this account fails to explain the significant number of regressions by these subjects in the ONLY-VP sentences.

plausibility is encountered after the point of ambiguity, however, its implementation in decision-making may be delayed even though this information may be available to the parser. In contrast, semantic/referential (e.g., focus) information is rapidly used to adjudicate among competing structural analyses. To conclude, the findings of these experiments are entirely consistent with the referential theory and the modularity hypothesis. Only the future will tell if other accounts of sentence processing can deal with these findings.

Appendix

In formal terms, the semantic value of the focus operator *only* is captured by the following rule (adapted from Krifka, 1991; also see Jackendoff, 1972, Rooth, 1985):

MEANING RULE FOR *ONLY*:

$$B(F) \;\&\; \forall X[\{\, X \in CON(F) \;\&\; B(X)\,\} \rightarrow X = F]$$

Where X is a variable of type F, and
CON(F) is a set of contextually determined alternatives to F.

In the meaning rule, B represents *background information*, F represents *the element in focus*, and CON(F) represents the *contrast set* -- the alternatives to the focus element. The first conjunct of the meaning rule, B(F), states that the background must apply to the focus element. The second conjunct is a typical Russellian statement of uniqueness: $\forall X[\{\, X \in CON(F) \;\&\; B(X)\,\} \rightarrow X = F]$. This guarantees the uniqueness of the focus element: for each member of the contrast set, if the background applies to it, then that member is the focus element itself. In this conjunct, the universal quantifier ranges over a *meta*variable, X. By replacing the metavariable X with actual variables of different types, different interpretations may be derived, depending on the nature of the entities that are being contrasted with the focus element. If the element in focus is an *individual*, then the contrast set contains individuals. In this case, the metavariable is replaced by an individual variable: x, y, and so on. By contrast, if the focus element is a *property* of individuals, then the contrast set consists of sets of properties of individuals, rather than individuals themselves; in such cases, the metavariable is replaced by a variable of this type: P, Q, and so on. This provides the parser with flexibility to cope with alternative interpretations for sentences with *only*.

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