Linguistic Complexity and Working Memory Structure: Effect of the Computational Demands of Reasoning on Syntactic Complexity

Yoonhyoung Lee

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Approved by:

Advisor: Dr. Peter C. Gordon

Reader: Dr. Robert C. MacCallum

Reader: Dr. Neil Mulligan

Reader: Dr. Joseph Hopfinger

Reader: Dr. Jennifer Arnold

ABSTRACT

YOONHYOUNG LEE: Linguistic Complexity and Working Memory Structure: Effect of the Computational Demands of Reasoning on Syntactic Complexity
(Under the direction of Peter C. Gordon.)

The manner in which sentence processing mechanisms interact with other cognitive processes was investigated by examining the interaction between the syntactic complexity of a sentence and the difficulty of reasoning about the information in the sentence. In the experiments, participants were presented with a sentence containing a relative clause (RC). Syntactic complexity factors (type of extraction for all four experiments, type of modified head for the first experiment) and complexity of reasoning factors (determinacy of the implicit relation present in a complex verb for Experiments 1-4 and the nature of the relation between verbs in a complex sentence for Experiments 2-4) were varied. Together the results of the four experiments show that reasoning occurs after basic processes of sentence interpretation and that those processes are not influenced by the cognitive demands of reasoning. These results provide evidence against the idea that sentence processing shares resources with more general processes (e.g. Just & Carpenter, 1992) and provide support for the idea that the resources used for sentence processing are separate from those used for consciously controlled processes (Waters & Caplan, 1996).

DEDICATION

To my family:

My mother has always encouraged and supported me unconditionally and with much love. No words can express my thanks to my wife. My daughter and son have given most of the happy moments in my life even before they were born.

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INTRODUCTION

1.1 Nature of working memory structure during sentence processing

The role of working memory in sentence comprehension is a central research topic in psycholinguistics. With respect to the structure of working memory, there is a major debate about whether syntactic processing is modular or whether it draws on the same memory resources used by other cognitive processes. For example, Just and Carpenter (1992) argued that sentence processing shares working memory resources with other cognitive processes, while Caplan and Waters (1999) proposed a sentence-interpretation resource separate from those used for consciously controlled processes. With respect to the manner in which working memory constrains performance during sentence comprehension and other tasks, most theories state that working memory has a limited capacity in terms of the number of items that can be stored (e.g., Waters & Caplan, 1996; Gibson, 1998). Other theories have emphasized representational factors, such as the frequency of patterns (MacDonald & Christianson, 2002) or the similarity of the items to be represented (Gordon, Hendrick & Johnson, 2001).

1.1.1 Syntactic complexity: Relative clauses

It is well established that subject-extracted relative clauses (RCs) (e.g. *The boy that hugged the girl kissed the baby*) are easier to process than object-extracted relative clauses

(RCs) (e.g. *The boy that the girl hugged kissed the baby*). It is also well established that RCs modify the main subject of a sentence (e.g. *The boy that hugged the girl kissed the baby*) are harder to process than RCs modify the main object of a sentence (e.g. *The boy kissed the baby that hugged the girl*). These differences in processing complexity have been demonstrated in many different ways: reading-time (King & Just, 1991), probe tasks (Wanner & Maratsos, 1978), ERP (King & Kutas, 1995), PET (Caplan, Alpert, & Waters, 1998; 1999), fMRI (Just, Carpneter, Keller, Eddy & Thulborn, 1996; Caplan, Vijayanm, Kuperberg, West, Waters, Greve, & Dale, 2001), and eye-tracking (Traxler, Pickering, & McElree, 2002).

To explain this difference, many hypotheses have been proposed. Because both subject-extracted RCs and object-extracted RCs have the same lexical context, most theories attribute the difference between these two types of RC sentences to the relative structural complexity of object-extracted RCs over subject-extracted RCs. For example, the structural distance hypothesis (O'Grady, 1997) explains the RC type effect in terms of the different structural positions of the subject and the object in syntactic structure. According to this hypothesis, the complexity of the structure increases with the number of syntactic items (e.g. nouns, verb phrases) between the locus of extraction and the element with which it is associated. Object-extracted RCs are more difficult because they have one more syntactic item between the head noun and the locus of extraction than subject-extracted RCs. The canonical word order hypothesis (Cooke, Zurif, DeVita, Alsop, Koenig, Detre, Gee, Pinago, Balogh, & Grossman, 2001) explains the complexity of object-extracted RCs as resulting from a violation of canonical word order that is maintained in subject-extracted RCs.

Memory-based accounts (Gibson, 1998; Gordon, Hendrick, & Johnson, 2001) state that the comprehension difficulties for complex sentences emerge mainly because of the memory demand that complex sentences impose in terms of the storage and integration of intermediate interpretations of the sentences. Therefore, they believe that the object-subject difference is due to the fact that understanding object-extracted RCs requires more working memory resources than does understanding subject-extracted RCs. According to the memory based accounts, structural integration complexity depends on the distance or locality between the two elements being integrated and object-extracted RCs are more difficult because they involve longer distances, thus requiring more integration resources.

1.1.2 Separate resource vs. general resource

Just and Carpenter (1992)'s common-working-memory-based approach is that linguistic working memory capacity directly constrains the operation of language comprehension processes. According to them, it is assumed that humans have a set of verbal processing resources that can be devoted to several different kinds of language processes (lexical, syntactic, etc.) as well as non-linguistic, verbally-mediated cognitive tasks. To test their idea, they tested high and low memory-span participants, as measured by the Daneman and Carpenter (1980) reading-span task, with two types of sentences. In the processing of sentences with subject-extracted RCs (low syntactic complexity) and object-extracted RCs (high syntactic complexity), they found an interaction between reading span and sentence type. Only for object-extracted RCs did low-span participants have longer main verb reading times than high-span participants. For subject-extracted RCs, there was no difference between the low- and high-span groups. These data were interpreted as showing that the object-extracted RCs imposed a higher demand on verbal working memory than subject-extracted RCs and only the high span readers had enough working memory capacity to interpret the object-extracted RCs efficiently.

Waters and Caplan (1996) had a different view of working memory structure for sentence processing than Just and Carpenter (1992). They divided the procedures involved in sentence processing into interpretive and post-interpretive processes. According to them, interpretive processing is an obligatory processing that is used to extract initial meanings, syntactic roles, and semantic roles from the sentence. Post-interpretive processing is a more conscious, controlled type of process that involves using the products of interpretive processing to carry out some task, such as sentence–picture matching or enactment of the action in the sentence.

One important way to empirically distinguish between the two kinds of working memory relates to complexity. Specifically, Caplan and Waters (1999) claimed that syntactic complexity affects processing in the interpretative working memory, whereas the post-interpretative working memory is influenced by a non-syntactic kind of complexity. To test their idea, Waters and Caplan (2001) tested reading span and on-line and off-line syntactic processing of five age groups from age 18 to 90. On-line sentence processing efficiency was assessed using a self-paced hearing paradigm. For the working memory measure, the sentences were divided into five sets at each of the span sizes from 2 to 6. After the last sentence in the series, the participant had to recall the last word of each of the sentences in the series. Older participants showed reduced working memory spans compared with younger participants, but both older and younger participants showed similar effects of syntactic complexity on the on-line measures. The results were interpreted as showing that the efficiency of on-line syntactic operations did not differ as a function of age despite reduced working memory capacity for the older group.

Using the eye tracking method, Kemper, Crow, and Kemtes (2004) tested the role of working memory capacity limitations and age differences in the processing of complex syntactic constructions. They tested young and old adults with different memory spans (high-span vs. low-span). According to Just and Carpenter (1992)'s view, low-span readers should have difficulty processing the syntactically ambiguous sentences and should exhibit ambiguity effects, while high-span readers should be able to avoid these effects by constructing multiple syntactic interpretations of the ambiguous phrases. Also, as older adults were claimed to resemble low-span readers, they should have more difficulty making and sustaining multiple interpretations of ambiguous phrases. According to Waters and Caplan (1996)'s view, all readers should show increased difficulty at points of maximal syntactic complexity. The results showed that the ambiguity effects were similarly regardless of age or working memory span. However, the results also showed that the fixation patterns of older adults and those of low-span readers resembled each other such that both groups made many more regressive eye movements to the previous region of a sentence for ambiguous sentences than their counterparts. In contrast, young adults and high-span readers seemed to be able to resolve the syntactic ambiguities without recourse to leftward regressions. Therefore, the results of Kemper and colleagues (2004) can be interpreted as showing mixed results of supporting both Waters and Caplan (1996)'s view and Just and Carpenter (1992)'s view.

1.1.3 Evidence from neuro-imaging studies

Neuro-imaging studies also have been used to provide insight into working memory processes during sentence processing, although they have been slow considering the boom of neuro-imaging studies in cognitive psychology. A highly consistent result across neuro-imaging studies concerning sentence processing is that Broca's area is engaged to a greater degree during the processing of complex sentences than during the processing of simple sentences. For example, Just and colleagues (1996) found that blood flow increased in both Broca's and Wernicke's area when participants read syntactically more complex sentences. Caplan and colleagues (2001) also found increased blood flow in Broca's area when participants made judgments about more complex sentences. More recently, Waters, Caplan, Alpert and Stanczak (2003) tested the influence of individual working memory capacity during sentence processing. They found increased blood flow in Broca's area for more complex sentences, but they did not find any significant differences between memory span groups. They concluded that blood flow in Broca's area is not dependent upon individual working memory capacity differences, which supports a specialized working memory system related to syntactic processing. However, different findings also have been reported. For example, Keller, Carpenter and Just (2001) reported that the blood flow in Broca's area was greatly increased when syntactically complex sentences contained less frequent words. Also, Fiebach, Vos, and Friederici (2004) showed that individual differences in working memory did influence the blood flow when they presented syntactically more demanding German sentences. They found that the blood flow in Broca's area varied as a function of both the syntactic complexity and the working memory span. Theses studies can be interpreted as supporting the idea that syntactic processes are constrained by the general working memory resources of the cognitive system.

Event related potentials (ERPs) research also has enhanced the understanding of sentence processing. Fiebach, Schlesewaky, and Friederici (2002) tested high and low working memory span groups to investigate whether working memory processes during sentence comprehension and syntactic integration processes draw upon the same processing resources. Syntactic working memory cost was manipulated by varying the distance (long vs. short) over which syntactic information had to be maintained in working memory. The necessity of integration for comprehending the sentences was also manipulated. The results showed stronger amplitudes of left anterior negativity (LAN) for long distance conditions and P600 for sentences requiring the integration[1]. However, there was no difference by working memory span group. They interpreted the LAN as reflecting working memory processes required for maintaining the dislocated object in memory and the P600 as representing processing costs associated with integrating the stored element into the phrase structure. Based on the different responses of the two ERPs, they concluded that maintaining information during sentence comprehension and integrating the stored information draw upon different processing resources.

However, Vos, Gunter, Kolk, and Mulder (2001) found evidence supporting a different conclusion. They tested the effects of external memory load on syntactic complexity for high and low working memory span groups. Whereas Caplan and Waters (1999)' view predicts that external load only affects the post-interpretative working memory, they

[1] Over the years, left anterior negativities (LANs) and later parietal positivity (P600) have been replicated numerous times in experiments manipulating syntactic factors. P600 has been claimed to reflect syntactic processing such as syntactic integration and syntactic reanalysis (Kolk et al, 2003). LAN has been found to respond not only to differences in grammaticality, but also to storage and retrieval load from verbal working memory (Felser, Clahsen, & Münte, 2003).

observed that external load affected grammatical processing. They observed not only a delayed onset of the P600 in the high load condition, but also a complexity by load interaction on the amplitude of the LAN such that, on the amplitude of the LAN, the effect of syntactic complexity was greater when there was a higher load.

A similar study was done using syntactically ambiguous sentences. Kolk, Chwilla, van Herten, and Oor (2003) tested the effect of syntactic complexity on processing of syntactically and semantically abnormal sentences using ERPs. According to them, both Just and Carpenter (1992)'s and Caplan and Waters (1999)' ideas predict that complexity will affect the processing of syntactically abnormal sentences. In particular, because working memory is considered to be a limited capacity system by both views, the detection of syntactic anomalies should be harder in complex sentences. However, with respect to the semantic anomalies, Caplan and Waters (1999)' theory does not predict an effect of complexity on the detection of semantic anomalies because these anomalies should be resolved by a separate post-interpretative working memory. So, the detection of semantic anomalies should be slower than the detection of syntactic anomalies and should involve other ERPs in other brain areas than syntactic anomalies. Kolk and colleagues (2003) found that the effects of syntactic and semantic anomalies had the same amplitude of P600 in the same brain region. Based on these results, they argued that verbal working memory is not divided into interpretative and post-interpretative components.

In sum, although much empirical evidence from various sources has been collected, the debate about the structure of working memory in sentence processing is far from being resolved.

1.1.4 Different approaches

Besides the two views explaining the structure of working memory for sentence processing mentioned above, there are several other accounts focusing on the factors affecting comprehension difficulty for different syntactic structures.

Connectionists try to explain the relationship between language processing and individual differences of reading span with the notion that reading span differences are due to variation in experience with language. MacDonald and Christiansen (2002) showed that the amount of training (experience) of a simulated language-processing network predicted the differences in performance due to syntactic complexity. From this viewpoint, high-span readers tend to be individuals who read more and so have more experience with complex sentences. They proposed that there is no structure like working memory and that language experience is the main source of the individual differences in sentence processing[2].

Gibson (1998) proposed the Syntactic Prediction Locality Theory (SPLT) model that differentiates syntactic memory costs and syntactic integration costs as two aspects contributing to processing difficulty in syntactically complex sentences. According to Gibson (1998), memory costs during sentence processing come from the number of incomplete syntactic predictions that must be maintained. Also, the integration costs get higher when new input must be integrated into the current structural representation of the sentence. Although he did not specify how the proposed memory cost and integration cost could be specialized to the working memory system, recent research from Fedorenko, Gibson, and

[2] According to Caplan and Waters (2002), no amount of practice seems to be able to make object-relative sentences as easy to process as subject-relative sentences even though MacDonald and Christiansen (2002)'s network showed equal performance for these sentences in cases of highly trained networks. Also, as Just and Varma (2002) mentioned, a large number of neuroscience studies have produced evidence for the reality of working memory.

Rohde (2006) showed that they do not follow the domain-specific view of working memory resources in sentence comprehension.

Gordon, Hendrick and Levine (2002) focused on the types of representations involved in language comprehension instead of focusing on the working memory capacity. They argued that limited capacity is not the only factor for the sentence complexity effects, but similarity of items being processed, which is one of the key properties affecting human memory, also affects the processing of complex sentences. In their research, Gordon and colleagues (2002) manipulated the representational characteristics of memory load (whether memory load items were matched to the type of noun phrases (NPs) of the target sentence or memory load items contained different types of NPs from the target sentence) rather than number of items in memory load. They observed a significant interaction between sentence type and the type of memory load. This interaction supports Just and Carpenter (1992)'s view that processing the syntactic structure of the sentences and maintaining the load items draw on the same memory resources. They concluded that Caplan and Waters (1999) failed to see such an interaction because they focused on number of items in memory load rather than the representational characteristics of memory load. They also proposed that the representational characteristics might be the most influential factor of sentence processing since complex sentences almost always require intermediate representations of parts of a sentence in order to be fully understood.

1.2 Computational processing demands and working memory

1.2.1 Working memory structure

Baddelely (1986) defined working memory as a system for temporary holding and manipulation of information during the performance of a range of cognitive tasks such as comprehension, learning, and reasoning. In a recent description of his working memory model, Baddlely (2000) proposed a four-component model including the phonological loop, the visuo-spatial sketchpad, the central executive, and the episodic buffer. The phonological loop is responsible for the maintenance and rehearsal of information that can be coded verbally. The visuo-spatial sketchpad stores and maintains information that cannot be coded verbally. The episodic buffer maintains information from several modalities that has been bound together by the central executive; it also serves as a scratchpad for the development of new mental representations during complex problem solving. The central executive is responsible for control of processing and for the manipulation and integration of information as tasks are performed[3].

1.2.2 Working memory and reasoning

Since Baddeley and Hitch (1974) showed that list memory and reasoning used separate resources within working memory, reasoning tasks have been used as a reliable measure of central executive function (Carter, Kenney & Bittner, 1981; Lynn & Irwing, 2002; Portala, Levander, Westermark, Ekselius & von Knorring, 2001).

In their seminal work, Baddeley and Hitch (1974) presented series of sentences, each describing the order of presentation of two letters, A and B (e.g. *A precedes B*). The

[3] There have been very large numbers of studies concerning the working memory structure proposed by Baddlely (1986; 2000) in various fields. Although this is one of the most important topics in cognitive science, it is beyond the scope of this research.

statements consisted of combinations of the various grammatical transformations: voicing (active, passive; e. g. *A precedes B, B is preceded by A*), negation (positive, negative; e.g. *A precedes B, B does not precede A*), polarity of verb (*precedes, follows*), and subject (*A, B*). Statements with active voice were easier to process than those with passive voice, and positive sentences were easier than negative ones. Also, because the letter A is the first letter of the English alphabet, sentences like '*B follows A*' were easier than '*A follows B'*. In this task, participants were required to respond 'true' or 'false' to an arrangement of the letters (either 'AB' or 'BA') as shown in the following examples. Example 3 was the most difficult among these three examples because it has passive voice and contains negation, while 1 was the easiest.

(1) *A follows B*
Question: BA (True/ False)?

(2) *B is followed by A*
Question: BA (True/ False)?

(3) *A is not preceded by B*
Question: BA (True/False)?

In the Baddeley and Hitch (1974) study, a concurrent memory load task (remembering numbers) was also performed during the reasoning task. They found that there were very few errors on either the memory load task or the reasoning task. Although there was a consistent tendency for reasoning to be slowed, the magnitude of the disruption was small. Particularly, small concurrent memory loads had no effect on reasoning accuracy or response times, and there was no meaningful interaction between concurrent memory load and reasoning task difficulty. Based on these results, they assumed that the list memory task and the reasoning task are not dependent on the same limited-capacity system but utilize separate modules of working memory.

Other studies have also shown that the central executive is the part critically engaging the reasoning task while the phonological loop is the part mainly responsible for the typical memory load tasks. For example, using a variety of secondary tasks, Toms, Morris and Ward (1993) found no evidence of phonological loop and visuo-spatial sketchpad functions on reasoning tasks. Also, Gilhooly, Logie, Wetherick, and Wynn (1993) tested verbal syllogisms and they found, similarly, that the central executive is critical for relational reasoning and the phonological loop is minimally involved.

1.2.3 Relational complexity and working memory

(4) *Suppose that five days after the day before yesterday is Friday. What day of the week is tomorrow?*

Sweller (1993) tested this problem and found that it is extremely difficult despite using simple concepts about days of the week. He suggested that the difficulty is due to the fact that all the elements are related to each other. This type of complex relational reasoning task attracted researchers who view working memory limits in terms of ability to process independent sources in parallel (Halford, Wilson & Phillips, 1998)

Traditionally, working memory limits have been defined in terms of number of items (Miller, 1956), limits on activation (Anderson, Reder & Lebiere, 1996), or number of new goals (Just et al, 1996). However, Halford and colleagues (1998) developed a relational complexity account of working memory capacity by focusing on the central executive function of working memory to measure working memory capacity. Instead of defining working memory limits as a limit of number of items, they suggested that information processing capacity limits should be defined in terms of the complexity of relations (*relational complexity*) that can be processed in parallel. The following example shows the influence of relational complexity in processing demand:

(5) *The boy the girl the man saw met slept.*

This type of doubly-embedded sentence is extremely difficult to understand. To understand this sentence correctly, we have to decide who saw, who met, and who slept as well as identify the objects of *saw* and *met* all together. The problem here arises not just from difficulty of the storage of either the original sentence or the results of partial processing; it also reflects the amount of information that must be integrated at the same time (Halford, Wilson, & Phillips, 1998).

In the relational complexity point of view, the processing load is determined by the number of independent sources that are related to each other and that must be processed simultaneously. Relational complexity increases with the number of relations that must be considered or inhibited simultaneously. For example, at the first level of complexity, only one relation needs to be considered in order to solve the task correctly. At the second level of complexity, two relations need to be considered at the same time.

(6) *John is taller than Tom, Mary is taller than Peter.*

(7) *John is taller than Tom, Mary is taller than John.*

(6) is an example of the first level of complexity because no two relations need to be integrated in order to make the correct inference of who is taller then whom. (7) is an example of the second level of complexity because we cannot decide who is tallest if we separately consider that *John is taller than Tom* and *Mary is taller than John*. These two propositions jointly determine that Mary is the tallest.

Using the transitive inferences like shown above, Viskontas, Holyoak, and Knowlton (2005) tested whether complexity of relational integration is affected differently by age. They varied the levels of relational complexity across the young, middle, and old age groups. The lowest level of relational complexity requires simple chaining of the names to solve the task (e.g. *Sam is taller than Sean, Sean is taller than Jane, Jane is taller than Eric*), the more complex condition requires integration of relations by considering two relations simultaneously (e.g. *Jane is taller than Eric, Sean is taller than Jane, John is taller than Sean*) and so on. In the most complex condition, the participants need to consider three relations together (e.g. *Sam is taller than Jane, Dan is taller than Eric, and Jane is taller than Dan*).

By holding visual and phonological demands constant across conditions, Viskontas and colleagues (2005) were able to assume that any increased demands on integration processing would reflect increased engagement of the central executive function, as the central executive is known to be the main component engaging the manipulation of information. They suggested that if the age-related decline of working memory occurs mainly in the storage capacity, then the results of all age groups should show similar results across all integration conditions as they vary only by the demands on the central executive. If central executive function also declines with age, the older group should show more difficulty with problems that require more integration processing, but they would perform similarly on problems that required low processing demand. The results showed a trend of increased difficulty for the older groups such that older people required more time to solve the problems when they required integration of multiple relations. Although it is far from conclusive, the results suggested that executive function also declines with age.

Relational complexity also can be measured by dimensionality (Andrews & Halford, 2002). Dimensionality is defined as the number of independent units of information that must be integrated. One-dimensional concepts are defined as predicates with one argument. For example, *Max is a cat* is one-dimensional. Two-dimensional tasks are defined as predicates with two arguments. A good example is a binary relation, such as *an elephant is larger than a dog*. Transitivity, such as *Jim is happier than Paul, Paul is happier than Dave*, is a good example of a three-dimensional concept (Andrews & Halford, 2002). Different dimensionalities also can be seen in linguistic examples. *'The dog ran'* is one-dimensional because the verb *ran* only needs its grammatical subject. However, *'The boy the girl the man saw met slept'* is five dimensional because 'slept' needs an argument (subject), 'met' needs two arguments (subject and object), and 'saw' needs two arguments (subject and object) (Halford et al, 1998).

1.2.4 Relational complexity and sentence comprehension

Only a few studies have characterized sentence comprehension in terms of relational complexity. For example, Andrews and Halford (1994) varied dimensionality from one to five using various sentence structures, and they found that the difficulty rating increased as dimensionality increased. Particularly, they found that doubly center-embedded structures (e.g. *The clown that the teacher that the actor liked watched laughed*) were almost always reported as incomprehensible because they require five arguments to be considered at the same time. They interpreted the results as readers having difficulty assigning words to more than four case roles for the center-embedded sentences, for which readers need to consider and integrate all case roles in parallel.

Andrews and Halford (1999) measured the correlation between ease of comprehending different levels of complex sentences and reading span.

(8) *The duck that the monkey touched walked.*

(9) *The clown that the teacher that the actor liked watched laughed*.

(10) *The monkey touched the duck that walked.*

(11) *The actor liked the teacher that watched the clown that laughed.*

According to the relational complexity account, sentence complexity corresponds to the number of role assignments that must be considered at the same time. This is based on the principle that each argument of a predicate constitutes a dimension. Therefore, sentences like (8) and (10) are easier than sentences like (9) and (11). Also, they assumed that center-embedded sentences (e.g. 8, 9) are harder to comprehend than right-branched sentences (e.g. 10, 11). For the center-embedded RCs like (8), no role assignments are possible until the verb *touched* is encountered. Right-branched sentences like (10) also need the same number of role assignments, but those assignments need not be made as part of the same decision[4]. In their experiment, Andrews and Halford (1999) found that the correlation between comprehension accuracy and reading span increased with the increase of the number of roles for center-embedded structures but not for right-branching structures. For the center-embedded sentences, the correlation between reading span and the easier sentence was ($r=.24$) while it was ($r=.56$) for the harder sentence. For the right-branched sentence, the correlations were ($r=.14$) and ($r=.15$), respectively. Based on these results, they concluded that reading span measure is sensitive to the types of sentences only if sentences required four or five role assignments.

[4] This view is in line with the memory resource view that center-embedded object-extracted RCs require more working memory resources than right-branching subject-extracted RCs (Gibson, 1998; Gordon et al. 2001).

CHAPTER 2

OVERVIEW OF THE PROJECT

The main goal of the current project is to understand the nature of working memory during sentence processing. More specifically, this study focuses on whether sentence processing demands and reasoning demands use the same working memory resources, a question that is addressed by examining the possible interaction of syntactic complexity and the difficulty of an inference based on a sentence.

As discussed earlier, the role of working memory in sentence comprehension has been a central research topic in psycholinguistics. While most sentence processing research has attributed the difficulty in understanding complex sentences to short-term memory (Lewis, 2000) or working memory demands (Gibson, 1998; Gordon, et al, 2002; Just & Carpenter, 1992; Waters & Caplan, 1996), there has been considerable debate about the structural specification of working memory in sentence processing. For example, Just and Carpenter (1992) have contended that the external memory load competes with language processing for shared working memory resources, but Caplan and Waters (1999) have argued that the working memory resources used for sentence processing are separate from those used for consciously controlled processes.

The two main functions of working memory during sentence processing are the manipulation of information (e. g., activation, interpretation and integration) and the maintenance of information because, for many complex sentences, various kinds of computations such as syntactic parsing and thematic role assignment need to be performed and partial results from earlier processing steps must be maintained for later integration. As syntactic processes involve manipulation and integration of information, it raises the possibility that syntactic processing is mainly performed by the central executive. However, most experiments that have examined the relationship between working memory and syntactic processing have manipulated demands placed by external memory loads (lists of digits or words) while subjects perform language comprehension tasks with the goal of determining whether the same resources support both sentence processing and lists memory. As discussed by Just and Carpenter (1992) and Traxler, Williams, Blozis and Morris (2005), this may not provide the best way of assessing the role of the central executive in language comprehension because an external memory load mostly engages the maintenance function of the working memory system. Therefore, the current project focuses on the computational and integration demands reflecting the central executive function during sentence processing.

To do so, the grammatical reasoning, which is known to be sensitive to central executive function (Baddeley & Hitch, 1974; Gilhooly et al, 1993), and the relational complexity, which is popularly used in reasoning and problem solving studies (Andrews & Halford, 1999; Halford, Wilson, & Phillips, 1998; Viskontas, Morrison, Holyoak, Hummel, & Knowlton, 2004), were employed into the sentence processing framework. More specifically, I varied difficulty of transitive inferences in sentences as well as difficulty of sentence complexity as illustrated below.

Syntactic complexity variables:

I. Type of extraction (object-extracted RC vs. subject-extracted RC)

(12) *John who Tom follows precedes Bill./*

(13) *John who follows Tom precedes Bill.*

II. Type of modification (object modification vs. subject modification)

(14) *John who follows Tom precedes Bill./*

(15) *John precedes Bill who follows Tom.*

As mentioned earlier, previous research on the understanding of RC sentences has consistently shown that: (I) object-extracted RCs (e.g. 12) are more difficult to understand than subject-extracted RCs (e.g. 13) and (II) subject modification (e.g. 14) is more difficult to understand than object modification (e.g. 15).

Computational complexity variables:

A. Determinacy of the implicit relation (determined relation vs. undetermined relation)

(16) *John who follows Tom precedes Bill. /*

(17) *John who follows Tom follows Bill.*

For (16), to fully understand the relations among *John, Tom, and Bill,* participants first need to consider the relation between *John and Tom* and the relation between *John and Bill*. Then they need to integrate the two relations to calculate the implicit order among *John, Tom, and Bill*. However, in (17), it is impossible to decide the order of all three elements. Participants can establish the relation between *John and Tom* and the relation between *John and Bill*, but they cannot decide the relation between *Tom and Bill* based on the given information. Therefore, undetermined sentences require an extra computational (decision making) process beyond those needed for the sentences that specify an implicit relation. For all syntactic conditions, half of the sentences contained a determined implicit relation and the rest of the sentences contained an undetermined implicit relation.

B. Nature of the relation between verbs (semantically related verbs vs. semantically unrelated verbs)

(18) *John who follows Tom precedes Bill. /*

(19) *John who follows Tom is taller than Bill*

In this example, (18) would be harder than its counterpart because two semantically related verbs need to be considered at the same time to understand the implicit relation. For (19), even though two successive relational processes are required, the readers would notice immediately the fact that it is impossible to compute a single integration of two relations.

The four experiments examined the effect of computational processing demands during sentence processing. The hypothesis was that if the working memory resources used for sentence processing were separable from the computational processing demands of the transitive inference processing (e.g. Caplan & Waters, 1999), this extra computational demand would not interact with syntactic variables but would show additive effects. However, the finding of an interaction between extra computational demands and syntactic complexity would support the idea that syntactic processing shares resources with more general aspects of processing (Just & Carpenter, 1992).

The first experiment focused on the effect of conscious computational processes on syntactic processing by manipulating the two syntactic processing variables (I, II) and a difficulty of transitive inference variable (A). In the second, third, and fourth experiments, a syntactic processing variable (I) and two computational demands (A, B) were manipulated.

The general method of the experiments was to present participants with a sentence on a computer screen and asked them to press a key when they were ready to answer a question about the sentence. The questions consisted of statements about the sentence and the subject could respond 'true', 'false', or 'Not enough information'. Experiments 1, 2 and 4 measured the total time taken to read the sentence and the accuracy of the answer. In Experiment 3, eye movements were recorded as the subjects read the sentence, allowing more information to be gathered about on-line processing patterns.

CHAPTER 3

EXPERIMENT 1

In this experiment participants read transitive inference sentences containing relative clauses (RCs). As explained earlier, it is well established that subject-extracted RCs are easier to process than object-extracted RCs, and object modifying RCs are easier than subject modifying RCs. However, as far as I know, no research has been done to test transitive inference sentences with relative clauses. Therefore, one important goal of the first experiment was to see whether those phenomena found in the sentence processing studies could be seen in the transitive inference sentences. If the transitive inference sentences are processed using the general sentence processing mechanism, we would expect that the transitive inference sentences containing subject-extracted RCs should be easier than those containing object-extracted RCs. Also, we would expect that the transitive inference sentences containing the object modifying RCs should be easier than those containing subject modifying RCs. Furthermore, we would expect an interaction between the type of extraction variable and the type of modification variable such that the difference between the types of extraction would be larger in subject modification conditions than in object modification conditions.

The main goal of the first experiment was to examine the effect of computational processing demands during sentence processing. If these syntactic variables interact with computational demands to establish the implicit relations, it would support the idea that syntactic processing shares resources with more general aspects of processing. If the computational demands do not interact with syntactic variables but instead show additive effects, it would support the separate syntactic processing resource idea.

In this experiment, both subject-extracted and object-extracted RCs were used as experimental sentences. Also, half of the RCs modified the matrix subject of the sentence and half of the RCs modified the matrix object. Thus, there were four types of experimental sentences as shown below:

(Subject modifying Subject-extracted RC (SM-SRC))
Tom who follows Ben precedes Paul.
(Subject modifying Object-extracted RC (SM-ORC))
Tom who Ben follows precedes Paul.
(Object modifying Subject-extracted RC (OM-SRC))
Tom follows Ben who precedes Paul.
(Object modifying Object-extracted RC (OM-SRC))
Tom follows Ben who Paul precedes.

Four possible combinations of the verbs 'follow' and 'precede' (follow-follow, follow-precede, precede-follow, and precede-precede) were used in all four types of experimental sentences, creating 16 experimental templates. Importantly, of all the experimental sentences, half of them contained a determined implicit relation and the rest contained an undetermined implicit relation.

SM-SRC (Undetermined): *Tom who follows Ben follows Paul.*
/SM-ORC (Determined): *Tom who Ben follows follows Paul.*

OM-SRC (Determined): *Tom follows Ben who follows Paul.*
/OM-ORC (Undetermined): *Tom follows Ben who Paul follows.*

SM-SRC (Determined): *Tom who follows Ben precedes Paul.*
/SM-ORC (Undetermined): *Tom who Ben follows precedes Paul.*

OM-SRC (Undetermined): *Tom follows Ben who precedes Paul.*
/OM-ORC (Determined): *Tom follows Ben who Paul precedes.*

SM-SRC (Determined): *Tom who precedes Ben follows Paul.*
/SM-ORC (Undetermined): *Tom who Ben precedes follows Paul.*

OM-SRC (Undetermined): *Tom precedes Ben who follows Paul.*
/OM-ORC (Determined): *Tom precedes Ben who Paul follows.*

SM-SRC (Undetermined): *Tom who precedes Ben precedes Paul.*
/SM-ORC (Determined): *Tom who Ben precedes precedes Paul.*
OM-SRC (Determined): *Tom precedes Ben who precedes Paul.*
/OM-ORC (Undetermined): *Tom precedes Ben who Paul precedes.*

For all four types of experimental sentences, half of the sentences contained a determined implicit relation and the other half contained an undetermined implicit relation. For the determined cases, to fully understand the relation among three names, the two explicitly stated relations (e.g. the relation between T*om and Ben*, the relation between *Tom and Paul*) need to be considered first. Then participants can establish the implicit relation among the three names when the two relations are integrated.

However, for the undetermined cases, participants cannot calculate the implicit order of the three names. Although the relation between *Tom and Ben* and the relation between *Tom and Paul* can be calculated, it is impossible to decide the order of *Ben and Paul* based on the given information. However, the participants must first try to integrate the relations before discovering that the implicit relation is undetermined. Therefore, undetermined condition requires extra processing demand for undetermined cases over and above the processing demand for determined sentences.

3.1 Method

3.1.1 Participants

Participants were native speakers of English attending classes at the University of North Carolina at Chapel Hill. Forty-five students served as participants in the experiment and received credit for an introductory psychology course for their participation. All had normal or corrected to normal vision.

3.1.2 Materials

96 sentences were created with four possible combinations of the verbs, ‘follow’ and ‘precede’ (4 * 24). The conditions of the type of extraction and the type of modification were combined so that there were four experimental conditions (Subject modifying subject-extracted RC, Subject modifying object-extracted RC, Object modifying subject-extracted RC, Object modifying object-extracted RC). In all the experimental conditions, half of the stimuli had a determined implicit relation and half of the stimuli had an undetermined implicit relation. Frequent, one-syllable male names were used to control any influence of frequency and semantic information. All names in a sentence started with different initials and any combination of the three names occurred only once.

3.1.3 Design and procedure

Four counterbalanced lists were created such that each experimental sentence appeared in only one condition in a list. Across lists, experimental sentences occurred in all conditions. Each run of the experiment presented 96 experimental sentences excluding the initial practice trials. Appendix A shows the examples of experimental sentences.

Participants were instructed to read the sentences as fast as possible while making sure that they understood the relations among the names. Participants pressed the space bar when they finished reading the sentence. Following the sentence, a comprehension statement, which presented the relative order of the two names, was presented. The participants were required to decide whether the order in the comprehension statement matched the order in the original sentence. They had to respond ‘true’, ‘false’, or ‘not enough information’ to answer the question. If the participant's answer was incorrect, 'wrong!' appeared on the screen before automatically continuing to the next trial. When the participant's answer was correct, a blank screen appeared. Regardless of the determinacy of the implicit relation, questions about the implicit relations were presented two third of the time and questions about the explicit relations were presented a third of the time. The correct answers were equally distributed in all responses across the conditions. There were six practice trials before the actual experiment began and the order of presentation of sentences was randomized. The reading time and accuracy were measured.

3.2 Results

Data from five participants were excluded because of the chance level accuracy for the questions. Table1 shows the mean reading times and accuracies for sentences with different syntactic complexity.

3.2.1 Effect of the type of questions

The type of question did not significantly affect the reading time for the experimental sentences (implicit relation question: 10,139 ms vs. explicit relation question: 9,957 ms), but it showed a significant effect on the accuracy for the questions. The explicit relation questions (.86) prompted more accurate responses than the implicit relation questions (.80)[5] [$F(1,39)=6.40$ $MSe=.46$ $p<.05$].

Because the participants did not know whether an implicit relation or an explicit relation question would be asked, it would be reasonable to find no effect of the type of

[5] Comparable analyses were performed on the next three experiments. They showed the same patterns of results as this experiment.

question on reading time. It also would be reasonable that the explicit relation questions were answered more accurately. Although the participants were asked to build the possible relations among the three names as accurately as possible, the explicit relations would be easier to build and maintain than the implicit relations.

3.2.2 Effect of the syntactic complexity variables

The reading time showed significant effects of the type of extraction, with object-extracted RCs (10,550 ms) taking longer to read than subject-extracted RCs (9,607 ms) [$F_1(1,39)=21.73$ MSe=39481136 $p<.001$, $F_2(1,95)=16.87$ MSe=50598308, $p<.001$]. There were significant effects of the type of modification on reading time, with subject modifications (10,600 ms) taking longer to read than object modifications (9,556 ms) [$F_1(1,39)=29.97$ MSe=34912894 $p<.001$, $F_2(1,95)=28.70$ MSe=36589684, $p<.001$]. Also, there were significant interactions between the type of extraction and the type of modification such that the differences of the reading times between the RCs were larger when the RCs modified subjects than when the RCs modified objects [$F_1(1,39)=7.49$ MSe=20781642 $p<.01$, $F_2(1,95)=4.36$ MSe=35923919, $p<.05$].

The answers to the comprehension question were more accurate for subject-extracted RCs (.82) than for object-extracted RCs (.78) [$F_1(1,39)=5.07$ MSe=.37 $p<.05$, $F_2(1,95)=10.67$ MSe=.18, $p<.001$]. The accuracy did not show any significant effect of the type of modification or of the interaction between the two factors.

3.2.3 Effect of the computational complexity variable

Table 2 shows the mean reading times and accuracies for sentences with different syntactic complexity for each type of determinacy of the implicit relation. The reading times were longer when the implicit relation was undetermined (10,717 ms) than when it was determined (9,439 ms) [$F_1(1,39)=23.21$ MSe=67661826 $p<.001$, $F_2(1,95)=52.44$ MSe=29941841, $p<.001$]. The answers to the comprehension questions were more accurate when the implicit relation was determined (.88) than when it was undetermined (.76) [$F_1(1,39)=28.20$ MSe=.53 $p<.001$, $F_2(1,95)=68.88$ MSe=.22, $p<.001$].

Importantly, the syntactic complexity variable and the difficulty of reasoning variable did not interact with each other. The reading time showed that neither the type of extraction variable [$F(1,39)=.12$ MSe=48578272 $p=.72$] nor the type of modification variable [$F(1,39)=.10$ MSe=42726040 $p=.75$] interacted with the determinacy of the implicit relation variable. The accuracy of the answers also showed no interaction between the type of extraction and the determinacy of the implicit relation [$F(1,39)=.97$ MSe=.26 $p=.33$] nor between the type of modification and the determinacy of the implicit relation [$F(1,39)=.08$ MSe=.16 $p=.78$].

3.3 Discussion

The results of the first experiment showed that transitive inference sentences were processed in a similar way as the other relative clause sentences. Support for this idea was found in the significant slowing of reading of object-extracted RCs as compared to reading of subject-extracted RCs. The finding of significantly slowed reading times when the RCs modified subjects as compared to when they modified objects also supported this idea. Moreover, the finding of the significantly increased difference between subject-extracted RCs and object-extracted RCs when they modified subjects than when they modified objects clearly demonstrated that transitive inference sentences were processed in the same way as other sentences having similar syntactic structures. Although the accuracy of the answers was affected significantly only by the type of extraction but not by the type of modification, these findings were still in line with many other studies which found that subject-extracted RCs are easier to process than object-extracted RCs, and object modifying RCs are easier than their counterparts.

The results also showed that the determinacy of the implicit relations is a very influential factor for the processing of sentences containing transitive inferences. The finding that sentences with undetermined implicit relations were read more slowly and less accurately is consistent with the idea that the undetermined implicit relation requires more processing demands than the determined implicit relation. As the undetermined implicit relation was revealed only after the participants tried to integrate the relations, this extra processing demand should mainly be due to the extra decision making process. Clearly, sentences containing a determined implicit relation should not require this extra demand.

It is important to note that this extra processing demand is qualitatively different from the demands placed by other studies with the same purpose of seeking the relation between working memory and sentence processing (e.g. Just & Capenter, 1992; Waters & Caplan, 2001). While these studies used list memory such as remembering digits or words, which mainly engage the maintenance function of working memory, the extra demand created in this study was the processing (decision making) demand that is known to be one of the main functions of the central executive of the working memory system (Baddeley, 2000).

Contrary to the highly significant effects of the syntactic complexity and the effects of the determinacy of the implicit relation, the effect of the syntactic complexity on sentence processing was not differently affected by the determinacy of the implicit relation. The finding of an interaction between the syntactic complexity and the extra computational demands from undetermined implicit relations would support the idea that syntactic processing shares resources with more general aspects of processing. However, the results showed no indication of interactions between the syntactic complexity variables and the computational complexity variable.

CHAPTER 4

EXPERIMENT 2

As mentioned above, several researchers have used transitive inferences in the framework of relational complexity to investigate the effects of different processing demands (Halford et al, 1998; Viskontas et al, 2005). To test whether the complex sentence processing shares resources with the computational demands of the reason processing, the second experiment applied the relational complexity concept within the relative clause sentences. The computational demands were controlled by manipulating the relational complexity as well as by the determinacy of the implicit relations. In this experiment, one syntactic processing variable (I) and two difficulty of transitive inference variables (A, B) were studied. Consider the following transitive relations:

Semantically related verbs: *Tom who follows Ben precedes Paul*
Semantically unrelated verbs: *Tom who follows Ben is taller than Paul*

From the relational complexity view, *Tom who follows Ben precedes Paul* would be harder than its counterpart because the former contains two verbs explaining the same type of relations but the latter contains two verbs explaining different types of relations. For the sentences with two semantically related verbs, the two explicit relations need to be considered at the same time to decide the relation among all three names. However, for the sentences with two semantically unrelated verbs, only two successive relation processes are required and no single integration of two relations is necessary.

In Experiment 2, in cases of sentences with semantically related verbs, half of the sentences have undetermined implicit relations and the other half of the sentences have determined implicit relations. This undetermined relation could be noticed only after two semantically related verbs were considered. In cases of sentences with semantically unrelated verbs, all sentences had undetermined implicit relations and readers would notice this as soon as they read the sentence. Therefore, in the computational processing demands point of view, we would expect different processes for sentences with two semantically related verbs and sentences with two semantically unrelated verbs.

For two semantically related verbs, we would expect several different types of computational processes: an initial relational construction process, an implicit relation building process, and a post-constructional decision process. First, the readers need to build the relations explicitly mentioned in the sentence (initial relation construction). Then they need to pursue building implicit relations among the three names (implicit relation building). In addition to these processes, the undetermined implicit relation condition requires more processing demands than the determined implicit relation condition to confirm that there is no determined implicit relation (post-constructional decision). However, for the semantically unrelated verbs, readers just need to build the relations mentioned in the sentence (initial relation construction) and neither implicit relation building nor post-constructional decision is required to know a certain relation is undecidable.

As mentioned in chapter 2, the key function of relational complexity processing and syntactic processing involves the formation and active manipulation of information. Therefore, if the initial relation constructional process and syntactic process share the same computational processing mechanism, they would compete with each other for the shared resources. In this case, as the initial relation constructional process should work both for the semantically related verbs and semantically unrelated verbs, there should be an increased difficulty for the object-extracted RCs regardless of the nature of the relation between verbs. If the implicit relational building or the post-constructional decision making process share resources with syntactic processing, but the initial relation construction reasoning process does not share resources with syntactic processing, there should be an increased difficulty only for the two semantically related verbs with object-extracted RCs. In this case, there would be no such pattern for the two semantically unrelated verbs. Finally, if syntactic processing is modular, relational complexity and syntactic complexity should not show an interactive pattern regardless of the determinacy of the implicit relation or the nature of the relation between verbs.

4.1 Method

4.1.1 Participants

Participants were native speakers of English attending classes at the University of North Carolina at Chapel Hill. Forty-six students who did not participate in Experiment 1 served as participants in the experiment. They received credit for an introductory psychology course for their participation. All had normal or corrected to normal vision.

4.1.2 Materials

96 sentences from the first experiment were modified such that two semantically unrelated verbs were added, replacing the object modifying conditions. The conditions of the type of extraction and the type of verb relations were combined so that there were four

experimental conditions (Semantically related subject-extracted RC, Semantically related object-extracted RC, Semantically unrelated subject-extracted RC, Semantically unrelated object-extracted RC). Just as in the first experiment, half of stimuli in the semantically related verbs conditions had a determined implicit relation and half of the stimuli had an undetermined implicit relation. There was no determined implicit relation in the two semantically unrelated verbs conditions.

4.1.2 Design and procedure

Four counterbalanced lists were created such that each experimental sentence appeared in only one condition in a list. Across lists, experimental sentences occurred in all conditions. Each run of the experiment presented 96 experimental sentences. The procedure was exactly the same as the first experiment. Appendix B shows examples of the experimental sentences.

4.2 Results

Data from six participants were excluded because of the close to chance level accuracy. Table3 shows the mean reading times and accuracies for sentences with subject-extracted RCs and object-extracted RCs for each type of the nature of the verb relation.

4.2.1 Effect of the syntactic complexity variable

The reading time showed significant effects of the type of extraction with object-extracted RCs (9,541 ms) taking longer to read than subject-extracted RCs (8,442 ms) [$F_1(1,39)=34.44$ MSe=33712255 $p<.001$, $F_2(1,95)=16.59$ MSe=75080148, $p<.001$]. The accuracy of the answers was not significantly affected by the type of extraction.

4.2.2 Effect of the computational complexity variables

The reading times were longer when the two verbs were semantically related (9,674 ms) than when they were semantically unrelated (8,305 ms) [$F_1(1,39)=25.21$ MSe=71803978 $p<.001$, $F_2(1,95)=69.05$ MSe=24222581, $p<.001$]. The answers were more accurate when the two verbs were semantically unrelated (.85) than when they were semantically related (.76) [$F_1(1,39)=14.06$ MSe=.45 $p<.001$, $F_2(1,95)=25.35$ MSe=.24, $p<.001$]. Also, there was a significant interaction between the type of extraction and the nature of the relation between verbs on the reading time such that the difference between the object-extracted RCs and the subject-extracted RCs was larger when the two verbs were semantically related than when they were semantically unrelated [$F_1(1,39)=6.14$ MSe=22724100 $p<.05$, $F_2(1,95)=4.40$ MSe=25956163, $p<.05$].

Table 4 shows the mean reading times and accuracies by the type of determinacy of the implicit relation across conditions. Overall, there was no significant effect of the determinacy of the implicit relation on reading time. However, when the data were grouped by the nature of the relation between verbs and analyzed separately, for the two semantically related verbs conditions the reading times were longer when the implicit relation was undetermined (10,446 ms) as compared to when it was determined (9,010 ms) [$F_1(1,39)=29.43$ MSe=33647137 $p<.001$] and the answers were more accurate when the implicit relation was determined (.84) as compared to when it was undetermined (.74) [$F_1(1,39)=11.00$ MSe=.54 $p<.01$].

Interestingly, there were significant interactions between the type of extraction and the determinacy of the implicit relation on both the reading time and accuracy such that the differences between the object-extracted RCs were larger when the implicit relation was undetermined as compared to when it was determined [Reading time: $F_1(1,39)=20.05$ $MSe=24752636$, $p<.001$, Accuracy: $F_1(1,39)=18.12$ $MSe=.12$, $p<.001$]. For the two semantically unrelated verbs conditions, there was no significant effect of the determinacy of the implicit relation. The determinacy of the implicit relation and the type of extraction did not show any significant interaction.

4.3 Discussion

The results of the second experiment again showed that object-extracted RCs were more difficult to process than subject-extracted RCs. However, unlike the first experiment, the determinacy of the implicit relations did not show significant effects. The reason for the lack of effect of the determinacy of the implicit relation should be the fact that there are no determined implicit relations for the two semantically unrelated verbs condition. Later analyses showed that there were significant effects of the determinacy of the implicit relation when the two semantically related verbs condition was considered separately.

Importantly, for the semantically related verbs conditions, there were significant interactions between the syntactic complexity demands and the extra computational demands from reasoning such that the processing of the complex sentence was differently affected by the determinacy of the implicit relations. The reading times were elevated and the accuracy dropped in the object-extracted RCs when the implicit relation was undetermined as compared to when it was determined. Contrary to the results of the first experiment, this finding suggested that syntactic processing shares resources with general aspects of processing.

However, to properly understand the results, they need to be viewed prudently since there could be some other reasons to explain the difference in results between the two experiments. One possible reason for this discrepancy is the fact that readers might develop different tactics for each experiment and thus process sentences differently in the two experiments. While the first experiment tested RCs modifying the object of a sentence as well as RCs modifying the subject of a sentence, the second experiment only tested RCs modifying the subject of a sentence. Although the second experiment contained different forms of verbs (follow/precede and is taller than/shorter than), as the sentences are only either object-extracted RCs or subject-extracted RCs with both modifying the subject of a sentence, it might be easier to notice the experimental sentence structures and build tactics in the second experiment.

To test this idea, I divided the experiment into two parts (materials presented in the first half and materials presented in the second half) and analyzed them separately. If the results of this experiment were mainly due to the tactics developed as a result of the frequent exposure to certain types of sentence structures, the responses to materials in the first half and the responses to materials in the second half should show different patterns of results. Also, the results of the first half should be more similar to the results of the first experiment. If the first half and the second half show similar response patterns, it would suggest that the results were not simply due to tactics developed by the readers.

4.3.1 First half

Tables 5 and 6 show the mean reading times and accuracies for sentences presented in the first half of the experiment. When the data were grouped by the nature of the relation between verbs and analyzed separately, for the two semantically related verbs conditions, the reading time showed significant effects of the type of extraction with object-extracted RCs (11,149 ms) taking longer to read than subject-extracted RCs (9,699 ms) [$F_1(1,39)=9.25$ $MSe=50610176$ $p<.01$]. The answers were more accurate for subject-extracted RCs (.78) than for object-extracted RCs (.72) [$F_1(1,39)=5.61$ $MSe=.22$ $p<.05$]. Unlike the first experiment, the determinacy of the implicit relation showed no effects [RT; $F_1(1,39)=2.02$ $MSe=46643223$ $p=.163$, Accuracy; $F_1(1,39)=2.02$ $MSe=.48$ $p=.163$]. However, importantly, the type of extraction did not interact with the determinacy of the implicit relation for reading time [$F_1(1,39)=.33$ $MSe=36334041$ $p=.57$] and accuracy [$F(1,39)=.77$ $MSe=.38$ $p=.38$].

For the two semantically unrelated verbs conditions, only the reading time showed significant effects of the type of extraction with object-extracted RCs (9,623 ms) taking longer to read than subject-extracted RCs (8,231 ms) [$F_1(1,39)=24.73$ $MSe=20171344$ $p<.001$].

4.3.2 Second half

Tables 7 and 8 show the mean reading times and accuracies for sentences presented in the second half of the experiment. When the data were grouped by the nature of the relation between verbs and analyzed separately, for the two semantically related verbs conditions, the reading time showed significant effects of the type of extraction with object-extracted RCs (9,718 ms) taking longer to read than subject-extracted RCs (8,202 ms) [$F_1(1,39)=30.82$ $MSe=17940974$ $p<.001$]. The type of extraction did not show significant effects on accuracy. Although the determinacy of the implicit relation showed no effects on reading time, it showed significant effects on accuracy. The answers on the questions were more accurate when the implicit relation was undetermined (.74) as compared to when it was determined (.84) [$F_1(1,39)=5.03$ MSe=.42 $p<.05$].

Also, critically, there was a strong interaction between the type of extraction and the determinacy of the implicit relation on the reading time such that the object-extracted RCs took much longer to read than subject-extracted RCs when the implicit relation was undetermined [$F_1(1,39)=16.84$ MSe=42582632 $p<.001$]. When the implicit relation was determined, the reading time of subject-extracted RCs and the reading time of object-extracted RCs were very close, while they showed a large difference when the implicit relation was undetermined.

For the two semantically unrelated verbs conditions, only the accuracy showed significant effects of the determinacy of the implicit relation with determined implicit relation conditions (.90) being answered more accurately than undetermined implicit relation conditions (.85) [$F_1(1,39)=5.21$ MSe=.11 $p<.05$]. Again, reading times of object-extracted RCs and subject-extracted RCs were very close.

4.3.3 Conclusion

The first half of this experiment showed similar patterns of results as the first experiment but showed conflicting patterns of results with the second half in various ways. The most prominent difference between the results of the first half and the second half was the pattern of interaction between the syntactic complexity variable and the computational complexity variable. While there was no interaction between the syntactic complexity and the determinacy of the implicit relation in the first half of this experiment, the processing of the relative clauses was differently affected by the determinacy of the implicit relation in the second half of this experiment. The main sources of interaction found in the second half of this experiment was the fact that there was no reading time difference between subject-extracted RCs and object-extracted RCs for the determined implicit relations while the reading times of object-extracted RCs were much longer than those of subject-extracted RC for the undetermined implicit relations.

Another difference between the results of the first half and the second half was the effect of type of extracted RCs. In the second half of this experiment, but not in the first half, the reading times of the different types of extracted RCs were almost the same when the two verbs were semantically unrelated. When the effect of the type of extracted RCs is considered together, it is reasonable to assume that the interaction found in the second half was mainly due to the tactical processes developed by participants. The effects of the type of extracted RCs have been especially robust across the studies and the effects were highly significant in the first half of this experiment as well as the first experiment. In fact, it is almost impossible to create a situation in which the object-extracted RCs would be processed as effectively as the subject-extracted RCs in normal sentence comprehension (Caplan & Waters, 2002). However, the RC type effect disappeared in the second half of this experiment.

One possibility for the RC type effect being completely wiped out is that syntactic processes and computational demand of reasoning processes share the same resources. In fact, the main purpose of the experiment was to investigate whether or not they share the same resources. If they do share the same resources, the computational demand should influence the processing of the relative clauses. Also, the influence would be shown such that 1) the difference between object-extracted RCs and subject-extracted RCs would be larger in the more computationally demanding undetermined relation condition than in the computationally less demanding determined relation condition or 2) there would be no reading time difference between object-extracted RCs and subject-extracted RCs when the computational demands were too high in the more computationally demanding undetermined relation condition (ceiling effect). However, the results showed neither of these patterns but instead showed exactly the opposite of what was expected.

The other difference was also the opposite of the expectation and the findings from elsewhere in this research. Only in the second half of this experiment were reading times faster for the undetermined implicit relations than for the determined implicit relations when the sentences contain subject-extracted RCs.

The differences between the first half and the second half suggested that the object-extracted RCs for the determined relations and the subject-extracted RCs for the undetermined relations had the biggest effect of repeated exposure of the sentence structures since they showed greater facilitation on reading time. The main explanation of why there was such a difference in benefiting from tactics that short-cut comprehension can be found when the verbs in the experimental sentences were considered. Of the two semantically related conditions, sentences with object-extracted RCs containing the determined implicit relations (e.g. *Ben who John precedes precedes Tom/ Ben who John follows follows Tom*) and sentences with subject-extracted RCs containing the undetermined implicit relations (e.g. *Ben who precedes John precedes Tom/ Ben who follows John follows Tom*) had two of the same verb. Other two semantically related verbs conditions had two different verbs (*precede-follow* or *follow-precede*), and all of the two semantically unrelated verbs conditions also had two different verbs (*precede-is taller (smaller) than* or *follow-is taller (smaller) than*). Therefore, it would be easier to notice the pattern of experimental sentences when the verbs were the same, and therefore participants might develop ways to process these types of sentences more quickly.

In sum, although the results of this experiment showed an interaction between the syntactic complexity demands and the computational demands of reasoning, further analyses suggested that the interaction was due to participants developing tactics of reasoning over the course of the experiment.

CHAPTER 5

EXPERIMENT 3

The first experiment showed strong effects of the type of extracted RCs and the type of modification for the relative clause sentences containing transitive inferences. The first experiment also showed that sentences with undetermined implicit relations require more processing time than those with determined implicit relations. However, the first experiment clearly showed that syntactic complexity demands are not affected by the conscious computational demands from reasoning. Unlike the first experiment, the results of the second experiment showed that the effect of syntactic complexity on ease of sentence processing was affected by the computational demands of the reasoning task. However, further analyses of the second experiment showed that this interaction occurred only after the participants were accustomed to the experimental materials, suggesting that participants developed tactics for the reasoning task over the course of the experiment that influenced how they approached comprehension of the sentence.

In the third experiment, using the same material as Experiment 2, eye movements were recorded as the subjects read the sentences to gather information about on-line processing patterns. Given the results of the first two experiments, this eye-tracking experiment became important because it allowed us to measure subjects' eye movements as they read, which provides a source of information about processing tactics that might be responsible for the interaction observed in Experiment 2. This experiment also aimed to test whether the tactical processes found in the second experiment were robust and could be replicated.

5.1 Method

5.1.1 Participants

Thirty-six students who did not participate in Experiment 1 or 2 participated in the experiment. All were native speakers of English attending classes at the University of North Carolina at Chapel Hill and had normal or corrected to normal vision. They received course credit for an introductory psychology class for their participation.

5.1.2 Materials and design

The materials and experimental design were identical to those used in Experiment 2.

5.1.3 Procedure

Participants performed the sentence reading task while wearing an EyeLink system eye-tracking device that was manufactured by Sensorimotoric Instruments (Boston, MA). The eye tracker sampled pupil location for every 4 milliseconds. The samples were automatically parsed into fixations and saccades by the tracker. Before the experimental run, the eye tracker was calibrated following a routine calibration procedure. The calibration was validated on a fixation point before each trial. Eye movements were recorded throughout the experiment. The experimenter used another computer to monitor eye movement. If the calibration of the eye tracker got worse, the experimenter would calibrate the device again between trials. Participants' eye movements also were visually checked during and after the experiment. All the other procedures were the same as in Experiments 1 and 2.

5.1.4 Eye tracking measures

Among fixations of less than 80ms, if there was an adjacent fixation that fell within the same word, the fixations were incorporated into larger fixations. Otherwise, they were deleted (e.g. Pickering, Traxler, & Crocker, 2000; Rayner, 1975, 1978). Using this criterion, 0.9% of total fixations were omitted and 0.5% of them were combined with longer fixations. Fixations longer than 800 ms were trimmed to 800 ms. Only 0.2% of total fixations were longer than 800 ms.

In this experiment, multiple measures of sentence processing were reported. First, overall sentence reading times and accuracy rates on the comprehension questions were reported. Also, gaze duration, regression path and rereading times were reported as online measures of sentence processing. These measures were chosen on the basis of other studies concerning eye-tracking measures during sentence reading (Inhoff & Radach, 1998; Liversedge, Paterson, & Pickering, 1998; Rayner, 1998; among others). Below, these eye-tracking measures are described.

Gaze duration: Gaze duration is the cumulative time spent on a word before the eyes move out of the region to either the left or right. This measure is the most popularly used measure of all, and it may be the most appropriate measure for quantifying initial stages of sentence processing (Rayner, 1998).

Regression path duration: Gaze duration is a spatially contiguous measure used to sum the durations of fixations neighboring each other in a specified region in the text.

However, researchers might obtain a clearer picture of the time course of complexity resolution by summing temporally contiguous fixations from the region causing the complexity (Liversedge, Paterson, & Pickering, 1998). Regression path duration is the temporally contiguous measure used to sum the duration of fixations occurring in a sequence over a specified period of time. This measure counts all the time spent on the target and pre-target words from the first fixation on a target word until the reader goes past the target word. Regression path duration seems to be the most sensitive index of the moment-to-moment processing load, especially when there is a specific part inducing a difficulty (Murray, 1998).

Rereading time: Rereading time is computed by subtracting the gaze duration on the region from the total time spent fixating the region. Therefore, rereading time is regarded as a late effect measure, and it is known to be sensitive to overall processing difficulty. If an effect is observed for rereading time but not for earlier measures such as gaze duration, this is generally taken as an indication that the manipulation has a relatively late effect (Juhasz & Rayner, 2003).

5.2 Results

Data from one participant were excluded because of the chance level accuracy. Table 9 shows the overall reading times and accuracies for sentences with subject-extracted RCs and object-extracted RCs for each type of the nature of the verb relation.

5.2.1 Overall responses

5.2.1.1 Effect of the syntactic complexity variable

Reading time showed significant effects of the type of extraction with object-extracted RCs (9,962 ms) taking longer to read than subject-extracted RCs (9,072 ms) [$F_1(1,35)=34.28$ MSe=19230499 $p<.001$, $F_2(1,95)=5.97$ MSe=106686017, $p<.05$]. The accuracy of the answers did not show an effect of the type of extraction.

5.2.1.2 Effect of the computational complexity variables

Reading times were longer when the verbs were semantically related (10,389 ms) than when they were semantically unrelated (8,645 ms) [$F_1(1,35)=44.06$ MSe=57515229 $p<.001$, $F_2(1,95)=128.32$ MSe=319609415, $p<.001$]. The answers on the questions were more accurate when the two verbs were semantically unrelated (.83) as compared to when they were semantically related (.77) [$F_1(1,35)=5.86$ MSe=.38 $p<.05$, $F_2(1,95)=8.68$ MSe=.26, $p<.01$]. There was a marginal interaction between the type of extraction and the nature of the relation between verbs on the reading time only by subject analysis [$F_1(1,39)=3.58$ MSe=6527053 $p=.067$]. The difference between object-extracted RCs and subject-extracted RCs was larger when the two verbs were semantically related than when they were semantically unrelated.

Table 10 shows the overall reading times and accuracies by the type of determinacy of the implicit relation across conditions. Overall, there were significant effects of the determinacy of the implicit relation on the reading times and the accuracy of the answers. The reading times were longer when the implicit relation was undetermined (9,686 ms) than when it was determined (9,326 ms) [$F_1(1,35)=5.66$ MSe=19265178 $p<.05$] and the answers were more accurate when the implicit relation was determined (.83) than when it was undetermined (.76) [$F_1(1,35)=10.33$ MSe=.39 $p<.01$]. Unlike Experiment 2, there was no interaction between the type of extraction and the determinacy of the implicit relation [$F(1,39)=.37$ $MSe=19182349$ $p=.55$].

When the data were grouped by the nature of the relation between verbs and analyzed separately, for the two semantically related verbs conditions, there also were significant effects of the determinacy of the implicit relation such that the reading times were longer and the answers were less accurate when the implicit relation was undetermined (RT; 10,731 ms, accuracy; .72) as compared to when it was determined (RT; 10,044 ms, accuracy; .83) [RT; $F_1(1,35)=8.72$ $MSe=22511560$ $p<.01$, accuracy; $F_1(1,35)=7.61$ $MSe=.59$ $p<.01$]. However, there was no significant interaction between the type of extraction and the determinacy of the implicit relation in both RT and accuracy [RT: $F_1(1,39)=.78$ $MSe=23279196$, $p=.38$, Accuracy: $F_1(1,35)=.08$ $MSe=.26$, $p=.78$]. For the two semantically unrelated verbs conditions, neither the effect of the determinacy of the implicit relation nor the interaction between the type of extraction and the determinacy of the implicit relation was significant.

5.2.2 Word by word analysis

Table 11 shows measures of reading time for five regions in the sentence: the matrix subject, the relative pronoun *'who'*, the relative clause (embedded noun + verb/ verb + embedded noun), the matrix verb, and the matrix object. Table 12 shows measures of reading time by the type of determinacy of the implicit relation across conditions.

For all five regions, gaze durations were reported as the measure of first-pass reading and initial processing. As the measure of the complexity processing, regression path durations from the relative clauses, matrix verb and matrix object were reported. Regression path durations of the matrix subject region and the *'who'* region were not reported since these are almost identical to the gaze duration by definition. For all regions except the last region (object), rereading times were reported as the measure of late processing. Rereading times of the object region were not reported because there were only a few rereading fixations in this region since it was the last word of the sentence.

5.2.2.1 Gaze duration

For all regions except the first region (subject), gaze duration showed significant (or marginal) effects of the type of extraction. Gaze durations were longer when the sentence contained object-extracted RCs than when it contained subject-extracted RCs: in 'who' [$F_1(1,34)=4.23$ MSe=38345 $p<.05$, $F_2(1,95)=23.38$ MSe=15798, $p<.001$], in the relative clause [$F_1(1,34)=5.44$ MSe=113123 $p<.05$, $F_2(1,95)=10.64$ MSe=63141, $p<.01$], in the matrix verb [$F_1(1,34)=3.18$ MSe=58883 $p<.05$, $F_2(1,95)=4.62$ MSe=60896, $p<.05$], and in the object [$F_1(1,34)=4.22$ MSe=18033 $p<.05$, $F_2(1,95)=3.74$ MSe=30333, $p=.056$]. Gaze durations in the matrix verb region showed significant effects of the nature of the relation between verbs, with the two semantically unrelated verbs condition taking longer to read than the two semantically related verbs condition [$F_1(1,34)=37.96$ MSe=173534 $p<.001$, $F_2(1,95)=79.64$ MSe=76962, $p<.001$].

5.2.2.2 Regression path

For the relative clause region, regression path duration was longer when the sentence contained object-extracted RCs than when it contained subject-extracted RCs [$F_1(1,34)=10.96$ MSe=2787134 $p<.01$, $F_2(1,95)=12.66$ MSe=2437031, $p<.001$]. Regression path duration in the matrix verb region showed significant (or marginal) effects of the type

RCs such that times were longer for sentences with object-extracted RCs [$F_1(1,34)=11.53$ MSe=5981040 $p<.01$, $F_2(1,95)=3.40$ MSe=20281297, p=.068]. Regression path duration was longer in the object region when the two verbs were semantically related as compared to when they were semantically unrelated [$F_1(1,34)=27.96$ MSe=34652397 $p<.001$, $F_2(1,95)=47.03$ MSe=20615054, $p<.001$].

5.2.2.3 Rereading

For all four regions, rereading times showed significant effects of the type of extraction and effects of the nature of the relation between verbs. Rereading times were longer when the sentence contained object-extracted RCs than when it contained subject-extracted RCs: in the subject [$F_1(1,34)=37.26$ MSe=1047794 $p<.001$, $F_2(1,95)=15.49$ MSe=2517416, $p<.001$], in 'who' [$F_1(1,34)=41.52$ MSe=1063540 $p<.001$, $F_2(1,95)=15.34$ MSe=2870790, $p<.001$], in the relative clause [$F_1(1,34)=6.62$ MSe=2833234 $p<.05$, $F_2(1,95)=1.16$ $p>.05$], and in the matrix verb [$F_1(1,34)=36.14$ MSe=809005 $p<.05$, $F_2(1,95)=7.16$ MSe=4017988, $p<.01$]. Rereading times were longer for the two semantically related verbs condition than for the two semantically unrelated verbs condition: in the subject [$F_1(1,34)=3.26$ MSe=934478 p=.08, $F_2(1,95)=5.83$ MSe=509423, $p<.05$], in 'who' [$F_1(1,34)=9.10$ MSe=1172350 $p<.01$, $F_2(1,95)=13.93$ MSe=772789, $p<.001$], in the relative clause [$F_1(1,34)=42.15$ MSe=8010906 $p<.001$, $F_2(1,95)=51.81$ MSe=6484357 $p<.001$], and in the matrix verb [$F_1(1,34)=34.50$ MSe=1694071 $p<.001$, $F_2(1,95)=35.45$ MSe=1676608, $p<.001$].

5.2.3 Grouped analyses: two semantically related verbs

5.2.3.1 Gaze duration

Gaze duration in the matrix verb showed a significant effect of the type of extraction, with object-extracted RCs taking longer to read than subject-extracted RCs [$F(1,34)=8.17$ $MSe=70308$ $p<.01$].

5.2.3.2 Regression path

For the relative clause region, regression path duration was longer when the sentence contained object-extracted RCs than when it contained subject-extracted RCs [$F(1,34)=5.43$ $MSe=1386344$ $p<.05$]. Regression path duration in the matrix verb region showed a significant effect of the type RCs such that times were longer for sentences with object-extracted RCs [$F(1,34)=13.76$ $MSe=7070242$ $p<.001$]. Regression path duration in the matrix object (post-matrix verb region) showed significant effects of determinacy of the implicit relation, with the undetermined implicit relation condition taking longer to read than the determined implicit relation condition [$F(1,34)=15.04$ $MSe=16193343$ $p<.001$].

5.2.3.3 Rereading

For all four regions, rereading showed significant effects of the type of extraction and effects of determinacy of the implicit relation. Rereading times were longer when the sentence contained object-extracted RCs as compared to when it contained subject-extracted RCs: in the subject [$F(1,34)=28.70$ $MSe=733715$ $p<.001$], in 'who' [$F(1,34)=35.75$ $MSe=709503$ $p<.001$], in the relative clause [$F(1,34)=15.36$ $MSe=1604320$ $p<.001$], and in the matrix verb [$F(1,34)=12.09$ $MSe=806593$ $p<.001$]. Rereading times were longer for the undetermined implicit relation condition than for the determined implicit relation condition: in ‘who’ [$F_1(1,34)=7.24$ MSe=481045 $p<.05$], in the relative clause [$F(1,34)=18.84$ MSe=2986712 $p<.001$], and in the matrix verb [$F(1,34)=34.97$ MSe=1073886 $p<.001$].

5.2.4 Grouped analyses: two semantically unrelated verbs

5.2.4.1 Gaze duration

Gaze duration in the matrix verb showed a significant effect of the type of RC, with the object-extracted RC condition taking longer to read than the subject-extracted RC condition [$F(1,34)=5.68$ MSe=49436 $p<.05$].

5.2.4.2 Regression path

For the relative clause region, regression path duration was longer when the sentence contained object-extracted RCs than when it contained subject-extracted RCs [$F(1,34)=11.75$ MSe=2196933 $p<.01$]. Regression path duration in the object region also showed a significant effect of the type of RC such that times were longer for sentences with object-extracted RCs [$F(1,34)=5.15$ MSe=5508780 $p<.05$].

5.2.4.3 Rereading

Rereading times were longer when the sentence contained object-extracted RCs than when it contained subject-extracted RCs: in the subject [$F(1,34)=28.32$ MSe=637629 $p<.001$], in ‘who’ [$F(1,34)=27.99$ MSe=686305 $p<.001$], and in the matrix verb [$F(1,34)=38.13$ MSe=536433 $p<.001$]. Surprisingly, rereading time in the subject region showed a significant effect of determinacy of the implicit relation, with the undetermined implicit relation condition taking longer to read than the determined implicit relation condition [$F(1,34)=7.17$ $MSe=252471$ $p<.05$].

5.3 Discussion

5.3.1 Overall sentence reading

The results of the overall sentence reading times again showed a clear effect of the type of extracted RC such that object-extracted RCs were more difficult to process than subject-extracted RCs. Several important differences were found between the results of this experiment and the results of the second experiment.

Firstly, while the determinacy of the implicit relations did not show any significant effects in the second experiment, there were significant effects of the determinacy of the implicit relation on the reading times and the accuracy in this experiment. When the implicit relation was undetermined, reading times were shorter and the answers were more accurate as compared to when the implicit relation was determined. However, this difference was not surprising since the determinacy of the implicit relation was not cross-balanced. As there were no determined implicit relations for the two semantically unrelated verbs conditions, only the two semantically related verbs conditions had the true determined and undetermined implicit relation comparison sets. Therefore, it is less meaningful to test the effect of the determinacy of the implicit relation while considering the two semantically related verbs conditions and the two semantically unrelated verbs conditions together. In both Experiments 2 and 3, the effects of the determinacy of the implicit relation were significant when the two semantically related verbs conditions were considered separately. The effect of the determinacy of the implicit relation was not significant when only the two semantically unrelated verbs conditions were considered.

The second and third differences in the results between Experiments 2 and 3 should be considered together. Unlike the second experiment, this experiment showed no interaction between the type of extraction and the determinacy of the implicit relation when we consider both the two semantically related verbs conditions and the two semantically unrelated verbs conditions together. Most importantly, when only the semantically related verbs conditions were considered, there was no sign of interaction between the type of extraction and the determinacy of the implicit relation in both reading time and accuracy, which contradicts the results of the second experiment and corresponds to the results of the first experiment. In the second experiment, the separate analyses of the first half and second half suggested that the interaction was mainly due to the tactics developed by participants as a result of frequent exposure to the sentence structures. In this experiment, the separate analyses of the first half and second half showed that there was a very weak sign of interaction between the type of extraction and the determinacy of the implicit relation in the second half [$F(1,34)=1.59$ $MSe=22614257$ $p=.216$] while no sign of interaction was observed in the first half [$F(1,34)=.22$ $MSe=24799099$ $p=.639$].

In the second half of Experiment 2, while the reading times of object-extracted RCs were much longer than those of subject-extracted RCs when the implicit relation was undetermined, there was no reading time difference between subject-extracted RCs and object-extracted RCs for the determined implicit relations. However, in this experiment, object-extracted RCs took longer to read than subject-extracted RCs in both the determined and undetermined implicit relation conditions.

The final difference in the pattern of results between the second experiment and the third experiment was the overall reading time difference between the first half and the second half. In this experiment, when the experiment was divided into two parts and analyzed separately, overall reading time of the first half (9,726ms) did not differ from the reading time of the second half (9, 619ms), while the second experiment showed a big difference between the first half (9,676ms) and the second half (8,364ms). This result again suggested the possibility that the participants in the second experiment might have used different tactics after they became accustomed to the experiment.

However, when 12 participants of the third experiment, who showed more than 1,000ms facilitation on the reading time for the second half compared with the first half (mean: 2,121 ms), were analyzed separately, it was shown that the reading times of the second half for these participants were similar to those of the second experiment. While the reading time of object-extracted RCs (9,124ms) and subject-extracted RCs (9,138ms) were very close when the implicit relation was determined, there was a larger difference between type of extraction and the determinacy of the implicit relation on the reading time when the implicit relation was undetermined, such that the object-extracted RCs (10,745ms) took longer to read than subject-extracted RCs (9,849ms)[6]. Overall reading times of object-extracted RCs (9, 798ms) and subject-extracted RCs (9,497ms) were relatively similar. These results showed that evidence of the tactical processing could be seen in the third experiment even though it was greatly reduced.

In sum, overall sentence reading times showed that the tactical effects were not robust since the effect of syntactic complexity on ease of sentence processing was not differently affected by the computational demands of the reasoning task in this experiment.

[6] The interaction was not statistically significant.

5.3.2 Word by word reading

5.3.2.1 Initial processing

On measures of initial processing, reading times were faster when the sentences contained subject-extracted RCs than when the sentences contained object-extracted RCs. This occurred as early as the relative pronoun *'who'*, before the actual relative clauses were seen. The reason why there was such an effect in this region should be the preview effect. One well-known fact about eye movements in reading is that words can be identified without direct fixation and the preview of the upcoming words helps in initiating lexical access and word identification (Rayner, 1998). Since the relative pronoun *'who'* is a highly frequent word and it does not contain semantic information, it is reasonable to expect that some processing of upcoming words would occur when the eyes are fixated in the relative pronoun. Particularly, because subject-extracted RCs and object-extracted RCs are structurally different from each other after the relative pronoun, this structure identification would occur when the eyes are fixated in that region. Significant effects of the type of extraction were observed in the RC region and in the later regions. These results clearly showed that the experimental sentences allowed us to detect differences at an early stage of sentence comprehension.

In the matrix verb region, the two semantically unrelated verbs conditions were read more slowly than the two semantically related verbs conditions. This result simply reflects the fact that the verbs (precede/follow) in the two semantically related verbs conditions were shorter than the verbs in the two semantically unrelated verbs conditions (is taller than/is shorter than).

The grouped analyses by the nature of the relation between verbs did not show any different pattern across groups except a minor point; the effect of the type of extracted RC occurred at the RC region for the two semantically related verbs conditions but the effect of the type of extracted RC was spilled over to the matrix verb region for the two semantically unrelated verbs conditions.

5.3.2.2 Complexity processing

The results showed that object-extracted RCs were read more slowly than subject-extracted RCs, which was observed in the regression path duration in the RC region and the matrix verb region. These results were in line with a previous study that tested subject-extracted RCs and object-extracted RCs with eye tracking (Gordon, Hendrick, Johnson & Lee, 2006).

The results also showed that regression path duration from the object region were much longer for the two semantically related verbs conditions than for the two semantically unrelated verbs conditions even though sentences with the two semantically related verbs were shorter than sentences with the two semantically unrelated verbs. This result was the opposite of the results found in gaze duration. In gaze duration, reading times were longer for the two semantically unrelated verbs conditions. While the gaze duration would be greatly influenced by the length of the region, the regression path duration from this region would reflect the overall processing difficulty of the sentence since readers had already seen the whole sentence at this stage[7].

The group analyses by the nature of the relation between verbs showed a very

[7] By definition, the regression path duration from the object region (last word) cannot be terminated unless the readers press the space bar. The regression path duration from the last word counts all fixations after the reader initially saw the last word.

interesting pattern of results. While the regression path duration in the relative clause region showed the effect of the type of extraction in both semantically related verbs and semantically unrelated verbs, these two conditions showed different results in the object region. While the RC type effect was still observable in the object region for semantically unrelated verbs, there were no significant effects for semantically related verbs. Instead, the effect of the determinacy of the implicit relation started to appear such that undetermined implicit relations took much longer to read tha determined implicit relations. This result suggested that when the syntactic complexity processing and reasoning processing needed to be done to perform a task, they were processed separately. It also suggested that the computational demands of reasoning started to affect sentence comprehension only after the effects of syntactic complexity were seen.

5.3.2.3 Late processing

After readers have acquired enough information from the sentence, readers should try to finish the task by understanding the sentence and deciding the relations of the nouns. At this stage, the type of extracted RC, the nature of the relation between verbs, and the determinacy of the implicit relation all affect the eye movements.

As expected, across all regions object-extracted RCs were read more slowly than subject-extracted RCs and the two semantically related verbs conditions were read more slowly than the two semantically unrelated verbs conditions. For the two semantically related verbs conditions, the undetermined implicit relation condition received more rereading than the determined implicit relation condition.

Surprisingly, for the two semantically unrelated verbs conditions, the undetermined implicit relation condition received more rereading than the determined implicit relation condition in the subject region. This result was hard to explain because there was no determined implicit relation in the semantically unrelated verbs conditions and thus the undetermined and determined relations were basically the same across conditions.

Except for this abnormality, word by word analyses of eye-tracking consistently showed that the syntactic complexity and reasoning complexity affected the comprehension of the transitive inference sentences in a temporally different manner; the syntactic complexity affected relatively earlier measures of eye-tracking before the computational demand started to have an affect, and the computational demands of the reasoning started to affect comprehension later.

CHAPTER 6

EXPERIMENT 4

The purpose of the fourth experiment was to determine experimentally whether the interactions between language comprehension and difficulty of reasoning observed in Experiment 2 were due to readers' tactics. In Experiment 4, the ease of developing effective tactics was reduced by using a broader range of sentence structures than were used in Experiments 2 and 3.

6.1 Method

6.1.1 Participants

Thirty-eight students who did not participate in the previous experiments participated in this experiment. All were native speakers of English attending classes at the University of North Carolina at Chapel Hill and had normal or corrected to normal vision. They received course credit for an introductory psychology class for their participation.

6.1.2 Materials and design

The materials used in Experiment 2 were modified for this experiment. One third of all experimental sentences from Experiment 2 were changed so that object modifying relative clauses were used instead of subject modifying relative clauses. All the other conditions were exactly the same as Experiments 2 and 3.

6.1.3 Procedure

The procedures were the same as those in Experiment 2. Appendix C shows examples of the experimental sentences.

6.2 Results

Data from two participants were excluded due to the poor comprehension rate. As the object modifying relative clauses served as fillers, only data from the subject modifying relative clauses were analyzed. Table 13 shows the mean reading times and accuracies for sentences with subject-extracted RCs and object-extracted RCs for each type of the nature of the verb relation.

6.2.1 Effect of the syntactic complexity variable

The reading time showed significant effects of the type of extraction with object-extracted RCs (11,031 ms) taking longer to read than subject-extracted RCs (10,146 ms) [$F_1(1,35)=8.35$ MSe=55766140 $p<.01$, $F_2(1,65)=6.69$ MSe=69571059, $p<.05$]. The accuracy of the answers also showed the same pattern of significant effects of the type of extraction (object-extracted RC: .78 vs. subject-extracted RC: .83) [$F_1(1,39)=7.23$ MSe=.20 $p<.05$, $F_2(1,65)=7.25$ MSe=.20, $p<.01$].

6.2.2 Effect of the computational complexity variables

The reading times were longer when the two verbs were semantically related (1,1131 ms) than when they were semantically unrelated (10,030 ms) [$F_1(1,35)=4.58$ MSe=153104749 $p<.05$, $F_2(1,65)=11.51$ MSe=60862366, $p<.001$]. The answers to the questions were more accurate when the verbs were semantically unrelated (.84) than when they were semantically related (.77) [$F_1(1,35)=6.23$ MSe=.32 $p<.05$, $F_2(1,65)=8.72$ MSe=.23, $p<.01$]. There was no interaction between the type of extraction and the nature of the relation between verbs.

Table 14 shows the mean reading times and accuracies by the type of determinacy of the implicit relation across conditions. Overall, the answers were more accurate when the implicit relation was determined (.85) than when it was undetermined (.75) [$F_1(1,35)=16.39$ MSe=.31 $p<.001$]. There was no interaction between the type of extraction and the determinacy of the implicit relation.

When the data were grouped by the nature of the relation between verbs and analyzed separately, for the two semantically related verbs conditions, the reading times were longer when the implicit relation was undetermined (11,686 ms) than when it was determined (10,561 ms) [$F_1(1,35)=7.19$ MSe=51818882 $p<.05$] and the answers were more accurate when the implicit relation was determined (.86) than when it was undetermined (.70) [$F_1(1,35)=21.29$ MSe=.35 $p<.001$]. Importantly, the type of extraction did not interact with the determinacy of the implicit relation [$F_1(1,35)=.25$ MSe=77561860 $p=.62$].

For the two semantically unrelated verbs conditions, there was no significant effect of the determinacy of the implicit relation. The type of extraction and the determinacy of the implicit relation did not interact with each other.

6.3 Discussion

The results of this experiment closely resembled those of the overall sentence reading time in Experiment 3. Importantly, the interaction between the type of extraction and the determinacy of the implicit relation was not observed when only the two semantically related verbs conditions were considered as well as when both the semantically related verbs conditions and the semantically unrelated verbs conditions were considered together.

The only difference in the results of these two experiments was that there was no significant effect of the determinacy of the implicit relation on the reading time in this experiment. However, as mentioned in Experiment 3, it was mainly due to the fact that the determinacy of the implicit relation was not cross-balanced (only the two semantically related verbs conditions had the true determined implicit relation). Just as in Experiments 2 and 3, the effect of the determinacy of the implicit relation was significant when only the two semantically related verbs conditions were considered.

In sum, the results of this experiment showed similar patterns to the first and third experiments such that reasoning occurred after basic processes of sentence interpretation and that those processes were not influenced by the cognitive demands of reasoning.

CHAPTER 7

GENERAL DISCUSSION

The four experiments reported here examined whether the resources being used in syntactic processes are separable from resources being used in other processes. To do so, the difficulties of reasoning as well as the syntactic complexities of a sentence were varied. The main hypothesis was that if computational demands and sentence complexity demands share the same working memory resources, they would show an interactive pattern. If they do not share the same resources, they would show an additive pattern. This study also examined the time courses of the syntactic processes and the reasoning processes using the eye-tracking method.

Across the experiments, this study provided no support for the idea that external reasoning processing demands and syntactic processing demands share general resources with each other. While the reading times were significantly affected by the complexity of the sentences and the complexity of the reasoning task, the processing demands from the reasoning did not differently affect the syntactic complexity variables.

The current results suggest that reasoning and language processing do not share the same working memory resources. The implications of these findings are discussed below.

7.1 Computational demands and transitive inference reasoning

This study was the first to attempt embedding computational demands from a reasoning task into syntactically complex sentences in order to test the hypotheses concerning the specificity of working memory structures for language processing. In this research, syntactically complex sentences containing transitive inferences were tested under different computational demands of reasoning. The computational processing demands were manipulated by varying the determinacy of the implicit relations and the nature of the relation between verbs.

7.1.1 Transitive inference processing

Relations that must be integrated to make inferences have been used as a framework for defining the level of the processing load in reasoning tasks since the manipulation of the complexity of transitive inferences (e.g. (6), (7)) should reflect pure computational demands if other demands are controlled (e.g. Viskontas, Holyoak, & Knowlton, 2005). Therefore, testing syntactically complex sentences containing transitive inferences should be a very useful tool for investigating the processing of computationally demanding sentences. However, there has been no research examining transitive inferences in sentences of differing syntactic complexity. For this reason, it was necessary to test whether the transitive inference sentences were processed in the same manner as other sentences with the same syntactic structures.

The current experiment clearly demonstrated that the effects found in previous sentence processing studies were easily detectable in the transitive inference sentences used in this study; transitive inference sentences containing subject-extracted RCs were easier to process than those containing object-extracted RCs, and the transitive inference sentences containing the object modifying RCs were easier to process than those with subject modifying RCs. Furthermore, there was an interaction between the type of extraction and the type of modification such that the difference between the types of extraction was larger in subject modification conditions than in object modification conditions.

7.1.2 Computational demands of reasoning tasks

The results of this study also showed that the determinacy of the implicit relation (determined relation vs. undetermined relation) and the nature of the relation between verbs (semantically related verbs vs. semantically unrelated verbs) had strong effects on the comprehension of sentences containing transitive inferences.

Although there was no previous research directly testing the effect of determinacy of the implicit relation, for the manipulations in this experiment, it would be reasonable to assume that determined implicit relations would be easier to process than undetermined implicit relations since the determinacy of the implicit relation would only be determined after attempting to decide the implicit order. The finding that reading times were longer and answers were less accurate for the undetermined implicit relation cases in all four experiments clearly supports this assumption. The decision making process required for the undetermined implicit relations should explain the differences.

The other manipulation of computational processing demand in this study is best understood using the relational complexity concept. According to the relational complexity point of view (Halford et al., 1998), semantically related verbs have higher relational complexity because the two relations need to be considered simultaneously while semantically unrelated verbs have lower relational complexity since there is no need to consider two relations at the same time. The results clearly support this idea in that less complex, semantically unrelated verbs had more accurate answers and quicker reading times than more complex, semantically related verbs.

7.2 Working memory and sentence processing

7.2.2 Separate resource vs. general resource

Some sentences, for various reasons, are much more difficult to understand than others. At the syntactic level, several accounts have been proposed to explain the difficulty of complex sentences in terms of memory load. For example, Gibson (1998) proposed that one major factor affecting comprehension difficulty of different syntactic structures is the complexity of the integration between nouns and verbs. Andrew and Halford (1999) proposed that the comprehension difficulty of complex sentences comes from the number of independent role assignments that must be processed simultaneously to understand the sentence properly. Gordon and colleagues (2002) showed that representational characteristics of memory load influence comprehension difficulty of complex sentences. Although there seems to be a consensus that memory loads are one of the main reasons for the difficulty of complex sentences, with respect to the structural specification of the working memory in sentence processing, there are large differences among the accounts.

Two major approaches have been used to examine the structural specification of working memory in sentence processing. In some studies, the effect of differences in working memory capacity on the comprehension of complex sentences was investigated by testing individuals who have shown different levels of ability in traditional working memory tasks. In other studies, the interactive patterns of the syntactic processes and concurrent memory load were investigated by manipulating lists of digits or words to be remembered during the sentence processing.

The results of these efforts have led to two opposing views. While Just and Carpenter (1992) and other researchers proposed that sentence processing shares resources with other kinds of general cognitive processes, Caplan and Waters (1999) and others assumed a separate resource for sentence interpretation from other types of cognitive processes. Particularly, Caplan and Waters (1999) assumed that interpretive aspects of sentence comprehension such as syntactic structure building and understanding the meaning of a sentence are processed in a part of the working memory system specialized for these purposes.

While most studies have focused on the interactive patterns of the syntactic processes and concurrent memory load from lists to assess working memory structure serving complex sentence comprehension, several accounts have proposed that the difficulty of complex sentences may be due mainly to integration processes (Gibson, 1998; Andrew & Halford, 1999; Traxler, et al., 2005). Furthermore, the fact that processing of complex sentences requires both syntactic structure building and integration of noun phrases with a certain verb, adding extra maintenance memory load may not provide the best way of assessing working memory structure in language comprehension. As syntactic processes involve manipulation and integration of information, it is possible that syntactic processes mainly rely on the central executive function, which would not be accessed by list memory load.

By manipulating the determinacy of the implicit relation and the nature of the relation between verbs, the results of the current experiments showed that the computational processing load from reasoning did not significantly influence the magnitudes of the impact of the syntactic variables. Furthermore, the results of the eye-tracking experiment clearly showed that reasoning processes were carried out after sentence parsing had already been attempted. Just and Carpenter (1992)'s general resource view cannot explain the results of this study.

Although this study showed no effect of external load on syntactic processing, there are several studies reporting significant effects of list memory load on syntactic processing, which contradicts the results of this study and the modularity view of syntactic processing resources (e.g. King & Just, 1991; Keller, Carpenter & Just, 2001; Fiebach, Vos, & Friederici, 2004). However, according to Caplan and Waters (1999), who investigated published articles that showed interactive patterns between list memory and syntactic processes, the interaction could be found only when normal sentence reading was interrupted by other tasks. No interaction was found when normal reading was not interrupted by another task. Caplan and Waters (1999) proposed that switching attention or other controlled processes rather than shared working memory resources might explain the interaction between list load and syntactic processes.

Gordon and colleagues (2002) was the first to report an interaction between syntactic complexity and memory load while using tasks that did not interrupt each other. Fedorenko and colleagues (2006) also reported similar findings of an interaction between syntactic complexity and the representational similarity of memory load. While these studies greatly weaken the argument of attributing the interaction to attention switching, they do not directly reject the separate resources view. Unlike other studies that varied the length of the lists to be remembered as memory load, these studies used an unchanging load length but varied the type of load. In both studies, the representational type of lists (three names vs. three descriptive nouns) was the manipulated load. Since it is known that the similarity of the nouns affects complex sentence processing at the stage of initial sentence building (Gordon, Hendrick, Johnson & Lee, 2006) even in normal sentence comprehension without any list load, the similarity manipulation could be viewed as a direct manipulation of the complexity of the sentence rather than a manipulation of external memory load. It is also possible that the observed interactions were not true on-line interactions between the syntactic processes and the representational characteristics since the interaction was found only for the accuracy of comprehension measure (Gordon et al, 2002) or the experimental conditions were not fully crossed (Fedorenko et al, 2006).

7.2.2 Tactical effects

Unlike the other experiments that showed no indication of an interaction between syntactic complexity demands and the computational demands of reasoning, the results of the second experiment showed a strong interaction between these two variables. However, when the data were divided into first and second halves, it showed evidence of tactics development by participants as they became accustomed to the experimental materials.

The first evidence of using tactics other than normal sentence processing mechanisms was the close reading time of object-extracted RCs and subject-extracted RCs. While the effect of the type of extraction has been very well established and it is almost impossible to remove the effect in normal reading unless the loads from other sources were so high that both object-extracted RCs and subject-extracted RCs became too difficult, the similar reading times of object-extracted RCs and subject-extracted RCs were only found in relatively easier reasoning conditions and not in more difficult reasoning conditions. Therefore, the similar reading time between object-extracted RCs and subject-extracted RCs in the second half of the second experiment could be explained only by the effect of abnormal tactics rather than normal sentence processing mechanisms.

Another indication of the use of tactics was the greater facilitation of the overall reading time for the second half over the first half in the second experiment. While the difference in reading times between the first half and the second half were only around 100ms for the third experiment, the reading time for the second half was decreased by more than 1300ms compared with the first half in the second experiment. This showed that the participants in the second experiment developed ways to process the experimental sentences more quickly as they got used to them.

The lack of an interaction in the third experiment despite the use of identical experimental materials in the second and third experiments also supports the idea of tactics development by participants. The main explanation of the differences in these two experiments should be the difference in the experimental setting. The eye-tracking experiment was performed in a much more controlled situation than the self-paced reading experiment. In the eye-tracking experiment, participants wore the eye-tracker on their head and the experimenter sat right next to the participants while monitoring their eye movements and responses as they read sentences. On the other hand, the self-paced reading task was performed in a group setting. Participants were one of a group of four so the experimenter was not able to monitor each participant's responses. Also, unlike the self-paced reading task in which the participants initiated and finished each trial, the experimenter initiated the presentation of the sentence in the eye-tracking experiment. This well controlled experimental setting might prevent participants from developing any tactics to finish the experiment more quickly.

The last experiment also showed that the tactical processing could be eliminated by adding more sentence structures even in the self-paced reading situation.

7.3 Limits and future directions

One possible reason for the lack of interaction is that the tasks used in this study forced participants to serially process the sentences and reasoning tasks even though they use the same resources. In this experiment, it was in principle impossible to know whether the sentence provided enough information to compute the implicit relationships among entities in the sentence until after the relative clause had been computed and resolved. Also, as the location of the difference in difficulty between object-extracted RCs and subject-extracted RCs is known at or immediately after the integration point (Warren & Gibson, 2006; Gordon et al, 2006), which is before the subjects start to build the implicit relationship, it is possible that the computational demands of reasoning did not affect the syntactic complexity simply because these two computational demands occur serially rather than in a parallel manner. However, the eye-tracking results of Experiment 3 showed that processing loads of syntactic complexity still exist after the integration point such that the effects of the extracted RC were found continuously in the rereading times along with the effects of the reasoning processes. Therefore, if reasoning and sentence processing share the same resources, we would see the interaction between them even if they have been processed serially.

The sentences that were used in this study were relatively short. Therefore, it would be possible for subjects to simply hold the sentences in a memory buffer until they knew which question they would be required to answer. However, if this were the case, we would expect no syntactic complexity or reasoning effects on reading times. Also, the response time would differ between types of questions. Neither of these occurred in any of the four experiments.

Finally, although this study showed quite clearly that the efficiency of on-line syntactic operations does not differ as a function of other cognitive operations, it is still possible that the main reason for finding no interaction between reasoning complexity and syntactic complexity is not a specialized memory system but the lack of statistical power to find an interaction. However, this is highly unlikely since the results were replicated in all experiments after considering the tactics effect in the second experiment. Also, while they were relatively very large for main effects, ANOVA statistics of the interactions were not close to 1 across the experiments.

7.4 Summary and conclusion

The presented study was the first to embed a reasoning task into sentence processing to test hypotheses concerning the structural specification of working memory structures in language processing. While most previous studies investigating working memory and sentence comprehension have stressed the limited capacity of working memory in the aspects of load maintenance, this study focused on the resources of working memory in terms of the computational load. To do so, the interaction between the syntactic complexity of a sentence and the difficulty of reasoning was examined. The main hypothesis of this study was that if syntactic demands and computational demands from reasoning processing share the same working memory resource, they would interact with each other (e.g. Just & Capenter, 1992).

However, if they show an additive effect but no interaction, it would support Caplan and Water (1999)'s separate resource idea.

The first experiment tested syntactic complexity variables and a reasoning variable. The results of the first experiment revealed several important points. As expected, it showed significant effects of sentence processing variables and significant effects of the difficulty of inference variables. Most importantly, it showed that the effect of syntactic complexity on ease of processing was not moderated by the complexity of the reasoning task.

Unlike the first experiment, the results of the second experiment showed that the effect of syntactic complexity on ease of sentence processing was affected by the computational demands of the reasoning task. However, further analyses showed that this interaction occurred only after the participants were accustomed to the experimental materials, suggesting that participants developed tactics for the reasoning task over the course of the experiment that influenced how they approached comprehension of the sentence.

In the third experiment, eye-movements were recorded as the subjects read the sentence, allowing more information to be gathered about on-line processing patterns. The results of the overall sentence reading showed that the tactical effects were not robust since the effect of syntactic complexity on ease of sentence processing was not differently affected by the computational demands of the reasoning task in this experiment. Word by word analyses of eye-tracking showed that the syntactic complexity affected relatively earlier measures of eye-tracking before the computational demand started to affect sentence processing.

In the fourth experiment, the ease of developing effective tactics was reduced by using a broader range of sentence structures than were used in Experiments 2 and 3 to determine experimentally whether the interactions between language comprehension and difficulty of reasoning observed in Experiment 2 were due to reading tactics. Unlike the second experiment, the results of this experiment showed similar patterns to the first and third experiments such that reasoning occurred after basic processes of sentence interpretation and that those processes were not influenced by the cognitive demands of reasoning.

In conclusion, the results showed no evidence of interaction between the syntactic complexity and the complexity of the reasoning task on ease of comprehension of the transitive inference sentences. The findings reported in this study also suggested that reasoning occurred after the syntactic processes were completed, and that those syntactic processes were not influenced by more general cognitive demands of reasoning. Overall, this study provided no support for Just and Carpenter (1992)'s general working memory resource view and provided support for the hypothesis that sentence processing uses separable resources from more general aspects of processing (Caplan & Waters, 1999).

Table 1

Mean reading time and accuracy by type of extraction and type of modification in Experiment 1

	Subject modification		Object modification	
	Subject-extracted RC	Object-extracted RC	Subject-extracted RC	Object- extracted RC
RT	9928	11273	9286	9827
Accuracy	.828	.773	.819	.785

Table 2

Mean reading time and accuracy by type of extraction and type of modification for each type of determinacy of the implicit relation in Experiment 1

		Subject modification		Object modification	
		Subject-extracted RC	Object-extracted RC	Subject-extracted RC	Object-extracted RC
Determined	RT	9372	10612	8643	9124
	Accuracy	.866	.837	.889	.870
Undetermined	RT	10484	11929	9930	10529
	Accuracy	.789	.710	.768	.750

Table 3

Mean reading time and accuracy by typeof extraction and nature of the verb relation in Experiment 2

	Semantically related verbs		Semantically unrelated verbs	
	Subject-extracted RC	Object-extracted RC	Subject-extracted RC	Object-extracted RC
RT	8938	10419	7946	8664
Accuracy	.783	.745	.841	.850

Table 4

Mean reading time and accuracy by type of extraction and nature of the verb relation for each type of determinacy of the implicit relation in Experiment 2

		Semantically related verbs		Semantically unrelated verbs	
		Subject-extracted RC	Object-extracted RC	Subject-extracted RC	Object-extracted RC
Determined	RT	9073	9599	7975	8700
	Accuracy	.808	.837	.870	.860
Undetermined	RT	8802	11238	7917	8623
	Accuracy	.787	.675	.820	.843

Table 5

Mean reading time and accuracy by type of extraction and nature of the verb relation for sentences presented in the first half of Experiment 2

	Semantically related verbs		Semantically unrelated verbs	
	Subject-extracted RC	Object-extracted RC	Subject-extracted RC	Object- extracted RC
RT	9699	11149	8234	9624
Accuracy	.784	.716	.791	.805

Table 6

Mean reading time and accuracy by type of extraction and nature of the verb relation for each type of determinacy of the implicit relation for sentences presented in the first half of Experiment 2

		Semantically related verbs		Semantically unrelated verbs	
		Subject-extracted RC	Object-extracted RC	Subject-extracted RC	Object-extracted RC
Determined	RT	9501	10727	8117	9327
	Accuracy	.820	.780	.829	.834
Undetermined	RT	9899	11548	8344	9918
	Accuracy	.790	.690	.780	.813

Table 7

Mean reading time and accuracy by time of extraction and nature of the verb relation for sentences presented in the second half of Experiment 2

	Semantically related verbs		Semantically unrelated verbs	
	Subject-extracted RC	Object-extracted RC	Subject-extracted RC	Object-extracted RC
RT	8199	9687	7834	7738
Accuracy	.800	.786	.884	.877

Table 8

Mean reading time and accuracy by time of extraction and nature of the verb relation for each type of determinacy of the implicit relation for sentences presented in the second half of Experiment 2

		Semantically related verbs		Semantically unrelated verbs	
		Subject-extracted RC	Object-extracted RC	Subject-extracted RC	Object-extracted RC
Determined	RT	8681	8546	7593	7594
	Accuracy	.855	.828	.918	.896
Undetermined	RT	7722	10889	7874	8072
	Accuracy	.746	.741	.838	.871

Table 9

Mean reading time and accuracy by type of extraction and nature of the verb relation in Experiment 3

	Semantically related verbs		Semantically unrelated verbs	
	Subject-extracted RC	Object-extracted RC	Subject-extracted RC	Object- extracted RC
RT	9853	10924	8288	9001
Accuracy	.792	.756	.825	.824

Table 10

Mean reading time and accuracy by type of extraction and nature of the verb relation for each type of determinacy of the implicit relation in Experiment 3

		Semantically related verbs		Semantically unrelated verbs	
		Subject-extracted RC	Object-extracted RC	Subject-extracted RC	Object-extracted RC
Determined	RT	9613	10475	8265	8986
	Accuracy	.843	.811	.849	.835
Undetermined	RT	10092	11370	8311	9015
	Accuracy	.743	.700	.801	.814

Table 11

Various reading time measures of critical regions by type of extraction and nature of the verb relation in Experiment 3

	Semantically related verbs		Semantically unrelated verbs	
	Subject-extracted RC	Object-extracted RC	Subject-extracted RC	Object-extracted RC
Gaze duration				
Subject	341	347	336	348
Who	226	249	222	249
RC	422	461	434	453
Verb	401	408	479	510
Object	234	245	235	252
Regression-path duration				
RC	927	1060	923	1169
Verb	2495	2978	2593	2689
Object	3012	3191	1895	2154
Rereading				
Subject	527	754	476	682
Who	734	982	639	850
RC	2387	2629	1841	1904
Verb	1026	1181	729	948

Note. Subject = the matrix subject; Who = the relative pronoun *'who'*; RC = the relative clause (embedded noun + verb/ verb + embedded noun); Verb = the matrix verb; Object = the matrix object.

Table 12

Various reading time measures of critical regions by type of extraction and nature of the verb relation for each type of determinacy of the implicit relation in Experiment 3

	Semantically related verbs				Semantically unrelated verbs			
	Determined		Undetermined		Determined		Undetermined	
	SRC	ORC	SRC	ORC	SRC	ORC	SRC	ORC
Gaze duration								
Subject	336	336	346	359	338	346	333	350
Who	224	247	227	248	219	254	224	245
RC	413	449	430	474	437	439	430	466
Verb	394	407	407	409	485	518	474	503
Object	238	233	229	257	253	261	217	244
Regression-path duration								
RC	886	1031	969	1090	942	1135	904	1203
Verb	2351	3035	2638	2922	2474	2761	2713	2618
Object	2691	2742	3333	3639	1938	1987	1850	2317
Rereading								
Subject	520	726	534	781	461	635	492	729
Who	675	949	792	1061	640	834	638	866
RC	2170	2477	2603	2731	1863	1870	1820	1937
Verb	896	1009	1155	1353	694	948	760	948

Note. SRC = subject-extracted RC; ORC = object-extracted RC. Subject = the matrix subject; Who = the relative pronoun *'who'*; RC = the relative clause (embedded noun + verb/ verb + embedded noun); Verb = the matrix verb; Object = the matrix object.

Table 13

Mean reading time and accuracy by type of extraction and nature of the verb relation in Experiment 4

	Semantically related verbs		Semantically unrelated verbs	
	Subject-extracted RC	Object-extracted RC	Subject-extracted RC	Object- extracted RC
RT	10598	11866	10743	11247
Accuracy	.811	.819	.744	.811

Table 14

Mean reading time and accuracy by type of extraction and nature of the verb relation for each type of determinacy of the implicit relation in Experiment 4

		Semantically related verbs		Semantically unrelated verbs	
		Subject-extracted RC	Object-extracted RC	Subject-extracted RC	Object-extracted RC
Determined	RT	10404	11432	10175	11256
	Accuracy	.842	.871	.861	.835
Undetermined	RT	10791	12302	10313	11238
	Accuracy	.645	.750	.838	.804

Figure 1

Overall reading times in Experiment 1

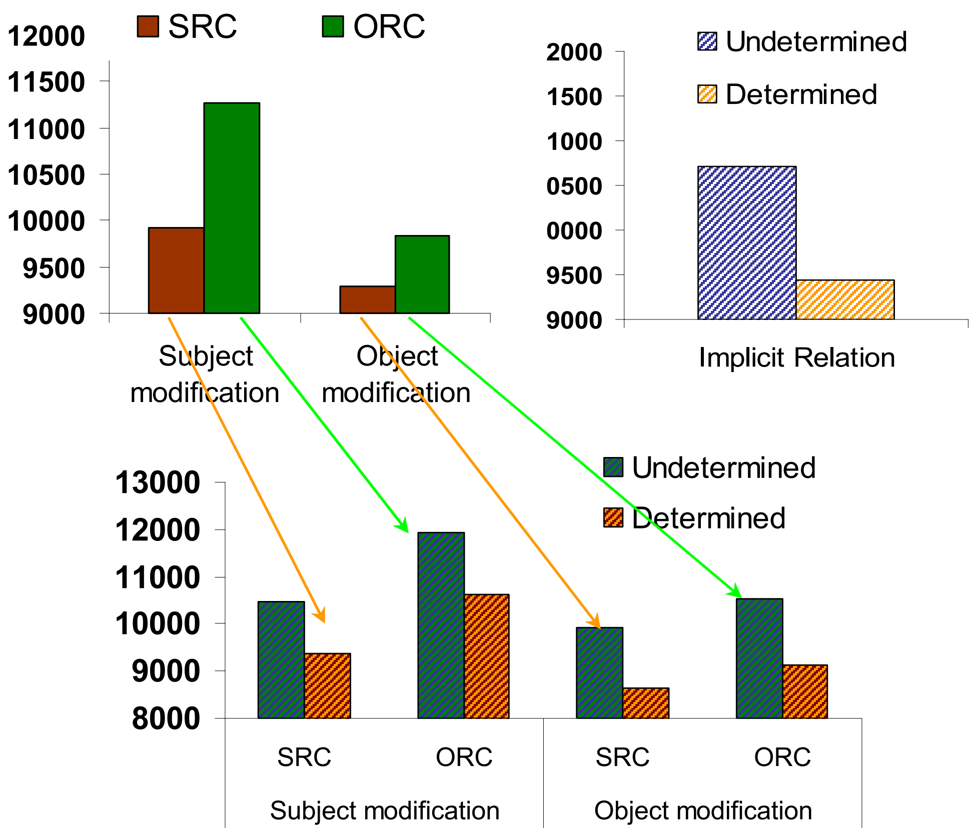


Figure 2

Overall Reading times in Experiment 2

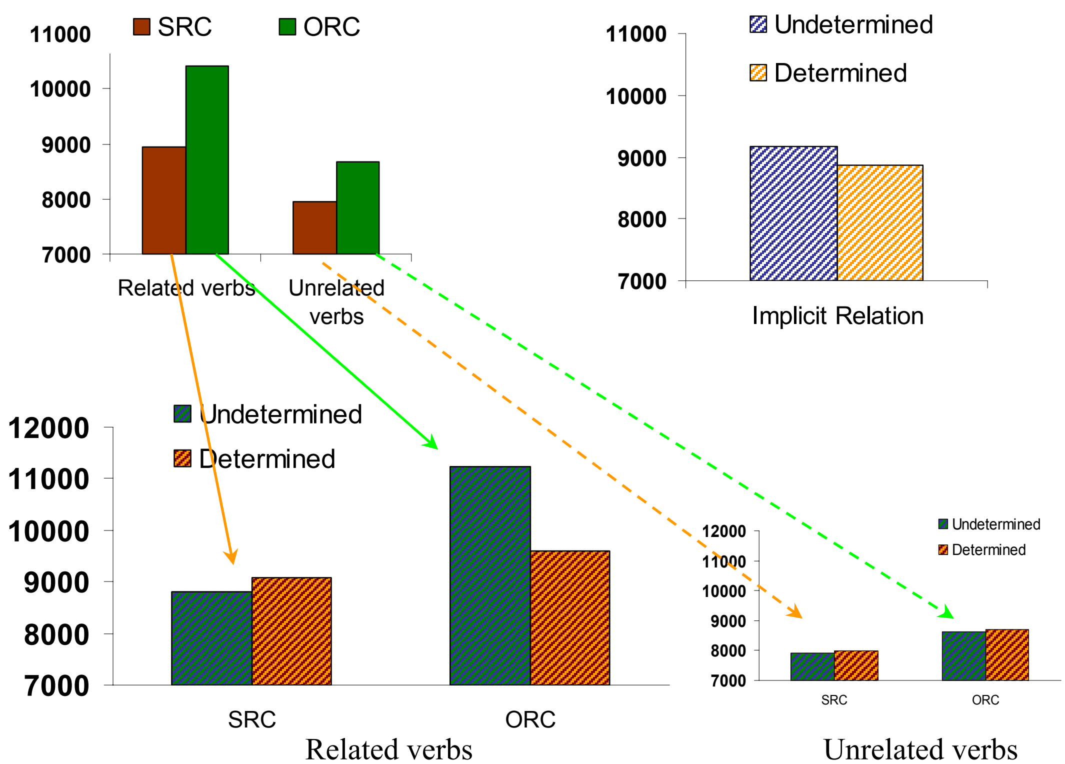


Figure 3

Reading times by the time of extraction and nature of the verb relation for sentences presented in the first half and sentences presented in the second half in Experiment 2

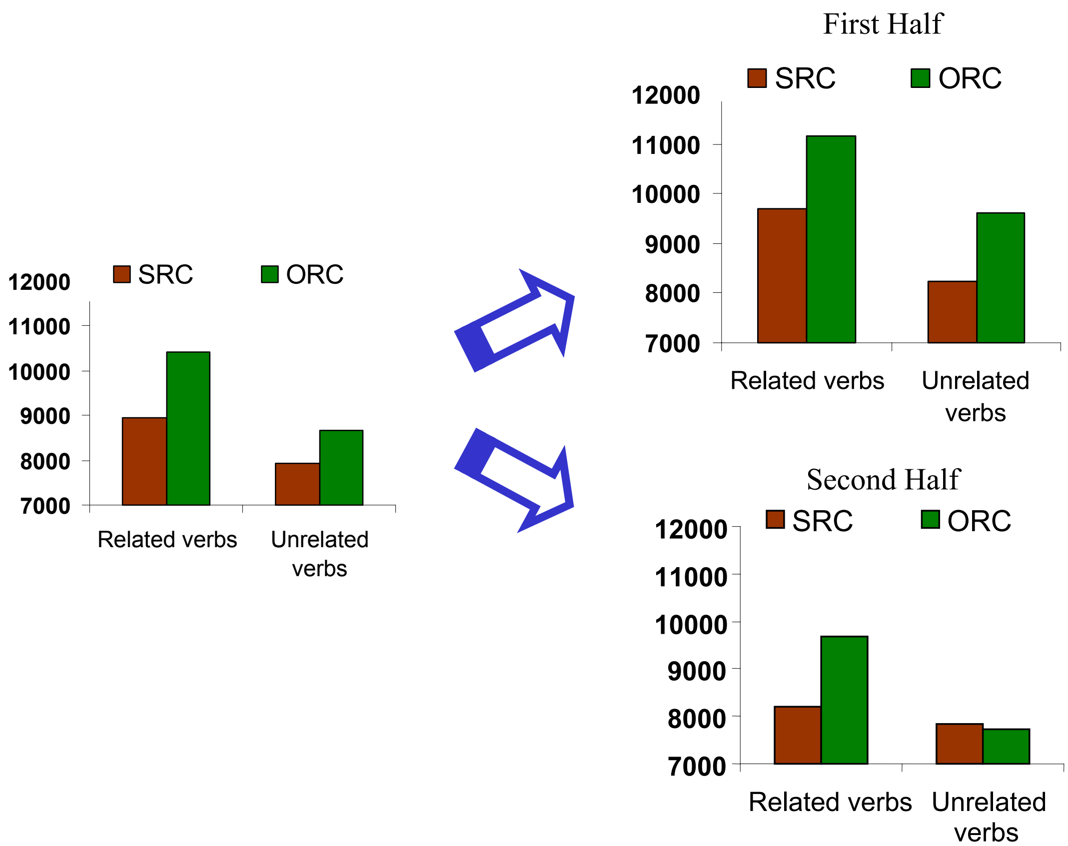


Figure 4

Reading times for semantically related verb conditions by the type of extraction and determinacy for sentences presented in the first half and sentences presented in the second half in Experiment 2

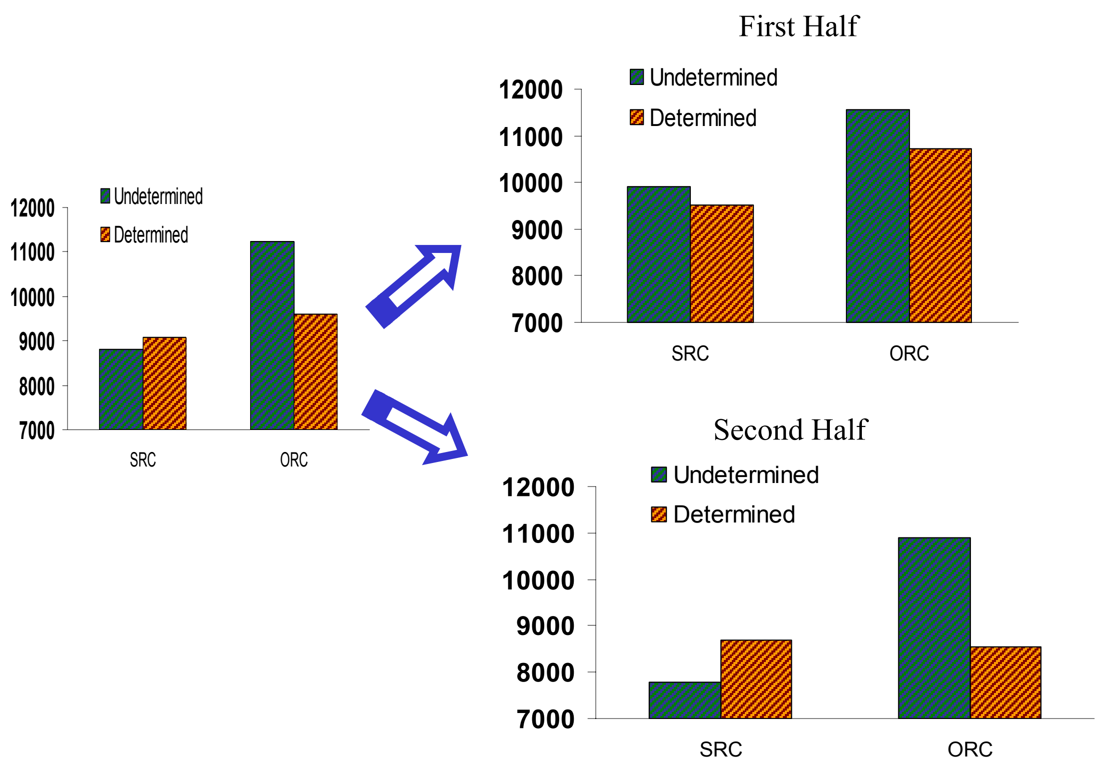


Figure 5

Reading times for semantically unrelated verb conditions by the type of extraction and determinacy for sentences presented in the first half and sentences presented in the second half in Experiment 2

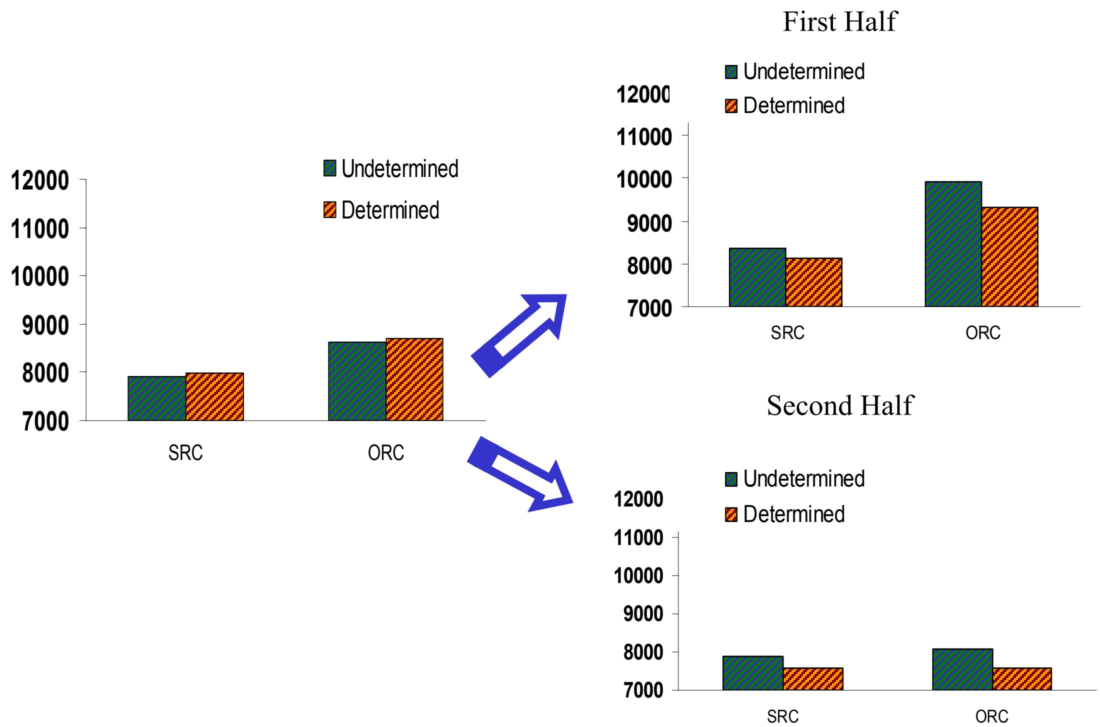


Figure 6

Overall Reading times in Experiment 3

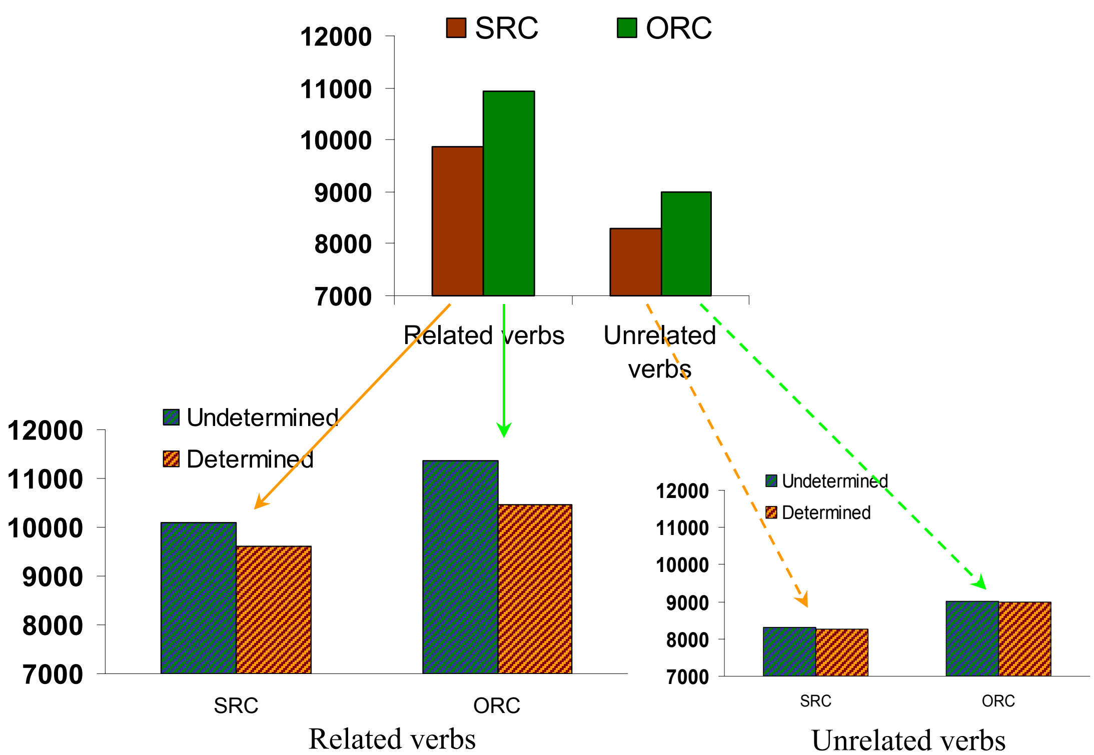


Figure 7

Gaze duration in Experiment 3

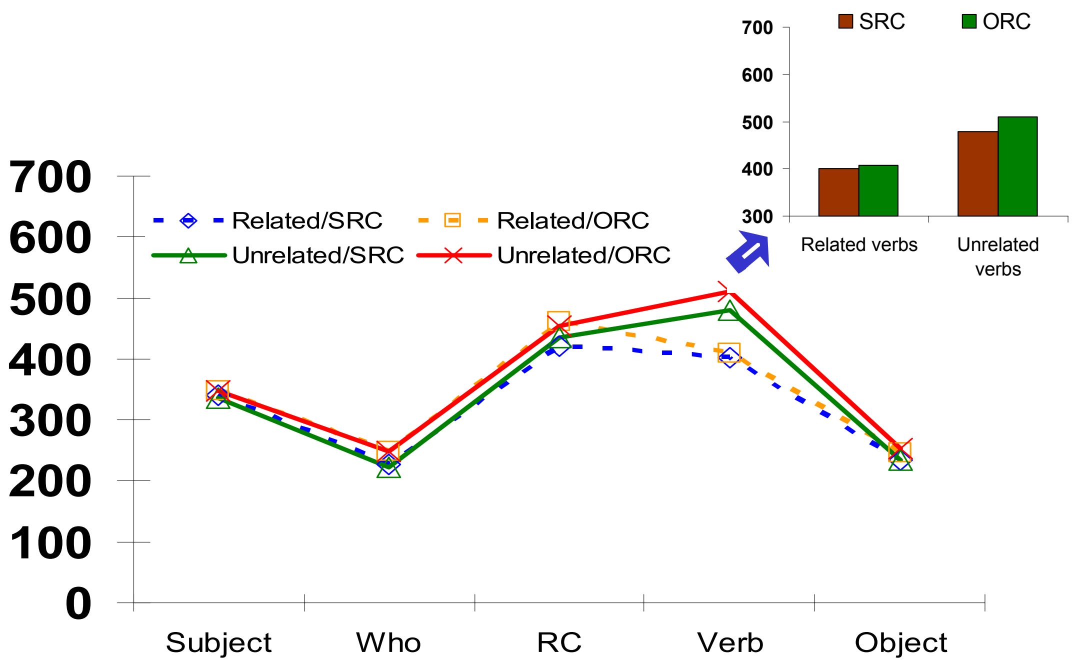


Figure 8

Regression path duration in relative clause region in Experiment 3

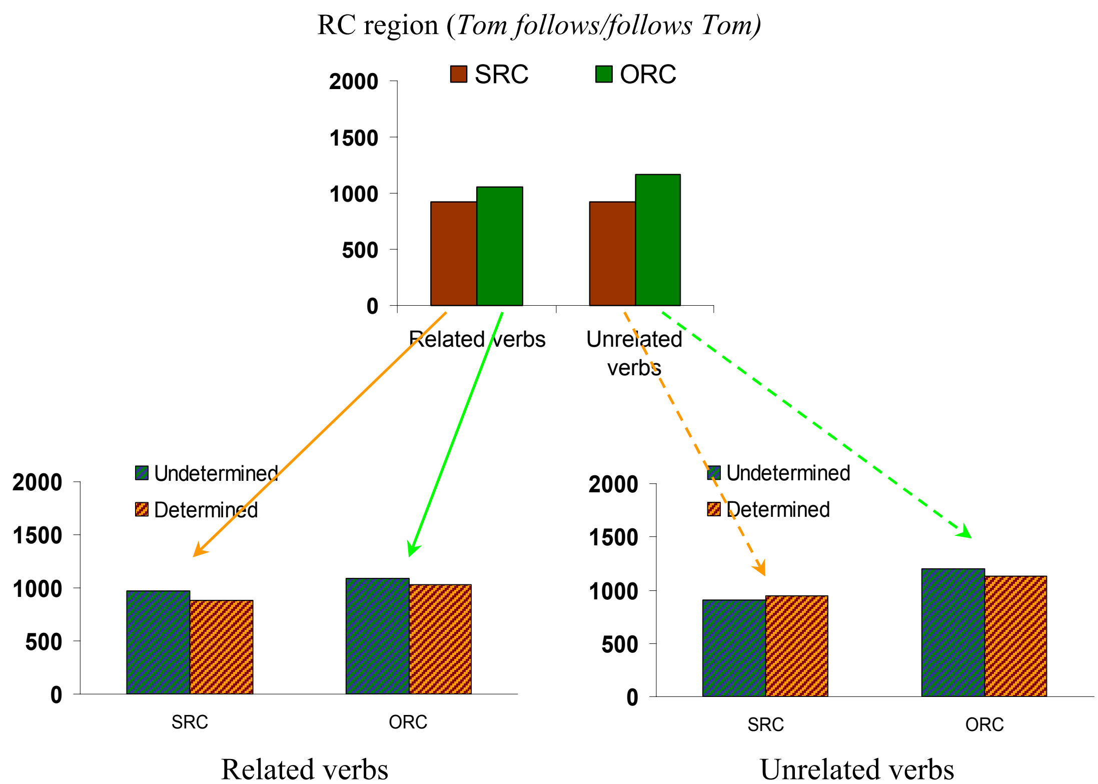


Figure 9

Regression path duration in last word region in Experiment 3

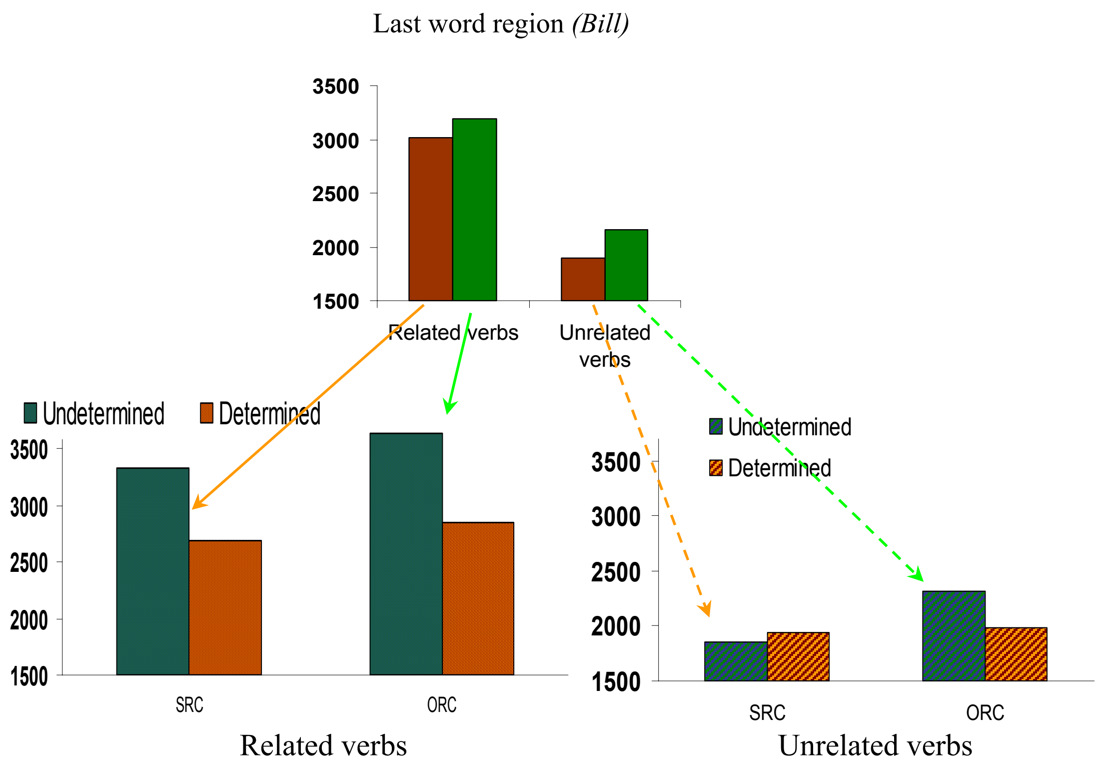


Figure 10

Rereading times in Experiment 3

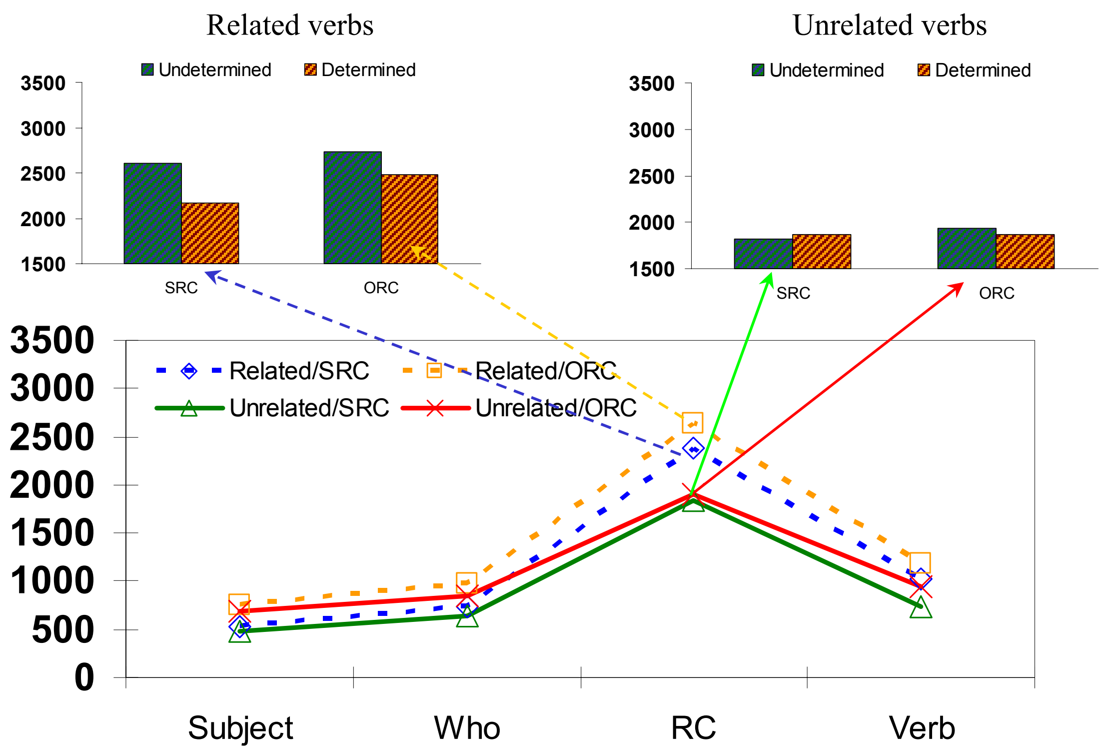
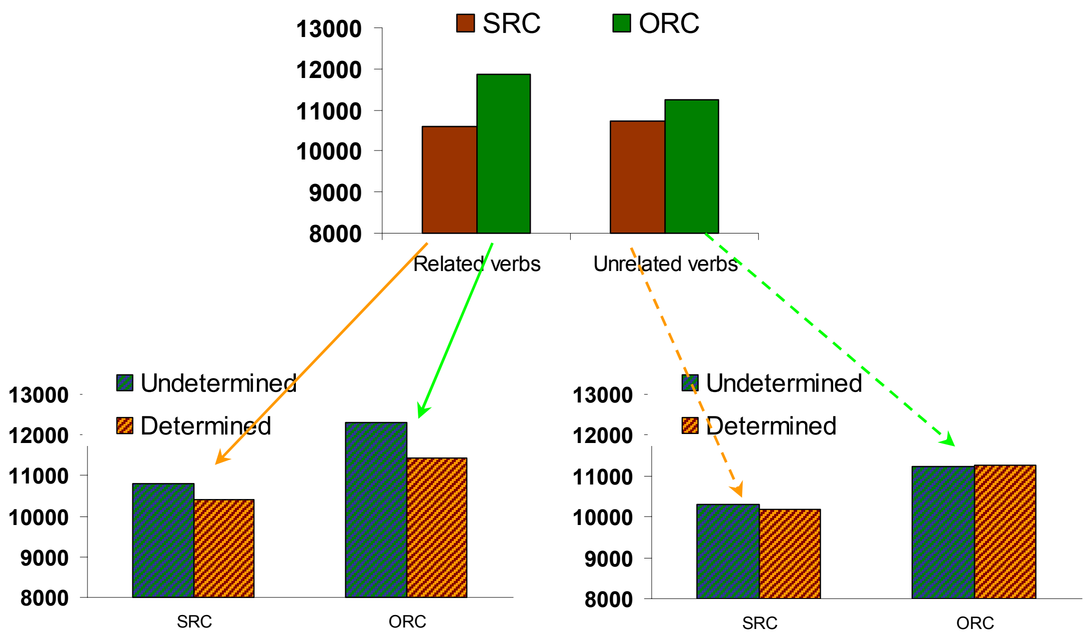


Figure 11

Overall reading time in Experiment 4



Related verbs

Unrelated verbs

8. APPENDICES

8.1 Appendix A

The stimuli for Experiment 1 are shown below in the subject modifying subject-extracted form. They were also presented in the subject modifying object-extracted form, object modifying subject-extracted form, and object modifying object-extracted form. The first four stimuli are shown in all four forms.

1. Ben who follows John precedes Tom
   Ben who John precedes precedes Tom
   John precedes Ben who precedes Tom
   John precedes Ben who Tom follows

2. Ben who precedes John precedes Paul
   Ben who John follows precedes Paul
   John follows Ben who precedes Paul
   John follows Ben who Paul follows

3. John who precedes Ben follows Matt
   John who Ben follows follows Matt
   Ben follows John who follows Matt
   Ben follows John who Matt precedes

4. John who follows Ben follows Mike
   John who Ben precedes follows Mike
   Ben precedes John who follows Mike
   Ben precedes John who Mike precedes

5. Ben who follows John precedes Mark

6. John who precedes Ben precedes Greg

7. Ben who precedes Jeff follows Tom

8. Ben who follows Jeff follows Paul

9. Ben who follows Jeff precedes Matt

10. Jeff who precedes Ben precedes Mike

11. Ben who precedes Jeff follows Mark

12. Ben who follows Jeff follows Greg

13. Josh who follows Tom precedes Ben

14. Paul who precedes Josh precedes Ben

15. Josh who precedes Matt follows Ben

16. Josh who follows Mike follows Ben

17. Josh who follows Mark precedes Ben

18. Greg who precedes Josh precedes Ben

19. Matt who precedes Tom follows Ben

20. Matt who follows Paul follows Ben

21. Matt who follows Greg precedes Ben

22. Tom who precedes Mike precedes Ben

23. Mike who precedes Paul follows Ben

24. Mike who follows Greg follows Ben

25. Ben who follows Mark precedes Tom

26. Mark who precedes Ben precedes Paul

27. Ben who precedes Mark follows Greg

28. Ben who follows Paul follows Tom

29. Ben who follows Tom precedes Greg

30. Paul who precedes Ben precedes Greg

31. Bill who precedes John follows Tom

32. Bill who follows John follows Paul

33. Bill who follows John precedes Matt

34. John who precedes Bill precedes Mike

35. Bill who precedes John follows Mike

36. Bill who follows John follows Mark

37. Bill who follows Tom precedes Jeff

38. Paul who precedes Bill precedes Jeff

39. Jeff who precedes Matt follows Bill

40. Jeff who follows Mike follows Bill

41. Jeff who follows Mark precedes Bill

42. Greg who precedes Jeff precedes Bill

43. Josh who precedes Bill follows Tom

44. Josh who follows Bill follows Paul

45. Josh who follows Bill precedes Matt

46. Bill who precedes Josh precedes Mike

47. Josh who precedes Bill follows Mark

48. Josh who follows Bill follows Greg

49. Tom who follows Matt precedes Bill

50. Matt who precedes Paul precedes Bill

51. Greg who precedes Matt follows Bill

52. Tom who follows Mike follows Bill

53. Paul who follows Mike precedes Bill

54. Mike who precedes Greg precedes Bill

55. Mark who precedes Bill follows Tom

56. Mark who follows Bill follows Paul

57. Mark who follows Bill precedes Greg

58. Bill who precedes Paul precedes Tom

59. Greg who precedes Bill follows Tom

60. Greg who follows Bill follows Paul

61. John who follows Paul precedes Tom

62. Matt who precedes John precedes Tom

63. John who precedes Mike follows Tom

64. John who follows Mark follows Tom

65. John who follows Tom precedes Greg

66. John who precedes Paul precedes Matt

67. Paul who precedes John follows Mike

68. Paul who follows John follows Mark

69. Paul who follows John precedes Greg

70. Paul who precedes Jeff precedes Tom

71. Jeff who precedes Matt follows Tom

72. Jeff who follows Mike follows Tom

73. Tom who follows Mark precedes Jeff

74. Greg who precedes Tom precedes Jeff

75. Paul who precedes Jeff follows Matt

76. Paul who follows Jeff follows Mike

77. Paul who follows Jeff precedes Mark

78. Jeff who precedes Paul precedes Greg

79. Tom who precedes Paul follows Josh

80. Tom who follows Matt follows Josh

81. Tom who follows Mike precedes Josh

82. Mark who precedes Tom precedes Josh

83. Tom who precedes Greg follows Josh

84. Paul who follows Josh follows Matt

85. Paul who follows Josh precedes Mike

86. Josh who precedes Paul precedes Mark

87. Paul who precedes Josh follows Greg

88. Matt who follows Paul follows Tom

89. Mike who follows Tom precedes Paul

90. Tom who precedes Mark precedes Paul

91. Greg who precedes Tom follows Matt

92. Greg who follows Tom follows Mike

93. Greg who follows Mark precedes Tom

94. Paul who precedes Matt precedes Greg

95. Mike who precedes Paul follows Greg

96. Mark who follows Paul follows Greg

8.2 Appendix B

Examples of stimuli for Experiments 2 and 3 are shown below. They were presented in the subject-extracted form with two semantically unrelated verbs, object-extracted form with two semantically unrelated verbs, the subject-extracted form with two semantically related verbs, and the object-extracted form with two semantically related verbs. The subject-extracted form with two semantically related verbs and the object-extracted form with two semantically related verbs were exactly the same as the subject modifying subject-extracted form and the subject modifying object-extracted form in Experiment 1. The entire set of stimuli is available upon request.

1. Ben who follows John precedes Tom
   Ben who John precedes precedes Tom
   Ben who follows John is taller than Tom
   Ben who John precedes is taller than Tom

2. Ben who precedes John precedes Paul
   Ben who John follows precedes Paul
   Ben who precedes John is taller than Paul
   Ben who John follows is taller than Paul

3. John who precedes Ben follows Matt
   John who Ben follows follows Matt
   John who precedes Ben is taller than Matt
   John who Ben follows is taller than Matt

4. John who follows Ben follows Mike
   John who Ben precedes follows Mike
   John who follows Ben is taller than Mike
   John who Ben precedes is taller than Mike

8.3 Appendix C

Examples of the stimuli for Experiment 4 are shown below. The entire set of stimuli is available upon request.

1. Ben who follows John precedes Tom
   Ben who John precedes precedes Tom
   Ben who follows John is taller than Tom
   Ben who John precedes is taller than Tom

2. Ben who precedes John precedes Paul
   Ben who John follows precedes Paul
   Ben who precedes John is taller than Paul
   Ben who John follows is taller than Paul

3. Ben follows John who follows Matt
   Ben follows John who Matt precedes
   Ben follows John who is taller than Matt
   Ben follows John who Matt is taller than

4. John precedes Ben who precedes Mike
   John precedes Ben who Mike follows
   John precedes Ben who is taller than Mike
   John precedes Ben who Mike is taller than

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