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Examining interactions among working memory, aging, and linguistic constraints in sentence comprehension

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Examining Interactions among
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in Sentence Comprehension

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Abstract

Language comprehension is affected by a variety of factors. For example, psycholinguists propose that various syntactic and semantic relationships in sentences affect linguistic complexity and processing difficulty (Hawkins, 1994, 2004; Gibson, 1998, 2000). In addition, researchers have demonstrated that working memory (WM) ability and age also influence the processing difficulty of linguistic material (Just & Carpenter, 1992; MacDonald & Christiansen, 2002).

Therefore, the main goal of this thesis was to examine how both linguistic and cognitive constraints affect sentence comprehension to determine which factors facilitate processing and how they interact to determine overall processing difficulty. To do so, I conducted three self-paced reading experiments with individuals who varied in age and WM ability, as assessed by the reading span (Daneman & Carpenter, 1980) and digit-letter sequencing tasks (Wechsler, 1997). The studies investigated reading times for sentences containing verb-particle constructions, a structure that varies in semantic and syntactic constraints that have been shown to affect processing difficulty (Gonnerman & Hayes, 2005).

The results from the three studies showed that although semantic and syntactic processing constraints affected reading times within each WM or age group (with slower reading times for sentences in which the particle was shifted away from the verb, especially when the verb and particle were highly dependent on each other for their meaning and a long or complex direct object noun phrase (NP) intervened), they did not have much influence on overall reading times across these groups. Regardless of sentence difficulty, reading times were slower for individuals who had lower scores on the WM assessments, especially when they were also in the older age group.

The findings from these studies indicate that linguistic and cognitive factors each play important roles in determining processing difficulty. However, individual processing ability has a stronger overall effect on reading times than the linguistic manipulations within a sentence. These results suggest that it is difficult to study the interaction between these factors, however, suggestions are offered for future investigations of these constraints.

Examining Interactions among Working Memory, Aging, and Linguistic Constraints in Sentence Comprehension

Language comprehension is influenced by a variety of factors. Many theorists have proposed that aspects of the linguistic input affect comprehension, with processing difficulty resulting from various syntactic and semantic factors within a sentence (Hawkins, 1994, 2004; Gibson, 1998, 2000; Lewis & Vasishth, 2005). However, individual differences in computational resources, such as working memory (WM) ability or age, have also been shown to influence the processing difficulty of various sentences, (Just & Carpenter, 1992; Caplan & Waters, 1999; Gibson, 2000; MacDonald & Christiansen, 2002), with increased difficulty for older adults or those with lower WM ability. This thesis assesses the interaction of linguistic and cognitive constraints in sentence comprehension, specifically, the influence of WM ability and age on reading times for sentences that vary in syntactic and semantic constraints that affect linguistic complexity.

LINGUISTIC PROCESSING CONSTRAINTS

Hawkins (2004) proposed that the linguistic complexity of sentences arises from various syntactic and semantic relations in a sentence, with the impact of these factors on processing varying according to the word order of the sentence. Results from several studies support Hawkins' view that word order plays an important role in processing ease, with faster reading times and production preferences for word orders which maximize processing efficiency (c.f. Gonnerman & Hayes, 2005; Stallings, MacDonald, O'Seaghdha, 1998).

Hawkins' (1994, 2004) explanation of these findings is based on the notion that language comprehension involves building a sentence structure, which is composed of the various phrases in the sentence. For example, the structure of the sentence, '*The child threw the ball to Jane*,' includes the subject noun phrase (NP) '*the child*,' and the verb phrase "*threw the ball to Jane*," which itself can be divided into the smaller direct object NP '*the ball*' and indirect object NP '*to Jane*.' Hawkins suggests that the word order of a sentence affects the time in which the total sentence structure is built and proposes that early recognition of all sentence elements facilitates processing efficiency. Therefore, under Hawkins' theory, sentence (1) is easier to process than sentence (2):

(1) [I]$_{NP\text{-}1}$ [lent]$_{VP}$ [to Jim]$_{PP}$ [the book about whales of the Atlantic Ocean]$_{NP\text{-}2}$.

1 2 3 4 5 6 7 8 9 10 11 12

(2) [I]$_{NP\text{-}1}$ [lent]$_{VP}$ [the book about whales of the Atlantic Ocean]$_{NP\text{-}2}$ [to Jim]$_{PP}$.

1 2 3 4 5 6 7 8 9 10 11 12

because all of the phrasal elements (NP-1, VP, NP-2, and PP), and thus the structure of the sentence, can be recognized in five words. In contrast, 11 words must be processed to recognize all of the elements of sentence (2).

Word order not only affects the amount of time in which the elements of a sentence are recognized, but also the proximity of semantically related items in a sentence. According to Hawkins (2004), reducing the distance between semantically dependent words facilitates processing because the complete meaning of the phrase is understood more quickly. Thus, sentence (3) is easier to process than (4) because the distance between the semantically dependent words '*chew*' and '*out*' is reduced in sentence (3), thus facilitating understanding of the phrase '*chew out.*'

(3) The man will *chew out* [the disruptive kids]$_{NP}$.

(4) The man will *chew* [the disruptive kids]$_{NP}$ *out.*

In contrast, reading sentence (4) involves maintaining the word '*chew*' over the entire sentence until the word '*out*' is encountered and the complete meaning of the verb phrase is apparent.

In addition, the strength of the semantic relationship between words has been shown to affect ease of processing (Lohse, Hawkins, & Wasow, 2004; Gonnerman and Hayes, 2005). For example, a sentence such as (5) is easier to process than (4):

(5) The man will *chew* [the delicious food]$_{NP}$ *up.*

In both sentences, the related words are separated by an intervening NP, however, this separation has less effect on the processing of sentence (5) since '*chew*' depends very little on '*up*' for its meaning. However, in sentence (4), '*chew*' depends highly on '*out*' for proper interpretation, thus processing is highly influenced by the separation of these two words. Therefore, the effect of word order on processing ease varies according to the strength of the semantic relationship between words, with greatest processing difficulty arising when highly dependent words are separated from one another (c.f. Gonnerman & Hayes, 2005).

Syntactic and Semantic Constraints in Verb-Particle Constructions

The placement of particles in sentences with verb-particle (VPt) constructions has long been a subject of interest in the linguistic literature, with researchers describing several phonological, syntactic, semantic, pragmatic, and discourse factors that affect particle placement (e.g., Bolinger, 1971; Gries, 1999, 2002, 2003; Live, 1965; van Dongern, 1919, see also articles in Dehé, Jackendoff, McIntryre, & Urban. 2002, for a variety of methodological and theoretical approaches to understanding verb particles in English and other languages).

Verb-particle constructions are particularly useful for the study of syntactic and semantic constraints on sentence processing since they allow for the concurrent examination of both syntactic and semantic domains. VPt constructions are phrases that include a verb (e.g., *look*) and a particle (e.g., *up*) that can either be produced adjacently as in *'he looked up the word'* or separately (with an intervening noun phrase (NP)) as in '*he looked the word up*'. In addition, VPt constructions vary in the extent to which the verb relies on its particle for the meaning of the complete construction. For example, '*finish*' does not rely much on '*up*' for its interpretation in '*finish up*', whereas '*chew*' depends strongly on the particle, '*out*', in '*chew out*' for its semantic interpretation. In the sections that follow, I first examine the syntactic and then the semantic factors that influence particle placement.

Syntactic Constraints on Verb-Particle Processing

Two syntactic factors play an important role in the processing difficulty of VPt constructions: 1) the adjacency of the verb and particle and; 2) the length of the direct object NP (Gries, 2003; Lohse et al., 2004, Gonnerman & Hayes, 2005). The adjacency of the verb and particle affects the syntactic recognition domain of sentence constituents, a factor which Hawkins' (1994, 2004) suggests affects processing ease. On this view, sentences in which the particle is shifted should facilitate processing since shifting the particle allows for the earlier recognition of the direct object NP. For example, sentence (6) is easier to process since all phrasal elements can be recognized in five words whereas it takes six words to recognize all of the phrasal elements of sentence (7).

(6) The boy will [*finish* [his dinner]$_{NP}$ *up*]$_{VP}$.

1 2 3 4 5 6 7

(7) The boy will [*finish up*]$_{VP}$ [his dinner]$_{NP}$.

1 2 3 4 5 6 7

In addition, the *length* of the direct object NP has been shown to affect ordering preferences in corpora (Gries, 2003; Lohse et al., 2004), indicating that speakers are more likely to produce verbs and particles adjacent to one another as the length of the direct object NP increases. Furthermore, the length of the direct object NP has been found to influence processing difficulty in sentence comprehension. Gonnerman and Hayes (2005) showed, in a self-paced reading task, that reading times (RTs) slowed for longer NP's, especially when they intervened between the verb and particle.

Semantic Constraints on Verb-Particle Processing

In addition to syntactic factors, the semantic dependency relationship between verb and particle can influence preferred word order and processing performance in language users (Lohse et al., 2004, Gonnerman and Hayes, 2005). For decades, the semantic dependency relationship between verbs and particles has been discussed as a dichotomy, with only idiomatic and literal verb-particle relationships considered (Chen, 1986; Gries, 2003). On this view, the meaning of idiomatic VPt's is not transparently based on the independent meanings of the verb and particle. For example, '*chew out*' does not clearly involve chewing, nor the notion of '*out*.' Therefore, the semantic dependency relationship between the verb and particle for these idiomatic VPt's is high since, using the previous example, the verb '*chew*' depends highly on the particle '*out*' for its meaning in '*chew out.*'

Conversely, the meaning of literal VPt's stems directly from the meaning of the verb and particle independently. For example, the VPt '*pull apart*' clearly involves the action of pulling and the direction '*apart*.' The semantic dependency relationship between the verb and particle for these literal VPt constructions is low since the meaning of the verb alone does not depend much on the particle. For example, '*finish*' does not depend much on '*up*' for its meaning in '*finish up,*' reducing the dependency relationship for this construction.

However, Lohse et al. (2004) and Gonnerman and Hayes (2005) illustrated that VPt constructions can have a more intermediate semantic relationship, for example, '*look*' depends slightly on '*up*' for its meaning in the phrase '*look the number up.*' Thus, the *degree of dependency* may be a more accurate way to portray this semantic relationship for all types of verb-particles, rather than a dichotomy between idiomatic and literal.

The psychological validity of this notion of dependency was examined by Gonnerman and Hayes (2005). They found that participants were sensitive to the degree of the dependency relationship between verbs and particles based on judgments of the semantic similarity between the verb alone (e.g., *stand*) and the verb-particle pair (e.g., *stand up*). Results showed a steady cline in similarity ratings from very dissimilar (e.g., '*blow*' versus '*blow off*'), to intermediate similarity (e.g., '*smell*' versus '*smell up*'), to high similarity (e.g., '*wring*' versus '*wring out*'). In addition, they showed that the semantic similarity between verb and verb-particle pair influenced lexical decision performance in an on-line masked priming task, with increased facilitation for the more semantically similar verb/verb-particle pairs (see Appendix A for sample similarity ratings and Appendix B for priming results).

The effect of VPt dependency on particle placement has been examined in several corpus studies that demonstrated that highly dependent particles were more likely to be placed adjacent to the verb than less dependent particles, thereby decreasing the distance between the related words, thus minimizing the *semantic* domain (Gries, 2003; Lohse et al., 2004). For example, sentences such as 'the teacher will *chew out* the students' appeared more often in corpora than 'the teacher will *chew* the students *out*,' indicating that sentences which minimize the distance between the very dependent verb and its particle are more commonly produced. In contrast, when the verb and particle do not have a high semantic dependency relationship, verb and particle adjacency is not much more likely than non-adjacency. For, example, the sentence 'The children will *finish up* their meal' is just as common as 'The children will *finish* their meal *up*,' indicating that particle position is less important when the semantic dependency relationship is low.

In a self-paced reading task, Gonnerman and Hayes (2005), found that the semantic dependency relationship between verb and particle affected processing difficulty, but mainly when the two words were separated. For example, sentences containing shifted and highly dependent verb-particles, such as 'the teacher will *chew* the students *out,*' were read more slowly than when the verb and particle were adjacent as in, 'the teacher will *chew out* the students.' Conversely, the separation of less dependent verbs and particles did not result in a drastic slow-down, with similar reading times for both 'the children will *finish up* their meal' and 'the children will *finish* their meal *up*,' Additionally, Gonnerman and Hayes found that the semantic dependency relationship did not influence reading times when the verb and particle were adjacent, with similar reading times across all levels of dependency when the particle immediately followed the verb indicting that minimizing the semantic domain facilitated understanding of all verb-particle constructions.

The results from both sentence comprehension and corpus studies indicate that semantic dependency plays an important role in determining processing difficulty in a self-paced reading task and the frequency of particle position in corpora. However, the relative influence of dependency varied with particle position, such that dependency exerted its largest influence on processing difficulty when the particle was shifted. This indicates that syntactic factors, such as VPt adjacency, and semantic factors, such as the dependency relationship between verb and particle, interact in verb-particle constructions, with overall processing difficulty resulting from the relative weighting of each factor. The integration of both syntactic and semantic influences on processing of verb-particle constructions is discussed in the section below.

Integrating Syntactic and Semantic Domains in Verb-Particle Constructions

Hawkins (1994, 2004) suggested that processing difficulty results from the overall size of the syntactic and semantic domains in sentences. As was discussed earlier, the size of the syntactic domain results from word order alternations or phrase lengths that affect the recognition domain of a sentence, that is, the number of words it takes to recognize all of the elements of a sentence, whereas, the size of the semantic domain results from the distance between semantically related items in a sentence. Hawkins proposed that sentences that minimize both of these domains result in faster comprehension since these sentences can be processed more efficiently (see the section 'Linguistic Processing Constraints' for a detailed review of syntactic and semantic processing domains).

However, in sentences with VPt constructions, the syntactic and semantic domains cannot be minimized concurrently. For example, when the particle is adjacent to the verb as in '*the teacher will chew out the disruptive students,*' the semantic domain is minimized at the expense of the syntactic. This ordering facilitates understanding of the verb and particle since the distance between the semantically related '*chew*' and '*out*' is minimized. However, when the particle is adjacent to the verb and the semantic domain is minimized, understanding of the syntactic domain is not facilitated since placing '*out*' adjacent to '*chew*' results in a one word increase in the syntactic recognition domain of the sentence.

On the other hand, when the particle is shifted to the end of the sentence as in, '*the children will finish the meal of fried chicken up,*' the syntactic domain is minimized at the expense of the semantic domain. This ordering allows the reader to recognize the direct object NP earlier than if the particle was adjacent to the verb which results in earlier recognition of all sentence elements, a factor which has been shown to increase processing efficiency (Hawkins, 2004; Stallings et al., 1998). However, when the particle is shifted away from the verb, the distance between the semantically dependent verb and particle is increased, hindering the understanding of the complete verb-particle construction (Lohse et al., 2004).

Gonnerman and Hayes (2005) showed that syntactic and semantic factors interact to affect the overall processing of sentences containing verb-particle constructions, with slower reading times for sentences in which the verb and particle were separated, especially when a long direct object NP intervened between highly dependency verbs and particles. This suggests that minimizing the syntactic domain hinders processing efficiency since it increases the distance between semantically related verbs and particles, even though this minimization allows for the earlier recognition of the direct object NP. The tendency to read particle-shifted sentences slower suggests that it is important for the comprehender to understand the complete meaning of the verb phrase before moving on to the direct object NP, especially when the verb and particle are highly dependent on each other for their meaning. However, when the dependency relationship between the verb and particle is low, shifting the particle to the end of the sentence results in faster reading times than when they were adjacent. Thus, there is a processing benefit to recognizing all elements of the sentence earlier, that is, minimizing the syntactic domain, but only when the semantic relationship between the verb and particle is not highly dependent.

These results support Hawkins' (1994, 2004) general notion that structures which maximize processing efficiency are less difficult to process. However, they also illustrate that when syntactic and semantic factors cannot be minimized concurrently, readers weight these factors differently, suggesting that comprehenders focus on the aspects of the linguistic input that will most facilitate understanding.

COGNITIVE CONSTRAINTS: WORKING MEMORY ABILITY

The previous sections illustrated the importance of syntactic and semantic linguistic constraints in determining processing difficulty, however, the *processing ability of the individual* was not examined. This ability is important in sentence comprehension because understanding the meaning of a sentence involves remembering and processing the content of the sentence, in addition to integrating the syntactic and semantic relationships among the words. To accomplish such a task, the comprehender requires a mechanism to process and store this information, namely working memory (WM). Working memory refers to the ability to store and manipulate information (Baddeley, 1986). Integral to WM ability is the notion of individual differences in working memory *capacity*. Working memory capacity refers to the *maximum* amount of information that can be stored or processed by an individual at any given time. WM capacity affects how well and how long information can be processed, with a trade-off between speed and accuracy when capacity is reached (Just & Carpenter, 1992). Thus, if working memory is limited, the understanding of a sentence suffers, either due to an inability to process the content of the sentence or to a need for increased processing time. Therefore, individuals with greater working memory capacity perform better on language tasks because they are able to keep more information active in working memory than people with lower working memory capacity (Just & Carpenter, 1992).

While theories of working memory generally agree that processing is limited by a certain "capacity," each theory varies in the extent to which working memory resources are divided. Some theories, which I will refer to as *multiple-resource theories*, suggest different pools of resources for different types of information, such as the division of visuo-spatial and verbal information (e.g., Baddeley, 1986) or conscious and unconscious language processes (e.g., Waters & Caplan, 1996). *Single-resource theories* suggest that one working memory resource underlies all verbally mediated activities (Just &

Carpenter, 1992). Finally, *connectionist theories* deny the separation of working memory resources at all, with working memory functionally inseparable from linguistic knowledge (MacDonald & Christiansen, 2002).

For the purposes of this thesis, I will focus on connectionist approaches to working memory. The main reason for this decision is related to the different explanations of working memory capacity espoused by each theory. MacDonald and Christiansen (2002) claim that working memory capacity *emerges* from experience with language and biological factors of the individual, such as processing speed due to age (Salthouse, 1996). In this approach, there are no distinctions between linguistic knowledge, processing, and capacity. Any individual's capacity is not due to some separate resource, but results from the individual's linguistic experience and general processing ability.

For MacDonald and Christiansen (2002), experience with language results mainly from language experience and age. Within an age cohort, however, they suggest that reading experience plays the major role in determining processing efficiency (this should not discount the role of language experience in oral contexts, however, reading experience is a commonly measured variable and thus 'reading experience' is highlighted in their account). Exposure to language through reading results in increased frequency with which an individual encounters linguistic structures, both common and uncommon. For example, it has been shown that words which are seen more frequently are recognized more rapidly and processed more quickly than lower frequency words (*e.g.*, Seidenberg, 1985). Therefore, MacDonald and Christiansen claim that individuals with more reading experience are able to process linguistic information more efficiently than those who do not read as often. This experience makes avid readers "more skilled comprehenders," which in turn affects their processing capacity. These more skilled individuals can utilize their experience to more rapidly comprehend information. This faster processing increases the amount of information that can be understood in a given amount of time, resulting in increased processing capacity. Thus, for MacDonald and Christiansen, an individual's working memory capacity is directly related to their processing ability or *speed*, which stems from experience with language. However, they argue that across the life-span, age also plays a significant role in determining processing ability. The role of aging on sentence comprehension and working memory ability is discussed in detail in the section "Study 3: Working Memory, Sentence Processing, and Aging."

Working Memory Tasks

In this thesis, I focus on two assessments of working memory ability: the reading span task and digit-letter sequencing task (Daneman & Carpenter, 1980; Wechsler, 1997, respectively). These tasks were chosen as WM assessments since both tasks tap the ability to simultaneously process and store information, a skill which is integral for sentence comprehension. The correlation between these tasks has been shown to be moderate (e.g., r=.24, Turner and Engle (1989)) which indicates that they measure similar, yet not completely overlapping abilities. I suggest that the differences result from the fact that the two tasks differ in the material that must be maintained and manipulated in working memory (see the Methods section of Study 1 for a detailed description of the two tasks). In the reading span task, participants must read sets of sentences while maintaining the last word from each of the sentences in memory. The participant's reading span score is determined by the largest set of sentences for which the participant can recall all of the sentence final words. Thus, performance on this task is reliant on language processing ability as well as more traditional working memory skill (basic storage and processing). As such, scores from this task are correlated with other measures of language ability, including reading comprehension (r=.55), verbal SAT (r=.49), and word span (r=.55) (Conway et al., 2004).

The reading span task has been used in many experimental investigations assessing the effect of linguistic working memory capacity on sentence processing, lexical ambiguity, and age-related differences in linguistic performance (c.f. Just & Carpenter, 1992; Waters, Caplan, Alpert, & Stanczak, 2003; Miyake, Just, & Carpenter, 1994; DeDe, Kemtes, Caplan, & Waters, 2004). For example, scores on the reading span task have been used to predict performance on sentence processing tasks (such as the self-paced reading task described in the Methods section of Experiment 1), with lower scores associated with slower reading times and less accurate reading (Caplan & Waters, 1999; Just & Carpenter, 1992, Gibson, 2000). Specifically, it has been shown that working memory ability, as assessed by the reading span task, affects reading speeds at regions of syntactic complexity with a greater slow down for those with low WM (King

& Just, 1991). Additionally, WM ability affects comprehension accuracy when a sentence is ambiguous, with greater accuracy for those with high WM capacity since they can maintain multiple interpretations of a sentence simultaneously (MacDonald, Just, & Carpenter, 1994).

These results are consistent with MacDonald and Christiansen's (2002) theory of linguistic WM, which predicts that those who perform well on the reading span task (high WM individuals), should also perform well on other language processing tasks. On their account, these individuals are more skilled readers resulting from increased experience with language and therefore process linguistic information faster than less skilled individuals. In addition, the more skilled readers encounter complex structures more often, resulting in decreased difficulty with these structures compared to their less experienced counterparts. Thus, increased linguistic processing efficiency results in a larger emerging capacity, which then increases performance on sentence processing tasks.

Unlike the reading span task, the digit-letter sequencing task requires that strings of numbers and letters are remembered and manipulated so that they are recalled in numerical and alphabetical order. Therefore, scores on this task are reliant on a more general capability to process and store information relatively free of the language skill factor. Daneman and Merkle (1996) reported that the correlation between scores on traditional digit span tasks (which do not require that the numbers are manipulated) and reading comprehension was low (r=.14). However, when the task required storage *and* processing, as in the digit-letter sequencing task, the correlation with reading comprehension was higher (r=.30). This indicates that basic *storage and processing* ability is an important component of reading comprehension, thus should have an influence on reading times.

INTEGRATING LINGUISTIC AND COGNITIVE CONSTRAINTS

While Hawkins' theory (1994, 2004) of linguistic complexity and MacDonald and Christiansen's (2002) theory of linguistic WM each explain some performance effects in language comprehension, they do not directly examine the effect of WM ability on processing difficulty for sentences with different syntactic and semantic relationships. Hawkins (2004) claims that WM ability can play an important role in explaining differences in linguistic performance. However, in his account, the general processing *efficiency* of structures, resulting from minimizing the syntactic and semantic domains of a sentence, is the ultimate predictor of performance. Hawkins suggests that sentences which minimize domains are processed more efficiently because they reduce processing effort, increase speed of understanding, or minimize ambiguity.

Interestingly, Hawkins claims that minimized structures are processed more easily even though they may increase WM load, a factor that has been shown to affect processing difficulty (Gibson, 1998, 2000). For example, according to Hawkins' theory, sentence (8) is syntactically more efficient than (9):

(8) The man will [look [the number of the Italian restaurant]$_{NP}$ up]$_{VP}$.

(9) The man will [look up]$_{VP}$ [the number of the Italian restaurant]$_{NP}$.

since the syntactic domain is minimized in (8) and the structure of the sentence is recognized faster, thus facilitating processing. However, earlier recognition of all the elements of sentence (8) requires that the dependency relationship of the verb and particle be held in memory across the integration of the direct object NP, increasing WM load. On the other hand, sentence (9) does not facilitate syntactic efficiency, but does minimize WM load since the verb and particle are processed before encountering the direct object NP.

Thus, in sentences with verb-particle constructions for which the syntactic and semantic domains cannot be minimized concurrently, the various orders affect the amount of time information that must be maintained in WM. Therefore, it seems logical that individual differences in WM ability would affect the processing of these sentences which vary in syntactic and semantic efficiency and presumably WM load. For example, '*the children will finish their delicious meal up*' may result in the more efficient recognition of all phrasal elements, but this benefit may not be realized in performance if an individual has lower WM ability and thus has more difficulty storing and processing the relatively long direct object NP that intervenes between the incomplete verb and particle. In contrast, individuals with higher WM ability may not be hindered by reading the direct object NP while also maintaining the unresolved verb in memory. Thus, these individuals may benefit from the early recognition of the direct object NP, since they can build the structure of their sentence sooner, but are also not deterred by the elongation of the semantic domain.

In this thesis, I conducted three self-paced reading studies on individuals who differed in WM ability and age to determine the influence of processing ability on reading times for sentences containing verb-particle constructions, which vary in syntactic and semantic constraints. In Study 1, I examined the effect of working memory ability in young adults on the comprehension of sentences that vary in linguistic demands and WM load. Specifically, I examined how WM differences affected processing of sentences that varied in syntactic and semantic domain minimization via the manipulation of verb-particle dependency, adjacency, and NP length. In Study 2, I investigated the role of working memory ability on processing VPt sentences with direct object NPs that varied in structural complexity and frequency, but were of constant length. The effect of this syntactic manipulation on processing efficiency and WM load was also assessed. Finally, Study 3 investigated the effect of aging on both working memory and sentence comprehension. To do so, I compared the performance of the young adults in Study 1 to a new population of older adults using the same WM and sentence processing tasks and materials. The effect of cognitive slowing due to aging was examined to determine whether a processing speed decline with aging plays an important role in determining both WM ability and the efficiency of processing sentences which vary in syntactic or semantic constraints.

STUDY 1: WORKING MEMORY AND SENTENCE PROCESSING

Many researchers have found that WM ability affects sentence comprehension, especially for more complex linguistic structures (King & Just, 1991; Just & Carpenter, 1992; MacDonald, Just, & Carpenter, 1994; Caplan & Waters, 1999; MacDonald & Christiansen, 2002). However, these studies do not investigate how the relative weightings of semantic and syntactic constraints in a sentence affect processing difficulty, nor how these linguistic factors affect comprehension for those with different WM ability. Therefore, the goal of this study is to investigate the role of WM in processing verb-particle constructions, a structure that permits variable word orders of differing syntactic and semantic complexity. Specifically, I examine the relative effects of three linguistic variables; verb-particle adjacency, dependency, and direct object NP length, on reading times in a self-paced reading task for groups of individuals with low or high WM ability.

For this study, I have three main hypotheses. First, I predict that the placement of the particle will affect the processing difficulty of each sentence, with increased reading times for sentences in which the particle is shifted to the end of the sentence, especially when the verb is heavily dependent on the particle for its complete meaning and a long direct object NP intervenes. I expect that shifting the particle to the end of the sentence and thus minimizing the syntactic domain will increase demands on WM since these sentences require maintaining the unresolved semantic relationship (from reading the verb without its particle) in memory while also integrating the content of the direct object NP. In contrast, this WM load increase should not occur when the particle is adjacent (and the semantic domain is minimized) since the meaning of the verb-particle is understood before the direct object NP is read, thus eliminating the need to maintain the dependency relationship in memory while reading the direct object NP.

Second, I predict that WM ability, as determined by the reading span and digit-letter sequencing tasks, will affect reading times, with those in the high WM group reading faster than their low WM counterparts. According to MacDonald and Christiansen, those who score better on linguistic WM tasks, such as the reading span task, have more experience with language which translates into 'language skill,' resulting in more efficient language processing. In addition, individuals with higher scores on the digit-letter sequencing task are better able to process and store information in general, thus contributing to their ability to process linguistic material more efficiently, a skill which should lead to faster reading times on the self-paced reading task.

Finally, I expect that WM ability will influence reading times differently for sentences that vary in processing load. Specifically, I expect that individuals in the lower WM group should have increased difficulty with sentences that lengthen the semantic domain and increase WM load, despite the fact that these sentences minimize the syntactic domain. Individuals with lower WM scores should have more difficulty processing these sentences since they require that the entire noun phrase is kept in working memory while waiting for the verb particle to complete the meaning of the sentence. In contrast, I expect that those with higher WM scores should benefit from their increased ability to process and store information in general, as well as their increased exposure to various linguistic structures. Thus, they should have less difficulty maintaining the unresolved verb-particle dependency relationship while reading the direct object NP, allowing them to benefit from the early recognition of the sentence structure in the particle-shifted sentences.

To test these hypotheses, three tasks were implemented: two WM assessments, the reading span task and digit-letter sequencing task (Daneman & Carpenter, 1980; Wechsler, 1997); and a self-paced reading task. The reading span and digit-letter sequencing tasks were used as an assessment of WM ability since they measure both more general and language specific working memory skills that are integral to reading comprehension (see the section 'Working Memory Tasks' for a more detailed discussion of these tasks).

To assess the relative affects of semantic and syntactic factors in a self-paced reading task, sentences were created that varied in: 1) **verb-particle dependency** on three levels: low (*e.g.*, '*finish*' does not depend on '*up*' for its meaning in '*finish up*'), middle (e.g., '*look*' depends moderately on '*up*' for its meaning in '*look up*'), and high (*e.g.*, '*chew*' depends highly on '*out*' in '*chew out*'); 2) **verb and particle adjacency**, in which the particle was either adjacent to the verb as in '*eat up the candy*' or shifted away as in '*eat the candy up*;' and 3) the **length of the direct object NP** which was two (*e.g.*, *her date*), three (*e.g.*, *her boring date*), or five (*e.g.*, *her boring and moody date*) words long.

Method

Participants

111 Lehigh undergraduates (67 females and 44 males) between the ages of 18 and 22 participated for course credit. All were monolingual native speakers of Standard American English.

Overall Session Procedure

Each participant completed all three tasks, the two WM tasks (reading span and digit-letter sequencing), as well as the self-paced reading task. The order of presentation of tasks was varied such that half of the participants did the self-paced reading task first and half did the working memory tasks first (the order of the two working memory tasks was also counterbalanced). The entire testing session lasted approximately 50-60 minutes. The individual materials and procedures for each of these tasks are discussed in the sections below.

Self-Paced Reading Task

Materials

A set of sentences was created to reflect the three main variables of interest: verb-particle dependency, verb and particle adjacency, and direct object NP length. Each of these factors is described in detail below.

Verb-particle dependency. 78 verb-particle constructions were used as the verb phrases for the target sentences. These 78 verb-particles were divided into three groups based on the semantic dependency relationship between the verb and particle: 26 low dependency (e.g., *finish up*); 26 middle dependency (e.g., *look up*); and 26 high dependency (e.g., *chew out*). Dependency scores were determined by a similarity judgment task (for details, see Gonnerman and Hayes, 2005). The verbs (e.g., *look*) and particles (e.g., *up*) in each group were matched for frequency (Kuçera & Francis, 1967) and word length. Additionally, the verbs and particles taken together as complete constructions (e.g., *look up*) were matched for frequency across groups. Verbs were not repeated (e.g., we did not include both '*run up*' and '*run out*').

Direct object NP length. For each verb-particle construction, three direct object NPs varying in length (short, medium, and long) were created. Short direct object NPs consisted of two words (e.g., *the class*), medium, three words (e.g., *the disruptive class*), and long, five words (e.g., *the class of disruptive students*). The direct object NPs were matched for the average frequency of the words in the NP. All of the NP's used the definite article, '*the*', or the possessive, '*his*' or '*her*,' as the determiner and only common nouns were used as the head noun of the phrase. Thus, the short NP's consisted of a determiner and head noun (e.g., *the meal; her date*), the medium NP's consisted of a determiner, adjective, and head noun (e.g. *the delicious meal; her boring date*), and the long NP's consisted of a determiner followed by either the head noun and a three word prepositional phrase (e.g., *the problem between the employees; the meal of fried chicken*) or a three word modifier followed by the head noun (e.g., *her boring and moody date; the very well behaved students*).

Verb and particle adjacency. Two versions of each sentence for each verb-particle construction and each NP length were created, one with the verb and particle adjacent (e.g., *finish up the meal*), and one with the particle placed after the direct object NP (e.g., *finish the meal up*).

Thus, for each of the 78 verb-particle constructions, 6 sentences were created, reflecting the three length possibilities (short, medium, and long) and two levels of adjacency (adjacent, shifted). In addition, each sentence began with a two-word subject NP (e.g., *the man*; *the teacher*) that was controlled for frequency across conditions. All of the verb phrases were in the future tense (e.g., the man *will look up* the number) to avoid irregular conjugations. Tag phrases were also created for the end of each sentence to avoid wrap up effects at sentence completion. See Table 1 for a sample set of sentences.

The resulting sentences were divided into six lists, such that each list contained only one sentence form for each verb particle construction, resulting in 78 target sentences per list. Therefore, each participant read only one version of a sentence containing each verb and particle.

To avoid a potential response bias to the target sentences, 78 filler sentences were created to reduce the proportion of sentences containing verb-particle constructions. Therefore, each participant read a total of 156 sentences, with the target sentences accounting for 50 % of the stimuli. The filler sentences varied in length, similar to the target stimuli. The shortest sentences were 7 words long and the longest were 14 words.

with a middle length of about 10 words. The filler sentences also varied in syntactic type, with the majority of the fillers composed of dative or passive phrases.

Procedure

Participants were tested individually in a sound-attenuated room. Sentences were presented and reaction times were recorded using Psyscope software (Cohen, MacWhinney, Flatt, & Provost, 1993). Sentences appeared on a computer screen, in black Arial, size 14 font on a white background. Participants first saw a blank white screen, and then with a button press, the first word appeared on the left side of the screen. The first word always appeared in the same location. No dashes were presented prior to reading the word to indicate the length of the forthcoming sentence.

Reading times were recorded for each button press as participants read the sentences word by word at their own pace. Participants pressed a button to replace the word just read with dashes and to display the next word of the sentence. Participants were given several practice items before beginning the test sentences. After reading each sentence, participants answered a yes-no content question to ensure careful reading. This task generally lasted twenty minutes.

Assessment of Working Memory

Two tasks were used for the WM assessment: the reading span task (Daneman & Carpenter, 1980); and digit-letter sequencing task (Wechsler, 1997) which are discussed in more detail below. The order in which these two tasks were given was counterbalanced.

Reading Span Task

Materials. The stimuli consist of 60 sentences drawn from the task developed by Daneman and Carpenter (1980). Each sentence was typed in a single line on a 5x7 index card in Times New Roman size 14 font.

Procedure. The task required the participants to read a set of sentences (starting with a set of two and working up to a maximum set of 6) and then to recall the last word from each of the sentences in that set. For example, set one included two sentences, '*The entire town arrived to see the appearance of the controversial political candidate.*' and '*The weather was very unpredictable that summer so no one made plans too far in advance.*' The participant read each of the sentences aloud and then recalled the sentence final words '*candidate*' and '*advance.*' There were three sets of sentences at each level: that is, 3 sets of 2 sentences, 3 sets of 3 sentences, all the way up to 3 sets of 6 sentences. The sentences were presented in the same order for every participant.

Digit-letter Sequencing Task

Materials. The stimuli consisted of combinations of numbers and letters drawn from a standardized task (Wechsler, 1997). The trials ranged from those with only 2 items (e.g., B 7) to those with 8 items (6 H U 4 9 J 1 T). There were three trials for each length, that is, 3 trials with 2 items, 3 trials with 3 items, up to 3 trials with 8 items in each trial. The trials with an even number of items always contained equal amount of letters and numbers, trials with an odd number of items varied so that sometimes there was one more letter than number and vice versa.

Procedure. The experimenter read a series of letters and numbers out loud to the participant. Experimenters were careful to always read at a slow and consistent pace (one second between each item). The participant was then asked to repeat the list of numbers and letters back to the experimenter, but with the numbers first, in numerical order, followed by the letters in alphabetical order. For example, if the experimenter said "J C 7 2 K "the correct response would be "2 7 C J K."

The session started with five practice trials with two or three numbers and letters in each. The test trials began with two items (one number and one letter) and ended with eight numbers and letters combined. The task was divided into 7 blocks (corresponding to the 7 different trial lengths; from 2 letters and numbers to 8 letters and numbers) with 3 trials of the corresponding length in each block. The experimenter continued on to the next block if the participant got at least one trial correct in the previous block. If the participant did not give any correct responses in the block, the session ended.

Results

Of the total 111 participants tested, 13 were removed from all subsequent analyses due to error rates above 25% on the comprehension questions from the self-paced reading task. Therefore, the following analyses are based on data from the remaining 98 participants.

Self-Paced Reading Task

Mean reading times per word were calculated for sentences in each condition. Reading times were then trimmed by removing any reading time that was more than two standard deviations above or below the mean. This excluded 10.3% of the original data.

Regions of Interest

I predicted that particle placement would affect WM load and therefore processing difficulty, with increased reading times for sentences in which the particle is shifted to the end of the sentence, especially when the verb is heavily dependent on the particle for its complete meaning and a long direct object NP intervenes. Thus, I examined reading times over the two regions of the sentence that are most affected by the adjacency of the verb and particle. The two regions of interest are: 1) the direct object noun phrase (e.g., 'the word,' 'the unusual word,' and 'the origin of the word'); and 2) the verb-particle itself. A series of analyses conducted on these two regions of interest is discussed in the sections below.

Direct Object Noun Phrase

The direct object noun phrase is a region of interest since the resulting WM load and time it takes to read this phrase should vary with the adjacency of the verb and particle, the dependency relationship between the verb and particle, as well as the length of the noun phrase itself. To assess how these syntactic and semantic manipulations affected reading times, the mean reading times per word over the direct object NP were entered into an ANOVA with the within subjects factors of Adjacency (adjacent, shifted), Dependency (low, middle, high), and NP Length (short, medium, long).

The overall interaction between the three linguistic variables (Adjacency, Dependency, and NP Length) was significant in the analysis by participants. F1 (4,376) =

6.92, $p < 0.001$, with slower reading times when the particle was shifted, especially when the intervening NP was long and the dependency relationship between the verb and particle was high (see Table 2 for cell means and the section 'Adjacency of the Verb and Particle' for a discussion of these effects by adjacency).

An analysis by items was also conducted with mean reading times by item entered into an analysis of variance with the between items factor of Dependency (low, middle, high) and the within items factors of Adjacency (adjacent, shifted) and NP Length (short, middle, long). The factor of Dependency was between items because the 78 target verb-particles used for the sentence stimuli were divided into three groups: 26 low, 26 middle, and 26 high dependency verb-particles.

The interaction over items was not significant, (F2 < 1). The reading time patterns across the cells for each of the items was not very consistent, with only about 16 of the items corresponding even moderately with the overall effects. This variability across the items is the most likely source of the non-significant effects in this analysis by items. In addition, the design of the item analysis could also have weakened the effects in this analysis since the Dependency variable was between items, resulting in a less powerful mixed-model design. In contrast, for the subject analysis, the Dependency variable was a within participants variable, resulting in greater error degrees of freedom for the participant analysis (376) versus the item analysis (138). The decreased error degrees of freedom in the item analysis resulted in an increase in MS error, the denominator of the F-ratio, thus decreasing the F-value and the overall significance of the interaction. Thus, given that the effects are variable by items and that the design for the item analysis is weaker than that for participants, I will only be reporting analyses by participants for the rest of this study.

Adjacency of the Verb and Particle

As predicted, reading times on the direct object NP were highly influenced by the position of the particle, with slower overall reading times when the particle was shifted (330 versus 322 msec when adjacent), F(1,94) = 15.5, $p < 0.0002$. Given the influence of adjacency across levels of both Dependency and NP Length, the overall interaction is best illustrated by examining the effects at each level of Adjacency (*i.e.*, particle-adjacent vs. particle-shifted).

As expected, when the verb and particle were adjacent to one another (e.g., '*chew out the students*'), there was not a significant effect of Dependency on reading times for the direct object NP. This suggests that when the particle was adjacent to the verb, the dependency relationship between them did not affect reading times since high dependency verbs were read at a similar pace to low dependency verbs (see Figure 1). However, when the particle was shifted away from the verb, there was a significant effect of Dependency on reading times, F(2,188) = 7.62, $p<0.0006$, with reading times increasing as the semantic dependency relationship between the verb and particle increased (*e.g.*, from '*finish the meal up*' to '*look the number up*' to '*chew the students out*' (see Figure 1)).

Thus, the dependency relationship played a significant role in processing speed, with high dependency verb-particles more difficult to process than low dependency particles, but only when the particle was shifted away from the verb. Sentences with high dependency verb-particles were more difficult to process when the particle was shifted because for these sentences, the particle was necessary for the correct interpretation of the verb. Since the particle was not read until the end of the sentence, the reader had to maintain both the content of the intervening direct object NP and the unresolved verb in memory over the entire sentence.

In addition, when the particle was shifted, there was a significant interaction between Dependency and NP Length, F(4,376) = 4.7, $p<0.001$, with the slowest reading times for sentences with highly dependent verb-particles and long intervening NP's (see Figure 2). Thus, it was harder to read and integrate the direct object NP when semantically dependent verbs and particles were separated, especially when the intervening NP was long (since the content of the long direct object NP must be integrated while also storing the unresolved verb-particle relationship in memory).

Consistent with my first hypothesis, these results suggest that processing is facilitated by sentences that decreased the amount of information that must be stored in WM, with those that minimized the semantic domain (keeping semantically dependent verbs and particles adjacent to one another) resulting in the fastest reading times overall, even at the expense of increasing the syntactic recognition domain. On the other hand, sentences which minimized the syntactic domain (shifting the particle to the end of the sentence) resulted in the slowest reading times, especially when a long NP intervened between a highly dependent verb and particle, suggesting that this sentence type most drastically increases WM load.

Particle Reading Times

The second region of interest was over the particle itself since WM load and particle reading times should be affected by the adjacency of the particle to the verb, the dependency relationship of the particle and verb, and the distance between the verb and particle when they are separated by direct object NP's of varying lengths. To assess these effects, mean reading times for the particle were entered into an ANOVA with the within subjects factors of Adjacency (adjacent, shifted), Dependency (low, middle, high), and NP Length (short, medium, long).

The overall interaction between the three linguistic variables (Adjacency, Dependency, and NP Length) was significant in the analysis by participant, F (4,316) = 3.98, $p < 0.003$, with reading times generally increasing as Dependency and Length increased, especially when the particle was shifted away from the verb (see Table 3 for cell means).

There was also a significant interaction between Dependency and Adjacency, F (2,158) = 3.41, $p < 0.035$, with reading times slowing as Dependency increased, but only in the shifted condition (see Figure 3). As predicted, this demonstrates that the dependency relationship between the verb and particle only has a strong effect on reading times when the particle is shifted away from the verb.

These results confirmed my hypothesis that processing difficulty would be affected by the adjacency of the verb and particle, with the fastest reading times occurring when the verb and particle were adjacent. Overall, adjacency tended to decrease WM load since the semantic relationship between the verb and particle was resolved before reading the direct object NP. On the other hand, there were increased reading times and WM load when the particle was shifted away from the verb, especially for sentences with long NP's and high dependency verb-particles since for these sentences, the semantic information from the unresolved dependent verb had to be maintained in WM for a longer period of time while the long direct object NP was processed.

However, as predicted, reading times on the particle were not always slower when the particle was shifted away from the verb. Faster reading times occurred on the shifted particle when dependency was low and the intervening NP was short (see Figure 4). This suggests that participants benefit from minimizing the syntactic domain (i.e., shifting the particle), but only when all other factors reduce WM load, that is, when the intervening NP is short and the dependency relationship between the verb and particle is lowest.

Overall, the results over both regions of interest confirmed my first hypothesis that particle placement affects processing difficulty, with increased reading times for sentences in which the particle is shifted to the end of the sentence. This was especially true when the verb was heavily dependent on the particle for its complete meaning and a long direct object NP intervened since these sentences increase the duration over which the semantic relationship between the verb and particle must be stored in WM. These analyses, however, did not distinguish how individuals with different WM ability process these sentences that vary in WM load. This question is investigated in the following section.

Working Memory Measures

Reading Span

Scoring. Scores on the reading span task were based on the maximum number of sentences for which the participant correctly recalled all of the final words in each sentence. Sentences were divided into sets corresponding to levels, with different numbers of sentences in the sets at each level (see Appendix C for a sample reading span sheet). There were three sets of two sentences each at level two, three sets of three sentences each at level three, and so on up to six levels. The level for which the participant recalled all of the sentence-final words in each of the three sets correctly was the participant's reading span score, with possible reading spans ranging from a score of 1 to 6. For example, if a participant correctly recalled the final words for both sentences in all three sets at level two, but made errors on all the sentences in level three, the participant's reading span score would be two. If the participant correctly recalled the final words of only one or two of the three sets in a level an intermediate score was assigned. For example, if a participant correctly recalled all three sets at the two sentence level, and none at the three sentence level, their reading span would be a 2. However, if the participant successfully recalled one of the sets at the three sentence level, the score would be 2.33; two correct sets at this level would be assigned a score of 2.66.

Results. The range of reading spans scores was from 1.33 (one set of two sentences successfully recalled) to 5.33 (all three sets of fives sentences and one set of six sentences recalled successfully). The full distribution of scores is reported in Table 4.

Digit-Letter Sequencing Task

Scoring. Participants were assigned one point for every trial for which they gave a correct response. Correct responses consisted of those for which the participant recalled all of the numbers and letters for the trial in the correct numerical and alphabetical order. Responses were not given credit if a number or letter was missing or if any item was out of order. For example, if the experimenter said "5 P 7 2 A," "2 5 7 A P" was the only response that would receive a point. This scoring allows for a fine-grained range of scores, since scores are given for every item, giving credit for partially completed levels.

Results. The scores on this task ranged from 7 to 19, with a mean score of 12.6. The full distribution of scores is listed in Table 4.

Working Memory Groups

The reading span and digit-letter sequencing tasks were chosen as working memory measures specifically because they both measure working memory skills which are integral to sentence comprehension (Daneman & Merkle, 1996). They differ such that the reading span task requires processing and storage of whole sentences, a skill which is reliant on language processing ability as well as more traditional working memory skill (basic storage and processing), while the digit-letter sequencing task may reveal a general ability to process and store information relatively free of the language skill factor.

In this study, the correlation between scores on the two WM tasks was significant, r=.39, $p < 0.0001$. In fact, these scores correlated more highly then in previous research (e.g., r=.24, Turner & Engle, 1989), suggesting that the two tasks measure overlapping abilities, but also that there are differences in the skills the tasks assess.

Scores from each of the tasks correlated significantly with average reading time over the direct object NP on the self-paced reading task (reading span task, r= -.21, $p <$ 0.05; digit-letter sequencing, r=-0.22, $p < 0.05$). Thus, scores from each of the tasks predicted a similar amount of the variation in reading times (reading span, $R^2 = 0.047$, digit-letter sequencing, $R^2=0.049$). Regressions including scores from both tasks predicted the most variation in the data ($R^2=0.07$, $p < 0.03$). However, it made little difference which predictor was entered first into the regression analysis as each WM score predicted a similar amount of the variation prior to the addition of the second predictor (see above R^2's for each task) and accounted for similar amounts of additional variability when added to the model second (reading span only, $R^2 = 0.047$, addition of digit-letter sequencing, $R^2 = 0.07$; digit-letter sequencing only, $R^2=0.049$, addition of reading span, $R^2 = 0.07$).

To better assess the combined effect of both WM tasks on reading times in the self-paced reading task, I divided the participants into groups based on the median score for each of the tasks (2.33 for the reading span task and 12 for the digit span task). I then entered mean reading times per word for the direct object NP into an analysis of variance with the factors of Reading Span Score (above median, at or below median) and Digit-letter Sequencing Score (above median, at or below median). This resulted in four cells containing: 1) individuals who scored above the median on both of the tasks (N=26); 2) those above the median on the reading span task, but at or below the median on the digit-letter sequencing task (N=19); 3) those at or below the median on the reading span task, but above the median on the digit-letter sequencing task (N=19); and 4) those at or below the median on both tasks (N=34).

There was a significant main effect of Digit-Letter Sequencing Score, F(1, 94) = 6.1, $p < 0.02$, with slower reading times for those who scored at or below the median on this task than those who scored above (342 msec versus 312 msec). The main effect of Reading Span Score was moderate, F(1, 94)= 2.6, $p < 0.10$, with slower reading times for those who scored at or below the median on this task than those who scored above (337 msec versus 317 msec). The interaction between Reading Span Score and Digit-Letter Sequencing Score was not significant (F < 1), as reading times increased comparably for those who scored at or below the median on the digit span task across both levels of Reading Span Score (see Table 5). However, those who scored above the median on both WM tasks had the fastest reading times (305 msec), while those who scored below the median on both tasks had the slowest reading times (354). These reading times suggest that those who have more skill or experience with language (and thus better scores on the reading span task (MacDonald & Christiansen, 2002)), but also have better general storage and processing ability (as assessed by better scores on the digit-letter sequencing task) are most efficient at sentence comprehension. On the other hand, those who have less skill or experience with language and thus perform more poorly on the reading span task, and *also* show decreased ability to process and store information more generally on the digit-letter sequencing task need the most time to read the sentences in the self-paced reading task.

Reading times for the individuals who scored above the median on only one of the two tasks fall directly between the two extreme groups. Interestingly, individuals who scored above the median on the digit-span task, but at or below the median on the reading span task had slightly faster reading times than those who scored better on reading span task only. This suggests that better performance on the assessment of more general storage and processing ability resulted in faster reading times than better performance on the more language-specific WM task. However, this difference was only 10 msec, and thus is probably not meaningful.

Given the small difference between these intermediate groups, as well as, the relatively low number of individuals in these groups, I chose to include only the participants in the extreme groups in the following analyses which investigate how WM ability affects reading times for sentences that vary in verb-particle adjacency, dependency, and NP length. Therefore, in the subsequent analyses, the 'low WM group' consisted of 34 individuals who scored at or below the median on both WM tasks (i.e., 2.33 and below on the reading span task, but also 12 and below on the digit-letter sequencing task). The 'high WM group' included 26 individuals who scored above the median on both WM tasks (i.e., 2.66 and above on the reading span task, but also 13 and above on the digit-letter sequencing task). Therefore, the following analyses for the self-paced reading task only include the data for the 60 participants included in the low and high working memory groups.

Self-Paced Reading and Working Memory Groups

WM Group Differences Across the Sentence

The word by word reading times across the entire sentence reveal a marked difference in reading times for the low and high working memory groups, with the high WM group reading the sentences faster than the low WM group across all conditions (see Figures 5a-f). This overall reading time difference between the two WM groups over the two regions of interest will be discussed in detail in the sections below.

Direct Object Noun Phrase

To assess how the syntactic and semantic manipulations affected reading times for individuals with varied WM ability, the mean reading times per word for the direct object NP region of interest were entered into a mixed model ANOVA with the within subjects factors of Adjacency (adjacent, shifted), Dependency (low, middle, high), NP Length (short, medium, long) and the between subjects factor of WM group (low, high).

Overall WM Group Differences

Across the direct object noun phrase, the reading times for each WM group were significantly different, with the high WM group (301 msec) reading significantly faster than the low WM group (351 msec), F(1, 55) = 10.6, $p < 0.002$.

Examining Interactions between WM Group and Linguistic Effects

Surprisingly, there was no interaction between the WM groups and linguistic variables (F < 1). I expected an interaction between WM ability and the linguistic variables since I predicted that reading times would increase more drastically for those with low WM ability as the difficulty of the linguistic material increased (e.g., highly dependent verbs and particles were separated by long intervening NP's). Instead, reading times generally increased comparably for those in both WM groups as linguistic difficulty increased.

This absence of interaction is most likely due to an inability to create WM groups that differed sufficiently in WM ability. The range of WM ability in this population of college-age students is likely not broad enough to elicit drastically different reading times, even for the most difficult sentences. Compounding this problem was the fact that the distribution of reading span scores attained in this study was much narrower than that reported in other studies, with very few participants, just 4 out of 98 total, scoring above four, the typical cut off for high WM groups (c.f. Daneman & Carpenter, 1980; MacDonald, Just, & Carpenter, 1994; Caplan & Waters, 2002).

Therefore, while I created the most extreme groups possible (by including only those who scored above the mean on both tasks in the high WM group and those who scored at or below the mean on both tasks in the low WM group), and these groups differed significantly in overall reading times, it appears that this difference was not influenced further by increased sentence difficulty. Thus, both WM groups slowed comparably to compensate for the increase in processing load. This suggests that the processing load incurred for these sentences did not cause either group to reach their processing capacity, a factor which has been shown to cause further increases in reading times (Just & Carpenter, 1992).

Particle Reading Times

To assess the effects of adjacency of the particle to the verb, the dependency relationship of the particle and verb, and the distance between the verb and particle when they are separated by direct object NP's of varying lengths, mean reading times for the particle were entered into a mixed model ANOVA with the within subjects factors of Adjacency (adjacent, shifted), Dependency (low, middle, high), NP Length (short, medium, long) and the between subjects factor of WM Group (low, high).

Overall WM Group Differences

On the particle itself, there was a significant difference in mean reading time across the two WM groups, with the high WM group (297 msec) reading significantly faster than the low WM group (346 msec), $F(1, 47) = 11.3$, $p<0.002$.

WM Group Interactions with the Linguistic Variables

The results from particle reading times showed an interaction between the WM ability of the participant and the linguistic variables. On the particle, there was an interaction between WM group, Adjacency of the verb and particle, and Length of the direct object NP, F (2, 94) = 5.9, p<.004. For the low WM group, reading times on the particle increased as NP Length increased, especially when the longer NP's intervened between the verb and the shifted particle (see Figure 6a). In contrast, for the high WM group, reading times were actually faster on the shifted particle (289 msec) than on the adjacent particle (314 msec), but only when the intervening NP was short. However, as the length of the intervening NP increased, reading times slowed for the high WM group as well (see Figure 6b). This suggests that those in the high WM group benefit from the early recognition of the direct object NP, but that this benefit is carried over to a faster reading time on the shifted particle only when the direct object NP is short and processing load is low.

This interaction supports my hypothesis that WM ability affects reading times for sentences that vary in processing difficulty. Specifically, that the low WM group has slower reading times when the syntactic domain is minimized since these sentences tax WM load and are thus more difficult and take a longer time to process. On the other hand, reading times for those with high WM ability were not as affected by sentences that increased WM load and in fact, this group did show some benefit of syntactic minimization since they had both the language skill and processing ability to efficiently read these more complex sentences.

In addition, these particle reading times suggest that WM differences may not be realized until the particle is read and the whole meaning of the sentence is integrated. That is, the slowing that I expected for the low WM group may not occur until readers encounter the shifted particle, a point at which they must integrate all of the syntactic and semantic material from the sentence. Similarly, a slow-down for the high WM group occurred only when the particle was shifted and the longest NP's intervened, suggesting that readers with high WM ability are not affected by processing load increases until they read the most difficult sentences.

Overview of Results

Effects of the Linguistic Variables

Across the direct object NP and particle regions of interest there was a significant interaction between the three linguistic variables, however, it was only when the particle was shifted away from the verb that dependency and NP length significantly influenced reading times. When the particle was shifted, reading times increased as dependency increased, with further slowing as longer NP's intervened between the verb and particle.

These results confirmed that particle placement affects processing difficulty, with sentences that minimize the syntactic domain (i.e., a shifted particle) having the greatest effect on reading times. One explanation of this is that these sentences tend to increase the duration over which the unresolved verb-particle must be stored in WM, while also integrating the direct object NP. Thus these sentences most likely tax WM load more than those with an adjacent verb and particle. Thus, when sentences were least demanding (i.e., when the direct object NP was short and the dependency relationship between verb and particle was low), there was a benefit to shifting the particle and realizing all of the elements of the sentence earlier. This suggests that the benefit of semantic or syntactic minimization depends highly on the WM load incurred from the word order of the sentence as well as the strength of the semantic dependency relationships across related items.

Overall WM Group Differences

Reading times across all conditions revealed a marked difference between the low and high working memory groups, with the high WM group consistently reading faster than the low WM group on both regions of interest, the direct object noun phrase and the verb-particle itself. This confirmed my second hypothesis that WM ability would affect reading times and supported the notion that better performance on both the reading span and digit-letter sequencing tasks results in the most efficient processing since these individuals not only have the increased ability to process and store information in general, but also have a particular skill with language.

WM Group Interactions with the Linguistic Variables

Over the direct object NP, there were no interactions between the WM groups and linguistic variables. This suggests that the range of WM ability for these participants was not broad enough to elicit drastically different reading time patterns across the two WM groups at this region of the sentence.

In fact, there were not clear interactions between the linguistic variables and WM groups until readers encountered the particle. Thus, WM differences may not be realized until the particle is read and the whole meaning of the sentence is integrated. For the low WM group, there was an increase in reading times as length and dependency increased, especially when the particle was shifted away from the verb. In contrast, the high WM group actually read the particle faster in the shifted position, but only when the direct object NP was short.

Discussion

Particle Position and Processing Difficulty

Hawkins (1994, 2004) suggested that sentences which minimize the syntactic and semantic domains are processed more efficiently because they reduce processing effort, increase speed of understanding, or minimize ambiguity. However, in sentences with verb-particle constructions, particle position determines whether the syntactic or semantic domain is minimized (Hawkins, 2004; Lohse et al., 2004; Gonnerman & Hayes, 2005). In addition, particle position affects the amount of information that must be stored and processed across the sentence, thus affecting WM load, a factor that has been shown to affect processing difficulty (Gibson, 1998, 2000).

In this study, sentences which minimized the syntactic domain (i.e., shifted the particle) resulted in slower reading times. I suggested that this increase in reading times was due to an increase in WM load since, for these sentences, the semantic information from the dependency relationship between the verb and particle had to be stored while also integrating the content of the direct object NP. This suggests that, overall, processing is not facilitated by syntactic minimization, but semantic minimization, for which the verb and particle are *adjacent*. However, when the semantic dependency relationship between the verb and particle was low, there was a benefit to syntactic minimization. In this case, readers were able to recognize all of the sentence elements earlier, but were not hindered by keeping a highly dependent verb-particle relationship in memory over the entire sentence. Therefore, these results suggest that for sentences in which both the syntactic and semantic domains cannot be minimized concurrently, processing efficiency, and thus reading times, were determined by the *relative* strength of the semantic and syntactic factors in the sentence. This is consistent with Hawkins' (1994, 2004) notion that the overall size of the syntactic and semantic domains in a sentence determine processing difficulty, however, these results clarify that when these factors act in opposition, comprehenders benefit from the domain which most facilitates processing.

The Role of Working Memory on Processing Efficiency

The results from this study showed that individuals who scored better on both tests of WM ability read consistently faster than those who scored more poorly on both WM tasks. These results support the notion that those who have more skill or experience with language (and thus better scores on the reading span task (MacDonald &

Christiansen, 2002)) read sentences more efficiently. However, they also illustrate that general storage and processing ability (as assessed by the digit-letter sequencing task) also plays an important role in determining overall reading speed, as individuals who scored high on the reading span task, but low on the digit-letter sequencing task read slower than the individuals who scored well on both tasks. These results support the notion that overall reading efficiency is not only influenced by language skill, but also general storage and processing ability, and that the combination of these two capabilities results in the most efficient language comprehension.

Results from this study also demonstrated that WM ability can mediate the relative weightings of the syntactic and semantic domains on processing. When WM ability was low, there was a tendency to read sentences faster when the verb and particle were adjacent, minimizing the semantic domain. This suggests that if the reader has low WM ability, processing is facilitated by understanding the complete meaning of the verb and particle before moving onto the direct object NP. This is especially true when the verb and particle are highly dependent on each other for their meaning or when the sentence contains a long direct object NP. If the particle is shifted in these conditions, the reader has to store the unresolved semantic dependency relationship in memory while integrating the long direct object NP, thus increasing reading times and WM load across the sentence.

Participants with high WM also benefited from the minimization of the semantic domain, especially when the direct object NP was long and the dependency relationship was high. However, there were times when those with high WM ability displayed reading times opposing this trend, such that they read *faster* when the particle was shifted away from the verb, minimizing the *syntactic* domain. Thus, there was a processing benefit to shifting the particle, but only when the verb and particle were not highly dependent and the intervening NP was short, and only for readers with high working memory. This result indicates that the processing load for these sentences is mediated by these individuals' increased storage and processing ability, as well as increased skill with language (MacDonald & Christiansen, 2002), thus reducing the effect of particle shifting, and allowing them to benefit from the earlier recognition of the direct object NP.

These results suggest that while Hawkins' (1994, 2004) theory explains linguistic efficiency, overall processing difficulty cannot be determined without also examining the cognitive ability of the individual since this can mediate how much one can benefit from syntactic and semantic minimization, especially when they act in opposition.

Conclusions for Study 1

As predicted, the results from this study indicated that the various syntactic and semantic factors interacted to determine overall processing difficulty. Additionally, they also showed that WM ability also influenced overall reading times. However, contrary to predictions, there were few interactions between WM ability and the syntactic and semantic variables, with reading times, in general, increasing comparably for both WM groups as sentence difficulty increased. As stated earlier, I suspect that this is due to the distribution of WM ability in this population, such that neither the low or high WM groups was additionally affected by the more demanding sentences. Therefore, in the next study, relative clauses of varying complexity, but constant length, are used as the direct object NP's. I expect that these sentences will be more difficult to process than those used in Study 1, thus they may better demonstrate how more structurally difficult material influences reading times for individuals who vary in WM ability. Thus, in the following study, I expect an interaction between the WM ability and linguistic complexity such that reading times will increase more drastically for the low WM group than for the high WM group as difficulty of the sentences increases.

STUDY 2: WORKING MEMORY AND NP COMPLEXITY

Hawkins' (1994, 2004) notion of processing difficulty relies on the overall size of the syntactic and semantic domains of a sentence. The size of these domains, and thus processing difficulty, is determined by the *distance* between semantically related items and the *number of words* it takes to recognize all of the elements of a sentence. In verb-particle constructions, the size of these domains is affected by the length of the direct object NP since it can intervene between the semantically related verb and particle, affecting the distance between them. The length of the direct object NP also influences the effect of word order on processing, with facilitation when the verb and particle are adjacent, even though this increases the number of words it takes to recognize all phrasal elements.

Other theorists have suggested that while the length of the direct object does play a role in processing efficiency, the complexity of the direct object NP may also affect performance (Fraser, 1976; Gries, 2003). For example, sentence (8) is noticeably harder to process than (7):

(7) The student *worked* almost all of the extremely difficult math problems *out.*

(8) The student *worked* the example which he recognized *out.*

even though eight words intervene between the verb and particle in sentence (7), as compared to five in (8). This discrepancy occurs because sentence (8) contains a relative clause, a phrase which is structurally more complex than NP in sentence (7).

Gibson (1998, 2000) has shown that as relative clauses increase in complexity, they also increase the amount of structural information that the comprehender must store and process in working memory, affecting WM load and processing difficulty. Thus, increasing NP complexity should tax working memory, especially in low-span participants, since reading more complex relative clauses requires the processing of more complex structural information.

Relative clauses have not only been shown to differ in linguistic complexity, but also in prevalence across and within languages of the world and in their impact on processing ease for individual speakers (c.f. Hawkins, 2004; Keenan & Comrie, 1977; Keenan and Hawkins, 1987). Keenan and Comrie (1977) illustrated the relationship between the linguistic complexity of different types of relative clauses and their prevalence across languages of the world in their Accessibility Hierarchy. The hierarchy is illustrated below, with structural complexity increasing from left to right and prevalence across languages decreases with increasing complexity.

(9) Subject > Direct Object > Indirect Object > Oblique > Genitive

Keenan and Hawkins (1987) conducted a repetition experiment designed to test whether structures considered linguistically more complex were actually more difficult for individuals to process. They showed that repetition accuracy of relative clauses correlated with their position of the Accessibility Hierarchy, with subject relatives (least complex, most common) repeated more accurately than object relatives or other less common and more complex relatives. Thus, examining complexity through the use of relative clauses may not only provide insight into the linguistic factors that affect processing difficulty, but also how WM ability affects reading times for phrases that vary in frequency.

MacDonald and Christiansen (2002) propose that increased experience with language affects processing skill and thus WM ability. They claim that increased experience with language through reading results in more frequent exposure to a variety of linguistic structures. This increase in frequency of exposure not only allows the more avid reader to process information more rapidly, thereby affecting the amount of information they can process in a given amount of time, but increases the frequency with which they encounter less common phrases. This increased experience with uncommon phrases, can explain why people who score well on the reading span task, which MacDonald and Christiansen claim is an assessment of language skill, also read more complex sentences faster than individuals who do not score well on the reading span task

(King & Just, 1991). Presumably high reading span individuals have decreased difficulty with the less frequent and more complex sentence because they have encountered them more often, resulting in more efficient processing of these structures.

In this study, I have two specific hypotheses about how the complexity of the direct object NP will affects processing difficulty. First, I predict that the complexity of the direct object NP will affect processing, with increased reading times for sentences containing more complex relatives since relative clauses of varied complexity have been shown to affect WM load (Gibson, 2000). Importantly, I expect that this will occur even when the length of the intervening NP is held constant (i.e., the overall *size* of the syntactic and semantic domains remains the same), indicating that it is not only the number of words that affects processing difficulty, but also the structural complexity of the phrase. Second, I predict that the WM ability of individuals will affect processing, with increased reading times for those with lower WM ability, especially for the less frequent, and more complex relatives. However, I also expect that participants with higher WM ability will not be as affected by the more demanding sentences as they not only have better storage and processing ability, which should facilitate reading times for these more complex sentences, but also more experience with language, a factor which should mediate understanding of the less frequent relatives.

Method

Participants

99 Lehigh undergraduates (56 women and 43 men) between the ages of 18 and 22 participated for course credit. All were monolingual speakers of Standard American English.

Self-Paced Reading task

Materials

The same materials were used for this study as those in Study 1 with the exception of the direct object NP content. In this study, for each of the 78 verb-particle constructions, four direct object NPs, varying in complexity, were created. Different types of sentences contained either no relative clause or a relative clause of increasing complexity (subject, object, or genitive). Thus, the complexity variable consisted of four phrases of the same length (5 words): no relative clause (e.g., *the class of disruptive students*); subject relative (e.g., *the class who always cheated*); object relative (e.g., *the class that teachers hated*); and genitive relative (e.g., *the class whose teacher fainted*). Again the adjacency and dependency variables remained the same as experiment 1, with 8 sentences created for each verb-particle, reflecting the 4 levels of NP complexity and 2 levels of adjacency.

These sentences were divided into eight lists, such that each list contained only one sentence form for each verb particle construction; each participant read one version of a sentence containing each verb and particle (see Table 6 for a sample set of sentences).

Procedure

The methods used in this experiment were the same as those used for the self-paced reading task in Study 1.

Working Memory Assessment

The materials and procedures for the working memory assessment were the same as those used in Study 1.

Results

Of the 99 participants tested, 4 were removed from all subsequent analyses due to error rates above 25% on the comprehension questions from the self-paced reading task. Therefore, the following analyses are based on data from the remaining 95 participants.

Self-Paced Reading Results

Mean reading times per word were calculated for sentences in each condition. Reading times were then trimmed by removing any reading time that was more than two standard deviations above or below the mean. This excluded 9.9% of the original data.

Effect of NP Complexity

I predicted that the complexity of the direct object NP would affect processing, with increased reading times for more complex relatives, especially when it intervened between a verb and particle, even when length was held constant. To assess the role of these factors, I entered reading times for the two regions of interest discussed in Study 1, namely the direct object NP and verb-particle, into an analysis of variance with the within subjects factors of NP Complexity (no relative clause, subject relative, object relative, genitive relative), Adjacency (adjacent, shifted), and Dependency (low, middle, high).

There was a significant interaction between Dependency, Adjacency, and NP Complexity, F1(6,564)=5.3, for the direct object NP and F1(6, 564) = 2.2 for the particle, $p<0.05$. As in Study 1, the three-way interaction over items was not significant, F2 = 1.1, for the direct object NP; F2=0.6, for the particle region of interest. However, contrary to the results from Study 1, effects which did not include Dependency were significant (see results below) indicating that only the analyses including this between-items variable were weaker (see Study 1 for a discussion of this effect). In addition, reading time patterns across Dependency were not as variable as in Study 1 (e.g., over half of the items showed reading time patterns across NP Complexity that were consistent with the trend of the overall effect pattern). I suggest that this increase in consistency resulted from the increased difficulty of the stimuli in this study, since across most items, sentences with the most difficult relative clauses took longer to process. Therefore, for this study, I will include the analyses by items since they confirm the effects by participants, especially when the analyses did not include Dependency.

Reading time patterns for the overall three-way interaction on both regions of interest showed that when the particle was adjacent, there was little effect of Dependency or NP Complexity on reading times (see Tables 7a and 7b). However, when the particle was shifted, reading times increased as NP Complexity increased. In addition, Dependency exerted its strongest influence on reading times when the complexity of the relative clauses was low (*i.e.*, no relative and subject relatives) and the particle was shifted. However, for the most complex genitive relatives reading times were slow regardless of Dependency (see Figure 7 for an illustration of the influence of Dependency and NP Complexity on the shifted particle). These results indicated a slow-down when any direct object NP occurred between the most dependent verbs and particles indicating that for any of these sentences, separating the most dependent verbs and particles negatively affected processing.

As expected, across the variables of Dependency and Adjacency, there was a main effect of NP Complexity by participants over both regions of interest: direct object NP, F1(3, 282)=5.8, $p < 0.007$, F2 (3, 207)=2.4, $p<0.05$; and particle, F1(3,282)=3.5, $p < 0.01$, F2 (3, 207)=3.4, $p<0.05$. Over the direct object NP, the reading times were similarly faster for the phrases containing no relative and subject relatives, and slower for those with object and genitive relatives (see Table 8). Over the particle, there was a more gradual increase in reading times, with increased reading times as the complexity of the phrase increased. This trend was significant, t=2.02, $p < 0.05$, with reading times increasing linearly as NP Complexity increased; from sentences with no relative clause, to those with subject relatives, to object relatives, and finally genitive relatives (see Table 8). This suggests that while reading the direct object NP itself, the phrases with no relative and subject relative are similarly easier to process, while those with object and genitive relatives are similarly harder to process. Reading times on the particle suggest that relative clauses which have been shown to be more difficult to process result in gradually slower reading times (Keenan & Hawkins, 1987).

However, this effect was driven by the interaction between Adjacency and Complexity, with increasing reading times over both regions of interest when the particle was shifted: F1(3, 282)=12.2, $p < 0.0001$; F2(3, 207)=6.0, $p < 0.0006$, for the direct object NP and F1(3, 282)=6.9, $p<0.0002$; F2(3, 207)=5.9, $p<0.0006$, for the particle. (see Table 9). This result is intuitive, since placing a more complex direct object NP between a verb and particle should increase processing difficulty on the particle. In these cases, the reader must store and integrate not only the dependency relationship, but also the complex NP. In contrast, when the particle is adjacent to the verb, the complete meaning of the verb and particle is understood before encountering the complex direct object NP, reducing the processing load of the sentence which should facilitate processing of the direct object NP.

The results from this analysis confirmed my hypothesis that the complexity of the direct object NP affects processing, with increased reading times for sentences containing more complex relatives. This supports the view that that it is not only the number of words that affects processing difficulty, but also the structural complexity of the phrase (Gibson, 2000), indicating that the processing load incurred by reading a more complex relative clause is greater than reading a less complex clause, even if the phrase remains the same length. Therefore, both Hawkins (1994, 2004) concept of phrase length and

Gibson's (2000) notion of complexity must be assessed to determine the processing difficulty of a sentence.

Additionally, these results demonstrated that the frequency of structures affects processing difficulty, supporting the findings of Keenan and Hawkins (1987) with the most common subject relatives processed more easily than less common object relatives when are in turn processed faster than the least common genitive relatives. This confirms the importance of frequency on processing load suggested by MacDonald and Christiansen (2002) since, on their account, the frequency of a particular relative clause increases the exposure that one has with that structure, thus facilitating processing of that phrase.

Taken together, these results suggest that processing ease is affected by factors other than the size or distance of the domain, namely the structural complexity and frequency of the linguistic material. In the following analyses, the role of individual differences in linguistic experience and skill is examined to determine how the structural complexity and frequency of the direct object NP affects processing in individuals with differing WM ability even when the overall size of the syntactic and semantic domains remains the same.

Working Memory Measures

Reading Span

Scoring. Scores on the reading span task were based on the same criteria as those used in Study 1, that is, the maximum number of sentences for which the participant correctly recalled all of the final words in each sentence.

Results. The range of reading spans scores was from 1.33 (one set of two sentences successfully recalled) to 5.33 (all three sets of fives sentences and one set of six sentences recalled successfully). The full distribution of scores is reported in Table 10.

Digit-Letter Sequencing Task

Scoring. Scores on the digit-letter sequencing task were based on the same criteria as those used in Study 1 with participants were assigned one point for every trial for which they gave a correct response.

Results. The scores on this task ranged from 7 to 20, with a mean score of 13.2. The full distribution of scores is listed in Table 10.

Working Memory Groups

As in Study 1, the correlation between scores on the two WM tasks was significant, r=.34, $p < 0.0008$, indicating that the reading span and digit-letter sequencing tasks measure overlapping, yet somewhat different, working memory skills. Since the reading span task requires processing and storage of whole sentences, it most likely taps a skill which is reliant on language processing ability as well as more traditional working memory skill (basic storage and processing), while the digit-letter sequencing task may reveal a general ability to process and store information.

In addition, scores from each of the tasks were correlated with average reading time over the direct object NP region of interest on the self-paced reading task (reading span, $r = -.27, p < 0.05$; digit-letter sequencing, $r = -0.34, p < 0.05$). Thus, scores from each of the WM tasks accounted for a similar amount of the variation in reading times (reading span, $R^2 = 0.07$; digit-letter sequencing, $R^2 = 0.11$), although it appeared that performance on the digit-letter sequencing task accounted for slightly more of the variation. In fact when reading span score and then digit span score were entered consecutively into a regression model, the value of R^2 increased from 0.07 for reading span only to 0.13 when digit-letter sequencing was added to the model. Additionally, when reading span was added to the model second, it did not cause the same increase in the amount of variation accounted for (R^2 increased from 0.11 for digit-letter sequencing only to 0.13 when reading span was added to the model). These regression models suggest that, in this study, performance on the digit-letter sequencing task seems to be a better predictor of reading times on the self-paced reading task, although scores from the reading span task did account for some of the variation in reading times.

Therefore, to more closely assess how performance on each of the working memory tasks affected reading times on the self-paced reading tasks, mean reading times over the direct object NP region of interest were entered into an analysis of variance with the factors of Reading Span Score (above the median (a score of 3 or above), at or below the median (2.66 and below)) and Digit-Letter Sequencing Score (above the median (a score of 13 or above), at or below the median (12 and below)). These divisions resulted in four cells containing: 1) individuals who scored above the median on both of the tasks (N=26); 2) those above the median on the reading span task, but at or below the median on the digit-letter sequencing task (N=11); 3) those at or below the median on the reading span task, but above the median on the digit-letter sequencing task (N=32); and 4) those at or below the median on both tasks (N=26).

There was a significant interaction between Reading Span Score and Digit-Letter Sequencing Score, F(1, 91) = 4.6, $p < 0.04$. The reading time patterns indicate that for those who scored at or below the mean on the reading span task, there was little influence of Digit-Letter Sequencing Score on reading times (see Table 11). However, for those who scored above the mean on the reading span task, reading times were faster for those who also scored well on the digit-letter sequencing task compared to those who scored at or below the mean on that task (see Table 11). These results indicate that, reading times are only faster for those who score well on both assessments of WM. For this study, this result makes sense, as the sentences are more difficult than those used in Study 1. Therefore, only individuals who have increased language processing ability (though exposure to the more difficult structures) *and also* have better storage and processing ability in general read the sentences more efficiently.

Interestingly, those who had lower scores on both tasks did not appear to, on average, read slower than those who scored well on only one of the WM tasks. This result was surprising, as I expected participants with lower scores on both tasks to demonstrate the slowest reading times overall. Therefore, although for this study there was not a combination of WM scores that resulted in a group with the slowest reading times, as in Study 1, I chose the individuals who scored lower on both WM tasks as the 'low WM group' and individuals who scored higher on both WM tasks as the 'high WM group' for the analysis comparing the effect of WM ability on reading times for sentences that varied in verb-particle adjacency, dependency, and NP complexity. Therefore, the following analyses for the self-paced reading task only include the data for the 52 participants included in the low and high working memory groups. That is, the 26 individuals who scored above the mean on both WM tasks (3 and above on the reading span task, but also 13 and above on the digit-letter sequencing task) and the 26 individuals who scored at or below the mean on both WM tasks (2.66 and below on the reading span task, but also 12 and below on the digit-letter sequencing task).

Effect of WM and NP Complexity on Reading Times

I predicted that the WM ability of individuals would affect processing, with better performance for those with high WM for the less frequent, and more complex relatives since these individuals not only have increased storage and processing ability, but also more skill with language, a factor which should mediate understanding of the less frequent relatives. In fact, the word by word reading times across the entire sentence reveal a marked difference in reading times for the low and high working memory groups, with the high WM group reading the sentences faster than the low WM group across all conditions (see Figures 8a-8h). This overall reading time difference between the two WM groups over the two regions of interest will be discussed in detail in the sections below.

To assess the effect of WM ability on the processing of sentences that vary in complexity, I entered mean reading times for both regions of interest into an analysis of variance with the within subjects factors of NP Complexity (no relative clause, subject relative, object relative, genitive relative), Adjacency (adjacent, shifted), and Dependency (low, middle, high) and the between subjects factor or WM Group (low, high).

Overall WM Group Differences

Across both regions of interest, the reading times for each WM group were significantly different: $F(1, 50) = 12.1$, $p < 0.001$, for the direct object NP; $F(1,50)=11.8$, $p < 0.001$, for the particle, with the high WM group reading significantly faster than the low WM group (342 versus 411 msec for the direct object NP and 343 versus 395 msec for the particle).

Direct Object NP Region of Interest

As was found in Study 1, there were no interactions between WM group and any of the linguistic variables over the direct object NP region of interest. This indicated that, although there was a main effect of WM group across the linguistic variables, contrary to predictions, the low WM group was not more affected by the linguistic manipulations. Thus, they did not incur a further slow-down in reading times for the most difficult sentences. I had expected that the increased complexity of the sentences in Study 2 would elicit a greater increase in reading times for the low WM group compared to the high WM group since I expected that these sentences would cause the low WM group to reach their processing capacity. However, as in Study 1, this was not the case, suggesting that for this population of college-age students, there is not a sufficient difference in overall processing ability to obtain an interaction between WM ability and the linguistic manipulations. Therefore, while the differences in WM ability, as assessed by both the reading span and digit-letter sequencing tasks indicated an overall difference in reading speed, this difference did not increase for the more demanding sentences, indicating that neither group reached their processing capacity, a factor which should cause further increases in reading times (Just & Carpenter, 1992).

Particle Region of Interest

Over the particle region of interest, there was one significant interaction between the WM groups and the linguistic variables, with the interaction of WM Group and Adjacency significantly affecting reading times, F(1, 50)=5.4, $p<0.03$. However, the reading time patterns were not expected, with faster reading times on the shifted particle (386 msec) than the adjacent (402 msec) for the low WM group, but slower times on the shifted particle (347 msec) than the adjacent (339 msec) for the high WM group. If anything, I had expected that the high WM group would have faster times on the shifted particle since they have shown more language skill than those in the low WM group, and should be able to use previous sentence material to predict the coming particle. However, upon closer examination of the reading times, it is clear that the reason for the low WM group having faster reading times on the shifted particle is due to exceptionally slow reading times on the *adjacent* particle, especially when the sentences contained subject relatives (419 msec for subject relatives versus 396 msec for no relatives, 397 msec for object relatives, and 397 msec for genitive relatives). The reason for these slow reading times is unclear, therefore, I do not feel that I can conclude anything concrete about the overall effect.

Thus, once again, there do not seem to be any meaningful interactions between WM group and the linguistic variables. As I explained for the direct object NP region of interest, this absence of any interaction is most likely due to a lack of range in WM ability within this population.

Discussion

Effect of NP Complexity

Results over both regions of interest demonstrate that the structural complexity of the direct object NP affects processing difficulty, even when the length of the phrase was held constant, with slower reading times as the complexity of the phrase increased (from no relative, to subject, object, and finally genitive relatives), especially when the more complex relatives intervened between the verb and particle. Additionally, results showed that the complexity of the intervening NP affected processing of the semantic dependency relationship between the verb and particle, with an increasing effect of dependency when the complexity of the NP was lower (no relative or subject relatives), but ceiling effects when a genitive relative intervened. Thus, reading a genitive relative makes the storage and processing of even the less difficult low dependency relationships harder, resulting in slower reading times for all dependency levels.

Thus, these results provided insight into the relative effect of length versus complexity on reading times. As predicted, when length was held constant, the processing of more complex NP's reflected the influence of additional content, not additional distance, on processing speed. Therefore, processing difficulty and working memory load not only result from having to integrate information over distance (i.e., the number of words (c.f. Hawkins (1994, 2004)), but from the amount of structural information contained in the sentence (Gibson, 2000). This suggests that processing ease may be affected by factors other than the size or distance of the domain, namely the structural complexity and frequency of the linguistic material.

Effect of WM Ability

Performance on the reading span and digit-letter sequencing tasks indicate that overall reading times are fastest for those who scored well on both assessments of WM. Individuals who had lower scores on both tasks did not appear to read slower than those who scored well on only one of the WM tasks. This result was surprising, as I expected participants with lower scores on both tasks to demonstrate the slowest reading times overall. However, given the more difficult sentences used in this study, I suggest that there could have been a ceiling effect on reading times, resulting in similarly slow reading times for individuals in all three of these groups. Therefore, only individuals who scored well on the reading span task and presumably had increased language skill (through exposure to the more difficult structures) *and also* scored well on the digit-letter sequencing task, and thus had better storage and processing ability in general, read the sentences more efficiently.

WM Ability and NP Complexity

Contrary to predictions, there were no interactions between WM group and any of the linguistic variables. I had expected that the increased difficulty of the sentences in this study would elicit a drastic increase in reading times for the low WM group. However, reading times for both WM groups increased comparably as sentence difficulty increased. Thus, the difficulty of these sentences affected each group similarly, as they both were able to process the more demanding sentences without a further slow-down from having reached their processing capacity.

Therefore, even though the low WM group did demonstrate lower scores on both the assessment of general storage and processing ability (digit-letter sequencing task) and language skill (reading span task), and the overall reading times between WM groups were significantly different (342 versus 411 msec for the direct object NP and 343 versus 395 msec for the particle), these differences did not cause increased reading times (compared to the high WM group) on the more demanding sentences. I suspect that the lack of such an effect indicates that the range of WM ability in this population is not broad enough to reflect WM capacity differences that would sufficiently cause increased reading times differences for the more difficult sentences. However, this effect could also indicate that WM ability does not have a significant influence on reading times for these linguistic manipulations.

Therefore, in Study 3, I examine a new population of older adults (age 65 or older), who have been shown to have both decreased WM ability (Norman et al, 1992; Waters & Caplan, 2005) and slowed processing speed (Salthouse, 1996) to determine whether the absence of interactions between WM groups and linguistic variables in Studies 1 and 2 are the result of the WM distribution in the younger population or if WM ability is simply not important for the linguistic manipulations made in these studies. I expect that the addition of this population will illustrate that WM ability does play an important role in determining reading times for the linguistic manipulations made in these studies as I predict that older adults with lower WM may be further affected by more difficult sentences than their high WM and younger age group counterparts.

STUDY 3: WORKING MEMORY, SENTENCE PROCESSING, AND AGING

Aging has been shown to have an effect on several aspects of language processing and WM ability, with older adults demonstrating slower reading and listening rates, reduced comprehension accuracy for speech and the written word, decreased use of contextual information in ambiguity resolution, and poorer scores on assessments of WM ability (Kemper, 1986; Stine-Morrow, Ryan, Leonard, 2000; Dagerman, MacDonald, & Harm, 2001; Norman et al, 1992; Waters & Caplan, 2005). For example, Kemper (1986) found that older adults were unable to correctly repeat sentences when they contained long constructions, while their younger counterparts could. Additionally, Waters and Kaplan (2005) have shown that older adults have longer listening times overall, while

Stine-Morrow et al (2000) demonstrated that it took older adults longer to read sentences which contained more complex relative clauses. Finally, both Norman et al (1992) and Waters and Caplan (2005) found that older adults scored significantly lower than younger adults on WM measures, including digit span and reading span tasks.

Several theorists argue that these age-related changes are due to reductions in WM capacity with age (Just & Carpenter, 1992; Waters & Caplan, 1996). On this view, these processing declines with aging are the result of a decrease in "computational workspace." This limits the amount of information that can be processed in a given amount of time which, in turn, both reduces WM task scores and limits the accuracy of sentence processing.

Conversely, MacDonald and Christiansen (2002) suggest that age-related differences in language processing are not due to a smaller working memory capacity or workspace per se, but suggest an alternative provided by Salthouse (1996) in which performance declines by older adults are the result of a general decrease in processing speed with age. This processing speed decline has been illustrated in many areas of cognitive functioning including: perceptual speed, reasoning, and spatial abilities (Salthouse, 1996). For example, older adults have been found to perform more poorly than young adults on several tasks, including the Digit Symbol Substitution task (Wechsler, 1981) in which older adults are slower to indicate if probe and target stimuli match or do not match.

Salthouse (1996) uses this decline in processing speed to explain the age-related differences found in both language processing and WM tasks. He suggests that processing speed affects performance on these tasks for two reasons: 1) because the relevant processes cannot be executed in a limited amount of time; and, 2) products of earlier processing may have decayed and are no longer available for integration with new information. Therefore, the rate at which information is understood limits the type and amount of information that can be processed at any given time, resulting in a more limited 'emerging capacity.'

However, according to MacDonald and Christiansen (2002), language processing ability is affected by more than processing speed. In their account, experience with language also plays a major role in determining performance on language processing tasks since exposure to language, mainly through reading, results in increased frequency with which an individual encounters a variety of linguistic structures. Increasing frequency of exposure facilitates processing because it reduces the effort associated with reading those structures. Thus, more avid readers are able to process linguistic information more efficiently than those who do not read as often. This more efficient processing increases the amount of information that can be understood in a given amount of time, resulting in increased processing capacity. Therefore, for MacDonald and Christiansen, an individual's linguistic working memory capacity is directly related to their language processing ability, which results from *both* experiential factors, such as reading skill and frequency, and biological constraints, such as decreased processing speed due to aging.

Consequently, when examining age-related differences in working memory and sentence processing ability, it is important not only to examine how cognitive slowing affects performance, but also how differential experience with language may mediate decreased processing speed. Therefore, while older adults may process information slower overall, their language processing ability should be mediated by their additional experience with language.

While we did not explicitly measure the factors of reading experience or processing speed per se, we did measure performance on the reading span task (Daneman & Carpenter, 1980), digit-letter sequencing task (Wechsler, 1997) , and a self-paced reading task (see the Materials section of Study 1 for a detailed description of these tasks). According to MacDonald and Christiansen (2002), increased performance on the reading span task indicates more experience with language since individuals who attain better scores process the sentences more efficiently, an ability that results from increased exposure to a variety of linguistic structures. This ability allows the more skilled individuals to focus on remembering the sentence final words, increasing the amount they can recall for this task. Therefore, I assume that better scores on the reading span task indicate that the individual is a more skilled reader based on increased experience with language.

In contrast, performance on the digit-letter sequencing task reflects a more general storage and processing ability, which is less influenced by language skill. Therefore, I assume that better scores on this task result from more efficient storage and integration of the stimuli since this reduces the amount of time over which the numbers and letters must be processed and stored, facilitating recall. However, I acknowledge that high scores on this task may also reflect other higher level differences in executive functioning, such as memory strategies, but these abilities are beyond the scope of the current study and therefore will not be discussed.

Finally, performance on the self-paced reading task should confirm both assumptions made about the underlying abilities reflected in the previous two tasks. Thus, reading times should indicate how efficiently individuals can process information, with faster reading times for those who have both increased general processing ability and more specific language processing skills (since according to MacDonald and Christiansen (2002), frequency of exposure to linguistic structures facilitates processing).

Importantly, language processing ability is also affected by the difficulty of the linguistic material (Hawkins, 1994, 2004; Gibson, 2000; Gonnerman & Hayes, 2005) with slower reading times as the difficulty of the sentences increases. This has been shown to be especially true for individuals with lower WM ability and for older adults (c.f., King & Just, 1991; Kemper et al, 1986; Stine-Morrow et al, 2000). However, in both Studies 1 and 2 reported here, there was little evidence that reading times increased more for individuals with low scores on the WM assessments, even for the more demanding particle-shifted sentences. Nonetheless, these sentences did cause the slowest reading times overall, thus, I concluded that particle-shifted sentences taxed WM load more than particle-adjacent sentences, especially when a long or complex direct object NP intervened between a highly dependent verb and particle. Thus, when the particle was shifted, both the semantic dependency relationship and content of the direct object NP had to be processed concurrently, increasing WM load.

However, since the WM groups were not differentially affected by the linguistic manipulations, I could not conclude that WM ability played an important role in determining reading times for sentences as they varied in linguistic processing constraints (although WM ability did play a role in determining *overall* reading times). Therefore, in this study, I examined a new group of older participants (age 65 or older) to determine how aging affects not only WM performance, but also reading times for these sentences that vary in linguistic processing constraints.

Effect of Aging on WM and Sentence Processing Ability: Hypotheses for Study 3

Based on the pervasive finding in the literature regarding general cognitive slowing with aging (c.f. Salthouse (1996) for a review of the effect of aging on processing speed), I predict that older adults should show slower reading times than their younger counterparts on the self-paced reading task and lower scores on the digit-letter sequencing task, but show preserved performance on the reading span task.

I predict an effect of age on reading times for the time-sensitive self-paced reading task, since I expect that cognitive slowing due to aging will drastically slow reading times for older adults. This should occur especially for sentences in which the particle is shifted since these sentences require concurrent storage and processing of both the semantic relationship between the verb and particle and the content of the direct object NP, thus increasing WM load.

I also expect that older adults will show decreased performance on the digit-sequencing task. As I discussed earlier, for tasks which are not assessments of language skill per se, like the digit-letter sequencing task, older adults should perform more poorly since they cannot utilize their language skill to mediate the effects of cognitive slowing. I expect that since performance on this task relies more on general processing ability, individuals who process the stimuli more slowly will have lower scores, as they must maintain the numbers and letters in working memory for a longer time.

Finally, I predict that older adults will not show such a decline on the reading span task since they can benefit from their additional experience with language to mediate slower sentence processing and, contrary to the more time-sensitive self-paced reading task, this experience should mask cognitive slowing.

Influence of Aging and WM ability on Reading Times

In this study, I expect an interaction between WM ability and age on reading times. I predict that younger adults who score well on both WM assessments should demonstrate the best language processing ability (i.e., fastest reading times on the self-paced reading task) since they not only have demonstrated language skill via high scores on the reading span task, but also are not hindered by decreased processing ability (as indicated by their scores on the digit-letter sequencing task). On the other hand, younger adults who score poorly on both tasks should process language less efficiently since they have demonstrated decreased language skill and general processing ability; however, I predict that they should still read faster than the older adults since they are not hindered by general cognitive slowing.

Therefore, while I expect that all older adults will show an overall increase in reading times due to aging, those who score poorly on both the reading span and digit-letter sequencing tasks should have the slowest reading times since their "emergent capacity" is reduced because they are limited by both decreased language skill and a decline in general processing ability, as indexed by their decreased performance on the two WM tasks. However, for older adults who score well on the WM assessments, reading times should be facilitated by their language skill and relatively better processing ability.

Finally, I predict an interaction between age and WM ability on reading times for sentences that vary in verb-particle adjacency, dependency, and NP length. In Study 1, I showed that for young adults these variables affected reading times (although not differently for the low and high WM groups), suggesting that while the different syntactic and semantic constraints influence reading times overall, they may not be influenced by WM ability. However, for this study, I predict an exaggerated slow-down on the more difficult, particle-shifted sentences for the older adults with low WM ability since these individuals are affected by both cognitive slowing and lower WM ability. Thus, their reading times should be even more affected since they have decreased ability to store and integrate the semantic dependency relationship between the verb and particle across the sentence, but also must do so over a longer period of time due to slower reading speed. Additionally, I expect that while the older adults in the high WM group will process sentences more slowly (than comparable young adults), they may show some beneficial effects of language skill and experience, with faster reading times when the particle is shifted, but only when dependency is low and the intervening NP is short. I expect that their skill with language and increased general processing ability will reduce their overall processing load, allowing them to benefit from factors such as the early recognition of sentence elements.

Method

Participants. 57 elderly adults (age 64-83) volunteered to participate in this experiment. Sixteen of the participants were female and forty-one were male. They were all Lehigh Alumni or their spouses. In addition, the data from the participants in Study 1 were used to compare performance between older and younger adults. Therefore, the participants for this study also included 111 Lehigh undergraduates (67 females and 44 males) between the ages of 18 and 22 who participated for course credit. All were monolingual native speakers of Standard American English.

Self-Paced Reading task

Materials. The materials and three independent variables were the same as those in Study 1, with three levels of verb-particle dependency (low, middle, and high), three levels of direct object NP length (short = 2 words, medium = three words, and long = 5 words) and two levels of adjacency (particle adjacent or particle shifted). For each of the 78 verb-particle constructions, 6 sentences were created, reflecting the three length possibilities (see Table 1 for a sample set of sentences). These sentences were divided into six lists, such that each list contained only one sentence form for each verb particle construction; thus, each participant read one version of a sentence containing each verb and particle.

Procedure. The procedure for the self-paced reading task was the same as in Study 1.

Working Memory Assessment

The same two tasks, reading span and digit-letter sequencing, were used in Study 3. All materials and procedures were the same as in Study 1.

Results

Of the total 168 participants tested, 18 (13 younger adults and 5 older adults) were removed from all subsequent analyses due to error rates above 25% on the comprehension questions from the self-paced reading task. Therefore, the following results are for the remaining 150 participants.

Effect of Age on Reading Times

Mean reading times per word were calculated for sentences in each condition. Reading times were trimmed by removing any reading time that was more than two standard deviations above or below the mean. This excluded 8.6% of the original data.

I predicted that age would have an effect on reading times with older adults reading more slowly than young adults, especially for particle-shifted sentences which require concurrent storage of the incomplete verb-particle dependency relationship and the semantic information from the intervening direct object NP. To determine if age does have such an effect, I entered reading times over both the direct object NP and particle regions of interest for both age groups into analyses of variance with the within subjects factors of Adjacency (adjacent, shifted), Dependency (low, middle, high), and NP Length (short, medium, long) and the between subjects factor of Age Group (younger, older). Reading times were also entered into an analysis of variance by items, however, as in Study 1, the analysis by items was not significant for either region of interest (F2=1.3, NS, for the direct object NP and F2=1.9, NS, for the particle. This is not surprising as this study used the same materials, as well as the same younger participants used in Study 1 (although this study also included 52 older participants). Thus, the effects in this study were subject to the same variability by items. Therefore, as in Study 1, I will only report the analyses by participants in the following results.

Overall Age Effect

Over both regions of interest there was a significant effect of Age Group: F(1,141)=144.2, $p < 0.0001$, for the direct object NP; and F(1,141)=132.7, $p < 0.0001$, for the particle. The older group had much slower reading times than the younger group (531 versus 326 msec for the direct object NP and 527 versus 323 msec for the particle).

Age and Linguistic Variables

Over the direct object NP region of interest, there was a significant interaction between Age group, Adjacency, and Dependency, F(2, 282)=4.1, $p < 0.02$, with slower reading times as Dependency increased, especially when the particle was shifted, with a more exaggerated slow-down for the older group compared to the younger (see Table 12).

Interestingly, this interaction was driven by the Age by Dependency interaction when the particle was shifted, F(2,282)=8.2, $p < 0.003$, showing that for these sentences, increasing the Dependency relationship between the verb and particle increased reading times, but especially for the older age group (see Table 12). This suggests that it is more difficult for the older adults than the younger adults to maintain a highly dependent semantic relationship in memory over the entire sentence. However, when the verb and particle were adjacent, reading times for the younger and older age group were similarly affected by dependency suggesting that sentences with adjacent particles are easier to process for both age groups.

Over the particle region of interest there was an interaction between Age Group and Adjacency of the verb and particle, F(1,141)=26.1, $p < 0.0001$, with a greater effect of Adjacency for the older adults (509 msec for the adjacent particle versus 545 msec for shifted) than the younger adults (320 msec for the adjacent particle and 326 msec for shifted). This suggests that particle-shifting affects older adults more, presumably because it is more difficult for them to store and integrate the semantic and syntactic information concurrently due to their slower reading times.

To determine if either age group benefited from particle shifting (a factor which should increase processing efficiency since it allows for earlier recognition of all sentence elements (Hawkins, 1994, 2004)), I examined the interaction between Adjacency and Age Group for the least demanding sentences only (those with short direct object NP's and low dependency verb-particles). This interaction was significant, F(1, 141) = 19.6, $p < 0.0001$, with the young age group showing faster reading times on the particle when it was shifted away from the verb and the dependency relationship was low and the intervening NP was short. On the other hand, the older age group had slower reading times when the particle was shifted, even for these less demanding sentences (see Figure 9). This suggests that the younger age group benefits from minimization of the syntactic domain and earlier recognition of all sentence elements, but only for the less demanding sentences, while overall, the older group does not show any benefit of particle-shifting.

These results confirm my first hypothesis that age has an effect on reading times with the older adults showing much slower reading times, especially when a highly dependent particle was shifted away from its verb. This indicated that older adults are more affected by sentences that increase WM load, suggesting that there is a compound effect of slower processing and WM load, with the slowest reading times for individuals who process sentences more slowly, especially when the sentences tax WM. This analysis, however, did not reveal how the age *and* WM ability of the participant influence reading times. The influence of age on WM ability and reading times is discussed in the following sections.

Effect of Age on Working Memory Ability

I predicted that performance for the older adults would be different for the two WM tasks, with preserved performance on the reading span task since it can be mediated by abilities other than working memory, including reading experience (MacDonald & Christiansen, 2002). Consistent with this notion, older adults' decline in processing ability is generally due to aging effects, such as general cognitive slowing (Salthouse, 1996), not necessarily a lack of experience with language. This interaction between experience and processing speed decline could result in older adults achieving similar reading span scores as younger adults, because even if older adults do process the information more slowly, they are more comfortable with the reading material which should mediate reading span scores. However, I predicted that older adults may not perform as well on the digit-letter sequencing task since this may tap more general storage and processing abilities, not mediated by language experience, and thus may be more influenced by cognitive slowing.

For the older adults, the correlation between scores on the two WM tasks was significant, r=.50, $p < 0.0002$, and higher than the correlation for the younger adults (r=0.39), suggesting that older adults who score well (or vice versa) on one of the WM assessments are more likely to score well on the other task. Therefore, to determine how individuals in each age group performed on each of the working memory tasks, I entered scores for each WM task into two separate analyses of variance, with the factor of Age Group (younger and older). Performance differences on the digit-letter sequencing task were significant, F(1, 149) = 3.7, $p < 0.05$, with lower scores for those in the older age group. The mean score for the older adults was 11.8 versus 12.7 for the younger adults (see Table 13 for the distribution of scores). This result was expected since I predicted that the older adults would perform more poorly on the digit-letter sequencing task. Unlike reading span, this task assesses more general storage and processing ability, not mediated by experience or skill with language.

Differences in scores for the reading span task were marginal across the age groups, with higher scores for those in the *older* age group, F(1, 149) = 3.2, $p < 0.07$. The mean score for the older adults was 2.8 versus 2.6 for the younger group (see Table 13 for the distribution of scores). This result confirms my hypothesis that the older adults show preserved performance on a task mediated by language ability. So while the older adults may have difficulty with storage and processing more generally, as indicated by their slightly lower scores on the digit-letter sequencing task, they are able to perform as well, if not better than younger adults when the task utilizes experience with language, a factor that should increase cumulatively with age.

These results confirm my hypothesis that aging affects performance on tasks that assess more general WM ability, but not tasks that are mediated by language skill. This supports MacDonald and Christiansen's (2002) account which suggests that experience and skill with language can off-set a decline in processing ability. Therefore, even though older adults did show a decrease in reading speed, as indicated by their performance on the self-paced reading task, their experience with language mediated the effects of cognitive slowing on less time-sensitive reading span task. Thus, they were able to read the sentences without stumbling, a factor which should reduce the processing effort associated with reading the sentences so that they can devote more resources to remembering the sentence final words. On the digit-letter sequencing task, however, there is little language skill benefit associated with remembering letters and numbers, therefore the older adults are hindered by their cognitive slow-down, which increases the time over which they must keep the number and letters in working memory, reducing processing ability.

Age, WM Scores, and Reading Times

For the older adults, the correlations between scores on each task and average reading time over the direct object NP on the self-paced reading task were significant, $p < 0.01$ for both the reading span, r= -0.38, and digit-letter sequencing tasks, r=-0.40. These correlations were higher than those for the younger adults (reading span task, r= -.21, $p < 0.05$; digit-letter sequencing, r=-0.22, $p < 0.05$), suggesting that scores on each task predicted more of the variation in reading times for the older adults than the younger (reading span task: R^2=0.14 for the older adults and R^2 = 0.047 for the younger adults; digit letter sequencing task: R^2=0.16 for the older adults and R^2=0.049 for the younger).

When the scores for older and younger participants were examined together, reading span scores did not predict a significant amount of reading time variation across the age groups, $R^2 = 0.01$, NS. However, digit-letter sequencing score did predict a significant amount of reading time variation across both age groups, $R^2 = 0.09$, $p < 0.0001$. This suggests that reading span score is preserved for the older adults, since their scores on this task were not predictive of their slower reading times.

Therefore, to determine if older adults process sentences significantly slower than younger adults with comparable scores on each of the WM assessments, I entered average reading times for both regions of interest into an analysis of covariance, with the covariate of Working Memory Score (Reading Span Score in the first analysis and Digit-Letter Sequencing Score in the second) and the factor of Age (younger, older).

Results indicate that after accounting for the covariate of Reading Span Score, there was still a significant effect of Age group, $F(1,149) = 178.5$, $p < 0.0002$, over both regions of interest with slower reading times for the older age group (327 versus 539 msec for the direct object NP and 325 versus 536 msec for the particle).

Reading times were also significantly different across age groups after accounting for differences in Digit Span Score $F(1, 149) = 175.5$, $p < 0.0005$, over both regions of interest with slower reading times for the older age group (333 versus 527 msec for the direct object NP and 331 versus 529 msec for the particle).

These results illustrate that older adults do process sentences more slowly even after accounting for performance on the WM assessments. Therefore, although cognitive slowing does not have such a drastic effect on WM ability, especially the reading span task which is mediated by language skill, older adults are affected by this slow-down as reflected by their slower reading times for the time-sensitive self-paced reading task.

Interactions between Reading Span, Digit-Letter Sequencing, and Aging

To examine how performance on the two WM tasks *combined* influenced reading times for each age group, mean reading times per word over the direct object NP region of interest were entered into an analysis of variance with the factors of Reading Span Score (above median, at or below median), Digit-letter Sequencing Score (above median, at or below median), and Age Group (younger, older). This resulted in eight cells, four for each age group, containing: 1) individuals who scored above the median on both of the tasks (N=35 for the younger adults and N=21 for the older adults); 2) those above the median on the reading span task, but at or below the median on the digit-letter sequencing task (N=10 for the younger adults and N=6 for the older adults); 3) those at or below the median on the reading span task, but above the median on the digit-letter sequencing task (N=28 for the younger adults and N=7 for the older adults); and 4) those at or below the median on both tasks (N=25 for the younger adults and N=18 for the older adults).

There was a main effect of Age Group, F(1, 142)=126.2, $p < 0.0001$, with slower reading times for the older age group (521 msec) compared to the younger (331 msec). Thus, preserved performance on the working memory tasks for the older adults did not result in preserved performance on the self-paced reading task. This suggests that cognitive slowing with aging plays a prominent role in the self-paced reading task.

resulting in slower reading times for older adults, even when they perform comparably to younger adults on the WM assessments.

This analysis also revealed that the interaction between Age Group, Reading Span Score, and Digit-Letter Sequencing Score was moderate, F(1,142)=3.3, $p < 0.07$. The results from this interaction showed that the fastest reading times within each age group occurred for those who scored above the median on the reading span task, regardless of their performance on the digit-letter sequencing task (see Table 14). However, for those who scored at or below the median on the reading span task, digit-letter sequencing score played a more prominent role in determining reading times, especially for the older adults. Thus, reading times were much slower for older adults who scored at or below the median on both WM tasks, compared to those who scored above the median on the digit-letter sequencing task only. The younger adults in these conditions showed the same pattern, although their slow-down was not as drastic when they had lower scores on both tasks (see Table 14).

These results support the notion that better performance on the reading span task (which presumably indicates better language skill (MacDonald and Christiansen, 2002)) facilitates reading times on the self-paced reading task since those who scored well on the reading span task showed similar reading times (within each age group) regardless of performance on the digit-letter sequencing task.

However, for individuals with lower scores on the reading span task (who presumably have less skill with language), decreased storage and processing ability (as assessed by the digit-letter sequencing task) caused a further increase in reading times, especially for the older adults. This suggests that without the mediating effect of language skill, reading times increased for those who did not store and process information as efficiently. This effect was compounded by cognitive slowing with aging, as reading times for older adults were drastically increased by poor performance on both WM tasks, as this group showed the slowest reading times by far.

Working Memory Groups

To examine how WM ability would affect reading times for sentences that varied in verb-particle adjacency, dependency, and NP length, I needed to create WM groups that reflected the widest range of processing abilities. Therefore, as in Study 1, I chose to include only the participants from each age group who scored above the median on both WM assessments or below the median on both tasks. Thus, in the subsequent analyses, the 'low WM group' consisted of 25 younger adults and 18 older adults who scored at or below the median on both WM tasks (i.e., 2.33 and below on the reading span task, but also 11 and below on the digit-letter sequencing task). The 'high WM group' included the 35 younger adults and 21 older adults who scored above the median on both WM tasks (i.e., 2.66 and above on the reading span task, but also 12 and above on the digit-letter sequencing task). Therefore, the following analyses for the self-paced reading task only include the data for the 99 participants included in the low and high working memory groups.

Effect of WM Group and Age on Reading Times

The word by word reading times across the entire sentence reveal a marked difference in reading times for the younger and older adults, especially when WM group was taken into account. The younger adults in the high WM group had the fastest reading times across all conditions, followed by the younger adults in the low WM group, the older adults in the high WM group, and finally the older adults in the low WM group. (see Figures 10a-f). This reading time difference between the age and WM groups over the two regions of interest will be discussed in detail in the sections below.

Interactions between Age, WM Group, and Linguistic Constraints

To examine the effect of the interaction between the cognitive constraints of age and WM ability and linguistic constraints of verb-particle adjacency, dependency, and NP length, reading times for each region of interest were entered into a mixed model ANOVA with the between subjects factors of Age Group(younger, older) and WM group (low, high), and the within subjects factors of Adjacency (adjacent, shifted), Dependency (low, middle, high), and NP Length (short, medium, long).

There was a significant interaction between Age and WM Group over both regions of interest: $F(1, 95)= 9.2$, $p < 0.003$ for the direct object NP; and $F(1,95)=14.5$, $p < 0.0003$ for the particle. This interaction showed that reading times increased with age, but more drastically for the older low WM group (see Figure 11) suggesting that the effect of WM was greater for the older group.

Direct Object NP Region of Interest

Over the direct object NP region of interest, there was a significant interaction between Adjacency, Dependency, Age Group, and WM Group, F(2, 190)=3.8, $p < 0.03$. Results from this interaction showed that reading times increased as Dependency increased, but only when the particle was shifted, and most drastically for older adults in the low WM group (see Tables 15a and 15b).

Interestingly, across both WM and Age Groups, when the dependency relationship between the verb and particle was low, reading times were similar regardless of whether the particle was adjacent or shifted (see Tables 15a and 15b). This suggests that when there is not much semantic information to retain across the sentence, there is little to no effect of particle shifting on reading times, even for the older adults with lower WM scores. This illustrates that when the semantic relationship between words in a sentence is low, it is just as efficient to shift the particle as it is to keep the particle adjacent to the verb, suggesting that minimizing the syntactic domain is just as beneficial as minimizing the semantic domain. However, when the dependency relationship between the verb and particle was high, reading times were consistently slower when the particle was shifted, suggesting that for these more dependent particles, there was no benefit of particle shifting regardless of age or WM ability. However, the younger adults in the high WM group did show the smallest increase in reading times when the particle was shifted and the older adults in the low WM group showed the largest increase.

suggesting that sentences containing a high dependency and shifted particle are harder for them to process.

Particle Region of Interest

Over the particle region of interest, there was a significant interaction between Adjacency, WM Group, and Age Group, F(1, 95)=7.7, $p < 0.007$, with increased reading times when the particle was shifted, but only for the older adults, and especially for the older adults in the low WM group (see Table 16). This suggests that participants who are constrained by cognitive slowing, decreased storage and processing ability, and decreased skill with language are most affected by particle shifting since these sentences require that the unresolved verb-particle relationship be maintained in WM across the intervening direct object NP. For the older adults with low WM, these sentences tax WM load even more since these participants read more slowly, increasing the duration over which they must maintain the semantic and syntactic content of the sentence, thus increasing WM load.

There was also a significant interaction between Dependency, WM Group, and Age Group, F(2, 190)=5.4, $p < 0.005$, with increasing reading times as Dependency increased, but only for those in the low WM groups, and more drastically for the older adults in the low WM group (see Table 17). This indicates that the dependency relationship exerts a stronger affect on reading times for those who score lower on the WM assessments, especially when they are also subject to cognitive slowing due to age. Thus, decreased performance on both WM tasks, when coupled with cognitive slowing, results in slower reading times across dependency because these individuals have both decreased language skill and storage and processing ability, but must maintain the highly dependent semantic information in WM over a long period of time since they read at such a slower rate. Unfortunately, this is speculative as the interaction between Age group, WM group, Dependency, and *Adjacency* was not significant here. However, after examining the means for this interaction, it does seem to be the case that the increasing effects of Dependency for the older adults with lower WM ability results mainly from an increase in reading times when the particle was shifted.

These results also support the notion that higher scores on the reading span task and digit-letter sequencing task can facilitate reading times for older adults. Thus, while the older adults in the high WM group may be slower than their younger counterparts, in this analysis they demonstrate a similar pattern of reading times (i.e., little effect of increasing dependency), indicating that their increased processing ability and skill with language mediates the effect of increasing the dependency relationship between the verb and particle.

Overall, the results from these analyses demonstrate that WM ability does play a role in determining reading times for sentences that vary in semantic and syntactic constraints. However, these results show that the range of WM ability must be broad enough to elicit further increases in reading times for the low WM group as the demands of the sentences increase. Therefore, reading times only increased drastically over the more demanding sentences for the older adults with lower WM scores indicating that processing load was increased more for these individuals who were subject to decreased processing ability, language skill, and also cognitive slowing.

Additionally, the results demonstrate that reading speed may be a critical factor in determining how individuals are affected by the various linguistic constraints. The older adults in the low WM group not only had lower scores on each of the WM tasks, but also had much slower reading times than both their older, high WM counterparts and younger adults. Therefore, reading speed affected the time over which they had to maintain both the semantic and syntactic information of the sentence in WM. Thus, as the difficulty of the sentences increased, these individual's processing load was increasingly taxed, both by their lower WM ability and the increased duration for which they had to store and integrate linguistic information, resulting in a further increase in reading times for the more demanding sentences. Therefore, consistent with both MacDonald and Christiansen (2002) and Salthouse (1996), both processing speed and WM ability (resulting from language skill and general storage and processing ability) play a role in determining reading times for these sentences.

Discussion

Processing Speed Decline with Age

It has been widely noted in the literature that processing speed declines with age on a variety of tasks, including perceptual speed, working memory ability, and language processing (c.f., Salthouse, 1996; Kemper, 1986; Stine-Morrow, et al, 2000; Norman, et al, 1992; and Roberts & Gibson, 2002). The results from the current study support this evidence for cognitive slowing due to aging, with much slower reading times overall for older adults than younger adults. These findings also demonstrate that decreased processing speed due to age has an exacerbating effect on processing difficulty for sentences that vary in WM load, with reading times increasing most drastically for the older adults as sentence difficulty increased. This supports the theories of Salthouse (1996) and MacDonald and Christiansen (2002), which state that cognitive slowing increases the time over which information is held and processed in WM, thus increasing processing load, especially when sentences require the storage and processing of significant amounts of syntactic and semantic information (as in particle-shifted sentences).

Aging, Language Skill, and WM Ability

Results from this study also showed that cognitive slowing with age does not always result in poorer performance. Scores from the reading span task illustrate that, as predicted, language experience plays a significant role in mediating the effects of processing speed decline. According to MacDonald and Christiansen (2002), the preserved performance shown by many older adults on the reading span task is due to their increased language experience or skill. They argue that an individual who has more experience with language, through reading, should be able to process linguistic information more efficiently since they encounter common and uncommon linguistic structures and words more frequently. This reduces the processing load incurred by reading the sentences which, in turn, allows for more accurate recall of the sentence final words. Therefore, while older adults may process the material on the reading span task more slowly, a factor which should tax WM, their increased experience and skill with language reduces the processing effort associated with reading the sentences so that they can devote more resources to the recall task.

However, for the digit-letter sequencing task, which relies less on language processing skill, there is decreased performance with aging, suggesting that cognitive slowing has a negative impact on general storage and processing ability. Thus, the older adults are hindered by their slowed processing speed, which increases the time over which they must keep the number and letters in working memory, thus taxing WM more for the older adults than the younger, and resulting in lower scores for the older adults on this WM task.

Processing Efficiency, WM Load, and Aging

Finally, results from this study showed that sentences that vary in syntactic and semantic constraints affect processing differently, not only for participants in the younger or older age groups, but also for those with low or high WM ability within these age groups. Importantly, reading times demonstrated that for older adults there is almost no benefit to particle shifting even if all other semantic and syntactic elements reduce processing load (i.e., low dependency verb-particles and short direct object NP's). Older adults did not show faster times when the particle was shifted, indicating that the WM load incurred by the storage and processing of both the dependency relationship between the verb and particle and the content of the direct object NP concurrently was too great for them to benefit from the early recognition of all sentence elements, a factor which Hawkins (2004) suggests increases processing efficiency.

Thus, these results demonstrate that Hawkins' (2004) principles of processing efficiency, particularly that of syntactic minimization, apply differently to individuals that vary in age and WM ability, especially for verb-particle constructions for which the syntactic and semantic domain cannot be minimized concurrently and whose word order differentially affects WM load. As was shown in Study 1, younger individuals with high WM benefited from early recognition of all sentence constituents with faster reading times when the particle was shifted and sentence difficulty was low. Thus, these participants had the resources to store and process the intervening NP and were not hindered by decreased processing speed, unlike their older counterparts. However, for older adults, especially those in the low WM group, syntactic minimization (separating the verb and particle) increased the processing difficulty of the sentence. Thus, when processing speed is decreased, the strong semantic influence of the relationship between the verb and particle, as well as the WM load and decay of information over the sentence incurred by particle shifting, overrides the benefit of early sentence element recognition.

Thus, the increased language experience associated with preserved performance for the high WM older adults on the reading span task does necessarily carry over to performance on a timed self-paced reading task. The older adults with high WM do not show the same syntactic minimization benefit as their younger counterparts suggesting that older adults were able to make up for their decrease processing speed on the reading span task, but not on the more time sensitive self-paced reading task.

Conclusions for Study 3

Overall, results from Study 3 showed that age, processing speed, WM ability, and sentence complexity all play important roles in determining overall reading times. These results confirm MacDonald and Christiansen's (2002) notion that sentence processing ability is not a static fixture, with performance differences resulting from a combination of the individual's processing speed at the time of comprehension, their experience with the particular linguistic structures (or those similar to them), and the relative difficulty of the sentence for that individual.

Also, these results demonstrate that while the factors that underlie linguistic efficiency, namely, minimizing semantic and syntactic domains, are important in predicting performance, they cannot be the whole story, especially when the syntactic domain is made more efficient at the expense of increasing WM load (since minimizing the syntactic domain increases the distance over which the semantic dependency relationship of the verb and particle must be maintained). Thus, contrary to Hawkins' (2004) claim that WM load is secondary to principles of efficiency, I have shown that when aspects of the linguistic signal drastically increase WM load, as in sentences with long direct object NP's intervening between dependent verbs and particles, processing is hindered regardless of whether the structure is theoretically more efficient (i.e., because you can build the phrasal structure of your sentence sooner or the size of the domain of interest has not increased in number of words). In addition, I have shown that this effect on performance is greater when the processing ability of the individual is decreased, either from lower working memory ability, cognitive slowing due to age, or both.

GENERAL DISCUSSION

Linguistic Constraints on Processing

The results from all three of the studies presented here indicate that reading times are influenced by the semantic and syntactic processing constraints in the sentence. Overall, the results from each study showed that, as Hawkins (2004) and Lohse et al (2004) suggested, particle position affected reading times since it influenced the amount of information that has to be stored and processed concurrently. When the particle was shifted, the semantic information from reading the verb alone had to be stored across the direct object NP, where the particle was finally read and integrated. This required the dependency relationship to be stored in WM while also integrating the content of the direct object NP, however, when the particle was adjacent, the meaning of the complete verb-particle construction was resolved before having to integrate the direct object NP, reducing the amount of information that had to be processed concurrently.

Importantly, these results hinge on the *relative weight* of the syntactic and semantic elements in the sentence. In verb particle constructions, there is a strong semantic domain which tends to trump the benefits of minimizing the syntactic domain (i.e., the earlier recognition of all of the grammatical elements of the sentence). Therefore, for these constructions, there is a consistent processing benefit associated with minimizing the semantic domain, with faster reading times for sentences with adjacent verbs and particles. However, the benefit of adjacency may not be as high in other constructions which rely less heavily on a particular word order for proper interpretation. Dative constructions, for example, are easily interpreted in either order (e.g., '*the boy will throw the pretty girl the orange ball*' versus '*the boy will throw the orange ball to the pretty girl*'). In contrast to verb-particle constructions, these sentences do not have such a strong semantic dependency relationship between phrases, reducing the competing weights between the semantic and syntactic elements of the sentence. Therefore, for these constructions, minimizing the syntactic domain will therefore be paramount (c.f. Stallings et al., 1998).

Cognitive Constraints on Processing: WM Ability and Aging

Across all three studies, there was a consistent effect of WM ability on reading times, with slower reading times for those who had lower scores on both WM tasks compared to those who scored better on both tasks. In addition, since those who had higher scores on only one of the tasks usually had reading times in between the two extreme groups, these results support the notion that those who have more skill with language (and thus better scores on the reading span task (MacDonald & Christiansen, 2002)), but also better general storage and processing ability (as assessed by the digit-letter sequencing task) read sentences most efficiently. In contrast, participants with less language skill and general storage and processing ability take the longest to read the sentences. This suggests that processing ability for those who are less able to store and process the information in general, is further hindered by decreased skill or experience with the linguistic structures, increasing the time that they need to process the sentence material.

Additionally, results showed that aging also influenced reading times, with older adults reading consistently slower than the younger adults. According to Salthouse (1996) this increase in reading times was the result of a general cognitive slow-down with age. Thus, processing speed also contributed to performance on the self-paced reading task, such that reading times for older adults were hindered since they read more slowly, increasing the time over which the sentence material must be integrated, especially for those who also had lower scores on the WM tasks.

Interestingly, these consistent differences across the age and WM groups occurred regardless of the difficulty of the linguistic material, with vastly different average reading times for the younger and older adults with either low or high WM. Thus, reading times were sufficiently different across each of these groups that even for the easiest sentences there were no overlapping reading times. This suggests that cognitive constraints of the individual are paramount in determining overall processing ability. This supports MacDonald and Christiansen's (2002) theory of linguistic WM, which states that overall language processing ability is determined by both experiential factors, such as reading skill and frequency, and biological constraints, such as decreased processing speed due to aging.

Integrating Linguistic and Cognitive Constraints

While the previous sections detailed the independent effects of linguistic and cognitive constraints on reading times, the main goal of this thesis was to examine the interaction of these two processing constraints. Unfortunately, contrary to predictions, in both Studies 1 and 2, reading times did not indicate that WM ability had a strong influence on reading times for sentences that varied in the linguistic factors of adjacency, dependency, NP length, or NP complexity, since, as predicted, reading times did not increase more drastically for the low WM group, even for the more demanding sentences. However, results from Study 1 did show that only the high WM group read the particle faster in the shifted position, but only when the direct object NP was short.
This result indicated that the processing load for these sentences was mediated by these individuals' increased storage and processing ability as well as increased skill with language (MacDonald & Christiansen, 2002), thus reducing the effect of particle shifting, and allowing them to benefit from the earlier recognition of the direct object NP.

However, it was only for the older adults in the third study that reading times increased further for the low WM group over the more demanding sentences. This suggests that WM ability does influence reading times for these sentences, but the range of WM ability must be broad enough (as it is for the older adults) to include individuals with sufficiently lower WM ability, which then elicits further increases in reading times for the more demanding sentences.

However, many researchers have found that low WM ability affects sentence comprehension, especially for more complex linguistic structures, even when they only examine younger age groups (e.g., King & Just, 1991; MacDonald, Just, & Carpenter, 1994; Caplan & Waters, 1999). I suggest that the lack of such an effect in this thesis may be the result of the small distribution of scores for the reading span task since, for example, in Study 1, just 4 out of 98 total participants, attained scores above four, the typical cut off for high WM groups (c.f. Daneman & Carpenter, 1980; MacDonald, Just, & Carpenter, 1994; Caplan & Waters, 2002). Given this distribution, it is possible that I was not able to create extreme enough WM groups to elicit the predicted effect.

Adding to this problem was the sheer number of variables manipulated in these studies. It is possible that some effects of WM ability would have been more clear had I simply reduced the number of levels within each variable (e.g., including only short and long direct object NP's, or only low and high dependency verb-particles). Thus, while I was able to show that the linguistic content plays an important role in determining reading times within each WM or age group, overall the linguistic effects tend to be overwhelmed *across* individuals of different processing ability.

However, I still feel that sentence processing cannot be fully understood without examining both the linguistic constraints of the sentence and processing aspects of the individual. In these studies, I was able to show that the strength and direction of the interaction between the linguistic factors in each sentence determines the general difficulty of the material, but the WM ability or age of the reader ultimately determines how much one is affected by the linguistic difficulty of a sentence, as well as how much one can benefit from available syntactic efficiency. Therefore, a performance theory of language, like that of Hawkins (1994, 2004), as well as research examining language processing, need to incorporate both the linguistic factors that affect the difficulty of sentences, and the cognitive factors that may facilitate or hinder the processing of the linguistic input.

CONCLUSIONS AND FUTURE DIRECTIONS

Although the results from the studies presented in this thesis did not allow me to conclude exactly how WM ability, independent of aging, affected reading times for sentences that varied in syntactic and semantic processing constraints, the results from these studies did indicate that other individual differences, namely reading experience and processing speed, may play an important role on reading times. In future experiments of this nature, I suggest collecting data regarding each participant's reading history and frequency, verbal SAT score, and an assessment of their general processing speed. These factors may be critical to explaining reading time differences for the sentences used in these experiments. They are also important to understand when operating under a connectionist approach to WM and language processing which relies on these factors to predict language processing ability. Therefore, a more explicit understanding of the individual's reading skill and processing ability may be an additional and more accurate way to determine language processing ability.

However, from the research conducted for this thesis, I can conclude that trying to integrate all of the factors that can influence language comprehension may be difficult to study. In theory, all of these factors should interact to determine overall language processing ability. However, in practice, manipulating too many variables can actually limit what one can conclude from research. In these studies, I have shown that the processing difficulty of the linguistic material alone was shown to be subject to many influences, including the complexity of the structure, the amount of semantic and syntactic information, and the relationships between related items. In addition, the processing ability of the individual was subject to many of its own constraints, such as working memory, reading experience, processing speed, and age. I have shown that while all of these factors may have important influences on reading times independently, it is difficult to examine all of these factors in conjunction. Thus, the pervasiveness of one constraint may wash out the effects of another, and variables that were shown to affect comprehension separately may not be as influential overall. Nevertheless, collectively, the findings from these studies suggest that a complete understanding of language comprehension cannot be achieved without taking both linguistic and cognitive factors into account.

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Appendix A

Sample set of mean similarity ratings for verb/verb particle pairs

Verb	Verb Particle	Mean Similarity Rating (SD)
start	start up	8.50 (0.50)
count	count off	6.75 (1.88)
block	block out	5.75 (2.62)
smooth	smooth over	4.64 (2.30)
shoot	shoot up	3.48 (2.04)
throw	throw up	2.52 (1.73)

Note: 1 = very dissimilar, 9 = very similar.

Appendix B

Mean response latencies for target words by prime types and degree of prime-target similarity

Prime Type	Prime-Target Similarity		
	Low (*finish up*)	Mid (*look up*)	High (*chew out*)
Unrelated control (*cast off/throw*)	550	553	557
Related test (*throw up/throw*)	543	532	537
Unrelated-Related	**7**	**21***	**20***

$* \ p < .05$

Appendix C

Sample Reading Span Test Sheet:

Each level consisted of three blocks, starting with two sentences in each block for the first level and ending with six sentences per block for the final level. The level for which the participant recalled all of the sentence-final words in each of the three blocks correctly was the participant's reading span score, with possible reading spans ranging from a score of 1 to 6.

Practice	Two Sentences	Three Sentences	Four Sentences	Five Sentences	Six Sentences
Set 1 Xxxxxxx Xxxxxxx	Set 1 status ground	Set 1 securely law stare	Set 1 student so voices distance	Set 1 land abruptly visit doubts town	Set 1 look bitter pinch door anger while
Set 2 Xxxxxxx Xxxxxxx	Set 2 campfire temper	Set 2 errors face objective	Set 2 sensitivity asleep answered mind	Set 2 enthusiasts lake God dish cold	Set 2 us made panes sorry design society
Set 3 Xxxxxxx Xxxxxxx	Set 3 life all	Set 3 dust circular vision	Set 3 community cheating maddening documented	Set 3 gum smell going superhuman pictures	Set 3 lunch style building followed be was

Table 1

Study 1: Sample Set of Sentences for the Verb-particle Construction 'look up' (middle dependency).

Length	Adjacency	Sample sentence
short	adjacent	The man will *look up* **the word**.
short	shifted	The man will *look* **the word** *up*.
medium	adjacent	The man will *look up* **the unusual word**.
medium	shifted	The man will *look* **the unusual word** *up*.
long	adjacent	The man will *look up* **the unusual and interesting word**.
long	shifted	The man will *look* **the unusual and interesting word** *up*.

Table 2

Study 1: Mean Reading Times (msec) and Standard Deviations by Dependency (low, middle, high), Adjacency (adjacent, shifted) and NP Length (short, medium, long) across the Direct Object NP Region of Interest.

	Low Dependency		Middle Dependency		High Dependency	
NP Length	Adjacent	Shifted	Adjacent	Shifted	Adjacent	Shifted
Short	309 (72)	321 (79)	320 (63)	315 (75)	331 (78)	334 (78)
Medium	323 (71)	315 (73)	325 (69)	334 (71)	332 (72)	339 (71)
Long	316 (64)	338 (65)	322 (61)	339 (67)	326 (65)	346 (65)

Table 3

Study 1: Mean reading times (msec) and Standard Deviations by Dependency (low, middle, high), Adjacency (adjacent, shifted) and NP Length (short, medium, long) on the Particle Region of Interest.

	Low Dependency		Middle Dependency		High Dependency	
NP Length	Adjacent	Shifted	Adjacent	Shifted	Adjacent	Shifted
Short	313 (69)	312 (72)	323 (64)	311 (66)	321 (69)	324 (66)
Medium	328 (74)	315 (63)	320 (68)	328 (56)	322 (74)	339 (71)
Long	311 (76)	341 (70)	324 (77)	333 (63)	312 (69)	331 (61)

Table 4

Study 1: Distribution of Scores on the Reading Span and Digit-letter Sequencing Tasks.

Reading Span Score	N	Digit Letter Score	N
1.33	1	7	1
1.66	6	8	2
2	15	9	7
2.33	31	10	9
2.66	19	11	16
3	4	12	18
3.33	16	13	16
3.66	3	14	6
4.33	2	15	7
5.33	1	16	5
		17	6
		18	4
		19	1

Table 5

Study 1: Mean reading times per word (msec) over the Direct Object NP Region of Interest for Participants who Scored at or Below the Median or Above the Median on the Reading Span and Digit-letter Sequencing Tasks.

	Reading Span Scores	
Digit-Letter Scores	Above Median (2.33)	At or Below Median (2.33)
Above Median (11)	305 (50)	319 (52)
At or Below Median (11)	329 (62)	354 (66)

Table 6

Study 2: Sample Set of Sentences for the Verb-Particle Construction 'blow off' (high dependency).

Length	Adjacency	Sample sentence
No relative	adjacent	The boy will *blow off* **his boring American history class**.
No relative	shifted	The boy will *blow* **his boring American history class** *off*.
Subject rel	adjacent	The boy will *blow off* **his class that lasts forever**.
Subject rel	shifted	The boy will *blow* **his class that lasts forever** *off*.
Object rel	adjacent	The boy will *blow off* **his class that Johnson teaches**.
Object rel	shifted	The boy will *blow* **his class that Johnson teaches** *off*.
Genitive rel	adjacent	The boy will *blow off* **his class whose teacher rambles**.
Genitive rel	shifted	The boy will *blow* **his class whose teacher rambles** *off*.

Tables 7a and 7b

Study 2: Mean reading times (msec) and Standard Deviations by Dependency (low, middle, high), Adjacency (adjacent, shifted) and NP Complexity (no relative, subject, object, and genitive relative) on the Direct Object NP (7a, top table) and Particle (7b, bottom table) Regions of Interest.

Table 7a: Direct Object NP

	Low Dependency		Middle Dependency		High Dependency	
	Adjacent	Shifted	Adjacent	Shifted	Adjacent	Shifted
NP Complexity						
No Relative	388 (83)	375 (92)	390 (79)	388 (84)	374 (79)	386 (98)
Subject Rel	392 (91)	370 (93)	386 (77)	382 (90)	394 (85)	385 (90)
Object Rel	394 (82)	386 (91)	399 (82)	401 (77)	393 (85)	400 (82)
Genitive Rel	378 (99)	417 (82)	394 (85)	409 (86)	384 (89)	418 (87)

Table 7b: Particle

	Low Dependency		Middle Dependency		High Dependency	
	Adjacent	Shifted	Adjacent	Shifted	Adjacent	Shifted
NP Complexity						
No Relative	387 (98)	360 (99)	390 (92)	376 (92)	373 (77)	382 (92)
Subject Rel	394 (93)	358 (97)	379 (93)	368 (91)	399 (96)	390 (87)
Object Rel	375 (95)	380 (94)	390 (98)	390 (94)	377 (75)	390 (81)
Genitive Rel	378 (92)	406 (95)	394 (97)	399 (84)	382 (84)	404 (90)

Table 8

Study 2: Mean Reading Times (msec) and Standard Deviations by NP Complexity for the Direct Object NP and Particle Regions of Interest.

	Region of Interest	
NP Complexity	Direct Object NP	Particle
No Relative	383 (84)	378 (97)
Subject Relative	385 (89)	381 (97)
Object Relative	396 (87)	384 (90)
Genitive Relative	395 (84)	392 (89)

Table 9

Study 2: Mean Reading Times (msec) and Standard Deviations for the Adjacent or Shifted Particle across Levels of NP Complexity.

	Particle Position	
NP Complexity	Adjacent	Shifted
No Relative	383 (101)	373 (92)
Subject Relative	390 (109)	372 (85)
Object Relative	381 (97)	387 (83)
Genitive Relative	385 (94)	400 (86)

Table 10

Study 2: Distribution of scores on the reading span and digit-letter sequencing tasks.

Reading Span Score	N	Digit Letter Score	N
1.33	1	7	1
1.66	3	8	1
2	12	9	4
2.33	22	10	8
2.66	20	11	10
3	4	12	13
3.33	11	13	17
3.66	4	14	13
4.33	10	15	13
4.66	2	16	6
5.33	6	17	5
		18	1
		19	2
		20	1

Table 11

Study 2: Mean reading times per word (msec) over the Direct Object NP Region of Interest for Participants who Scored at or Below the Median or Above the Median on the Reading Span and Digit-letter Sequencing Tasks.

	Reading Span Scores	
Digit-Letter Scores	Above Median (2.33)	At or Below Median (2.33)
Above Median (11)	345 (61)	400 (71)
At or Below Median (11)	416 (52)	408 (74)

Table 12

Study 3: Mean reading times per word (msec) over the Direct Object NP Region of Interest for the Younger and Older Age Groups for Sentences that Vary in Verb-Particle Adjacency (adjacent or shifted) and Dependency (low, middle, high).

	Adjacent		Shifted	
Dependency	Younger	Older	Younger	Older
Low	316 (72)	518 (125)	325 (63)	523 (126)
Middle	322 (78)	525 (121)	330 (79)	539 (122)
High	327 (75)	522 (114)	336 (78)	558 (135)

Table 13

Study 3: Distribution of Scores on the Reading Span and Digit-letter Sequencing Tasks for both Younger and Older Adults.

Reading Span Score	N (Younger)	N (Older)	Digit Letter Score	N (Younger)	N (Older)
1.33	1	0	7	1	2
1.66	6	2	8	2	2
2	15	5	9	7	4
2.33	31	18	10	9	6
2.66	19	11	11	16	11
3	4	3	12	18	9
3.33	16	5	13	16	5
3.66	3	4	14	6	7
4.33	2	2	15	7	5
4.66	0	1	16	5	2
5	0	1	17	6	0
5.33	1	0	18	4	0
6	0	1	19	1	0

Table 14

Study 3: Mean reading times per word (msec) over the Direct Object NP Region of Interest for Younger or Older Adults who Scored at or Below the Median or Above the Median on the Reading Span and Digit-letter Sequencing Tasks.

	Above Median		At or Below Median	
	Reading Span (2.33)		Reading Span (2.33)	
	Younger	Older	Younger	Older
Above Median				
Digit-Letter (11)	313 (55)	474 (108)	332 (50)	505 (81)
At or Below Median				
Digit-Letter (11)	326 (61)	470 (110)	354 (75)	632 (149)

Tables 15a and 15b

Study 3: Mean Reading Times per Word (msec) over the Direct Object NP for the Younger (15a, top) and Older (15b, bottom) Age Groups with either Low or High WM for Sentences that Vary in Verb-Particle Adjacency (adjacent or shifted) and Dependency (low, middle, high).

Table 15a: Younger	LowWM		HighWM	
Dependency	Adjacent	Shifted	Adjacent	Shifted
Low	349 (83)	346 (88)	309 (64)	309 (69)
Middle	351 (76)	358 (88)	312 (57)	315 (68)
High	350 (86)	365 (86)	310 (67)	319 (64)

Table 15b: Older	LowWM		HighWM	
Dependency	Adjacent	Shifted	Adjacent	Shifted
Low	620 (164)	623 (166)	466 (119)	468 (119)
Middle	639 (172)	627 (149)	461 (113)	487 (115)
High	626 (156)	662 (172)	466 (116)	491 (124)

Table 16

Study 3: Mean Particle Reading Times (msec) for Younger and Older Adults in either the Low or High WM Group for Sentences with either Adjacent or Shifted Particles.

	Younger		Older	
Adjacency	LowWM	HighWM	LowWM	HighWM
Particle-Adjacent	352 (79)	311 (73)	606 (167)	452 (104)
Particle-Shifted	348 (76)	317 (65)	662 (166)	479 (106)

Table 17

Study 3: Mean Particle Reading Times (msec) for Younger and Older Adults in either the Low or High WM Group for Sentences that Vary in Verb-Particle Dependency (low, middle, high).

	Younger		Older	
Dependency	LowWM	HighWM	LowWM	HighWM
Low	346 (81)	306 (69)	615 (166)	461 (106)
Middle	350 (75)	318 (66)	633 (160)	471 (106)
High	352 (77)	318 (72)	654 (174)	465 (105)

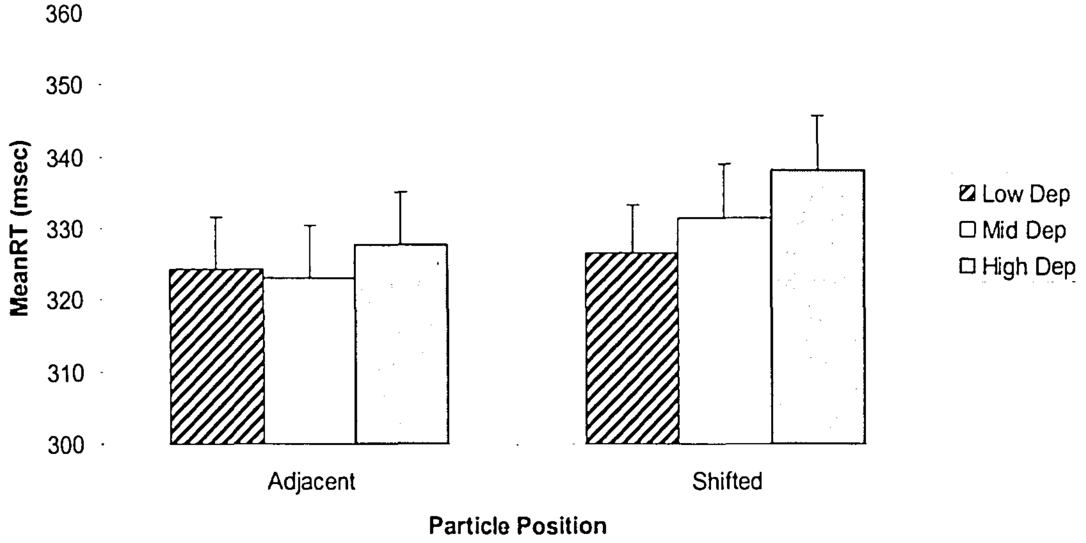


Figure 1. Study 1: Mean reading time per word (msec) across the direct object NP for sentences that varied in particle position (adjacent or shifted) and verb-particle dependency (low, middle, or high).

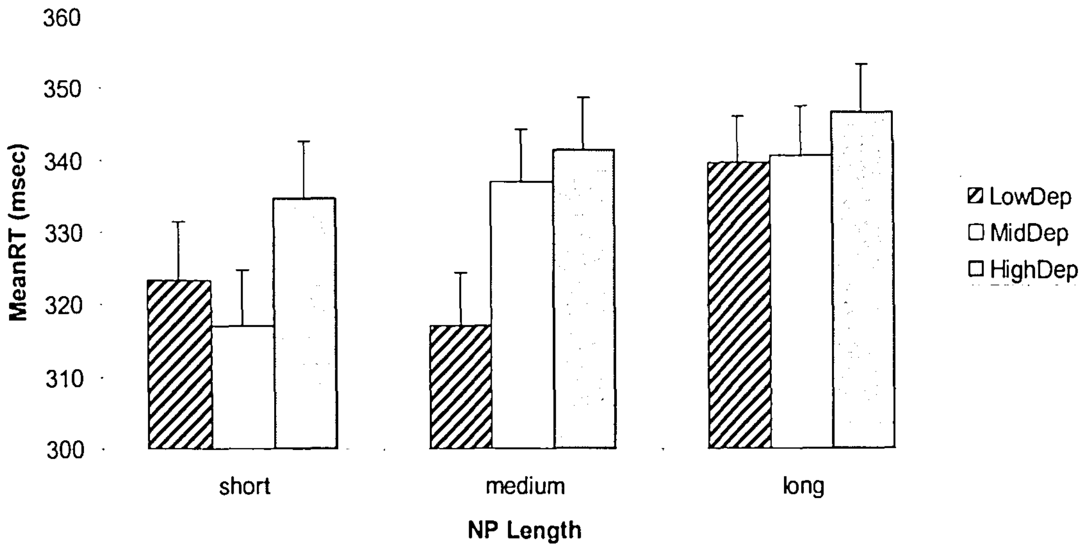


Figure 2. Study 1: Mean reading times (msec) across the direct object NP for particle-shifted sentences that varied in verb-particle dependency (low, middle, or high) and NP length (short, medium, long).

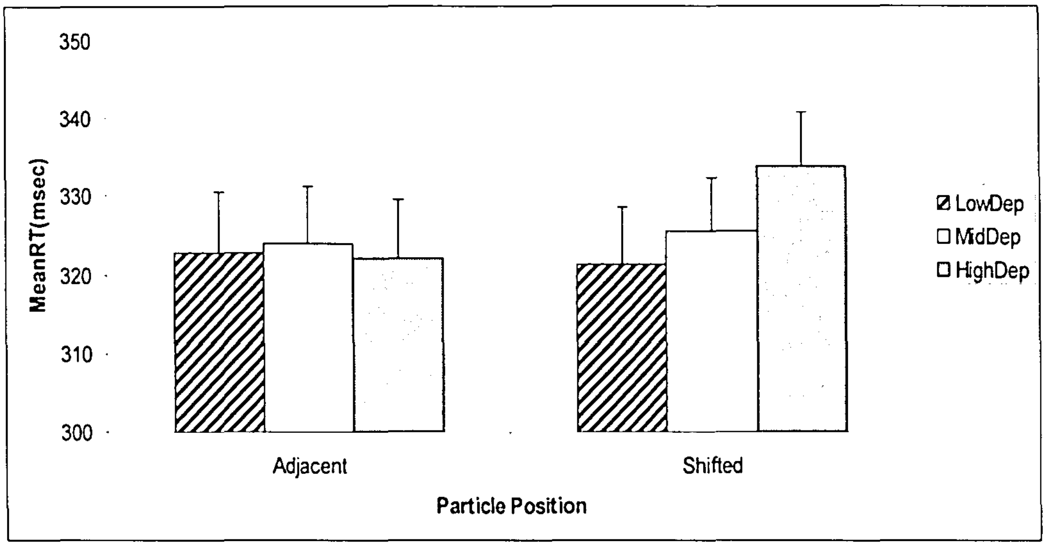


Figure 3. Study 1: Mean particle reading times (msec) on the adjacent and shifted particle for sentences that varied in verb-particle dependency (low, middle, or high).

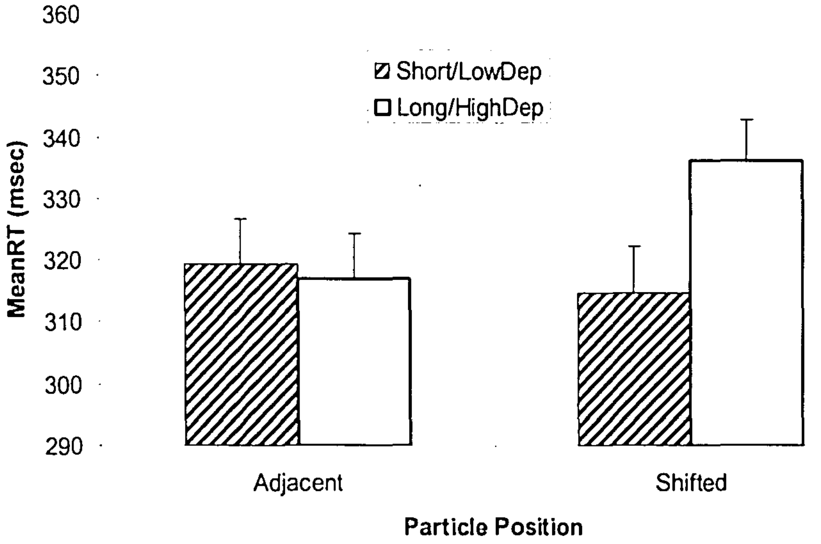


Figure 4. Study 1: Mean particle reading times (msec) for sentences with adjacent or shifted particles and either *low* dependency verb-particle constructions and *short* direct object NP's or *high* dependency verb-particle constructions and *long* direct object NP's.

Figure 5a. Particle-Adjacent Short Sentences

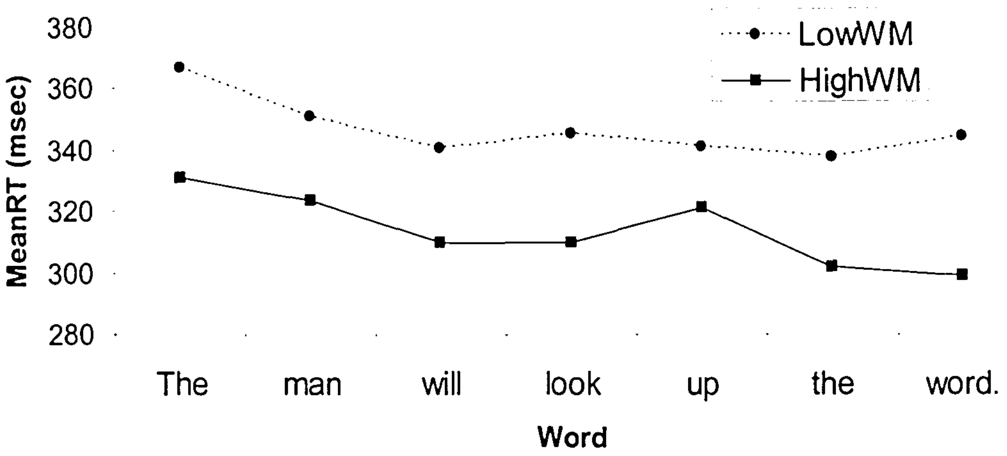
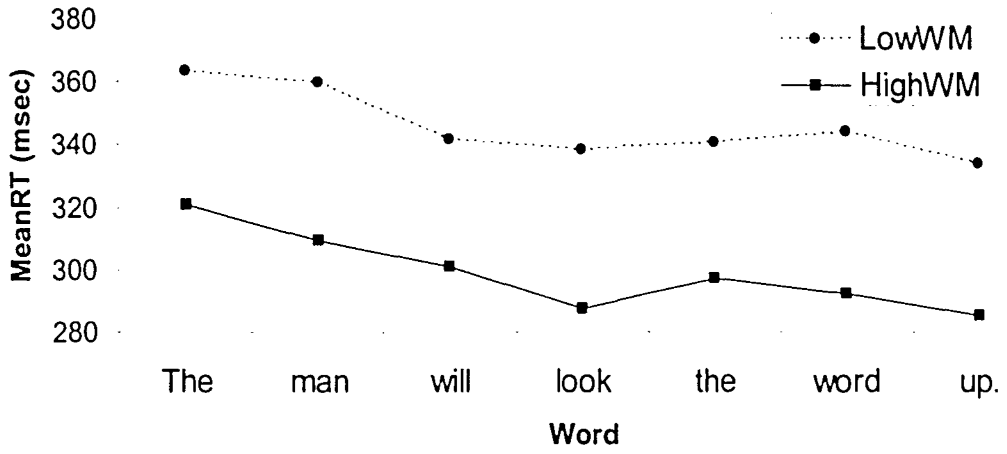


Figure 5b. Particle-Shifted Short Sentences



Figures 5a-5b. Study 1: Mean word by word reading times (msec) for the low and high WM groups reading particle *adjacent* (Figure 5a, top) and *shifted* (Figures 5b, bottom) sentences with *short* direct object noun phrases.

Figure 5c. Particle-Adjacent Medium Sentences

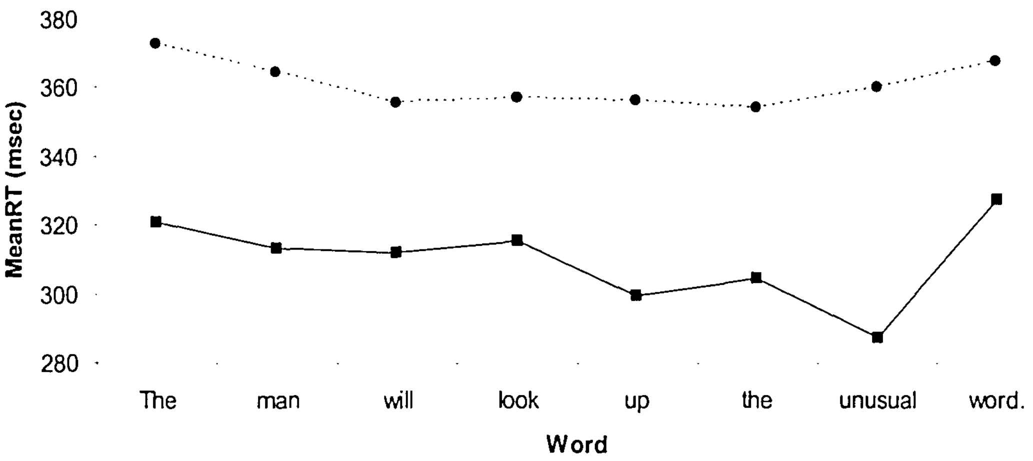
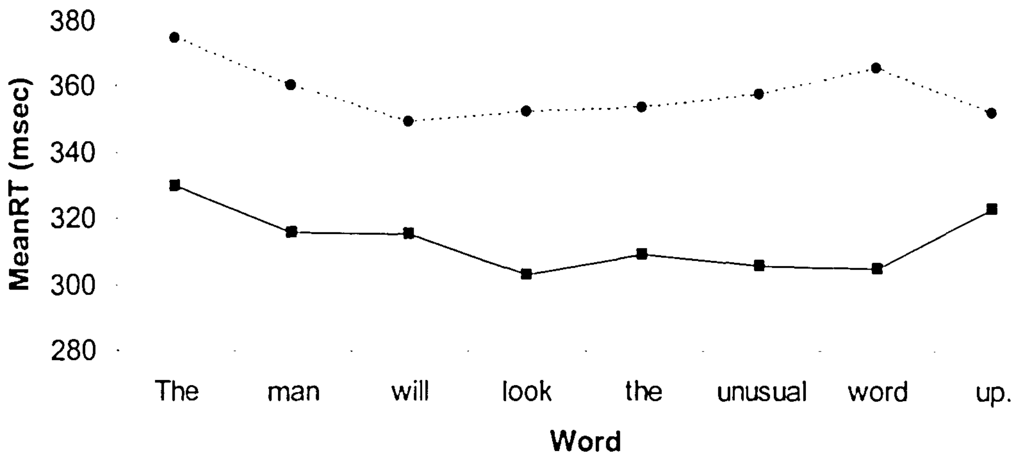


Figure 5d. Particle-Shifted Medium Sentences



Figures 5c-5d. Study 1: Mean word by word reading times (msec) for the low and high WM groups reading particle *adjacent* (Figure 5c, top) and *shifted* (Figure 5d, bottom) sentences with *medium* direct object noun phrases.

Figure 5e. Particle-Adjacent Long Sentences

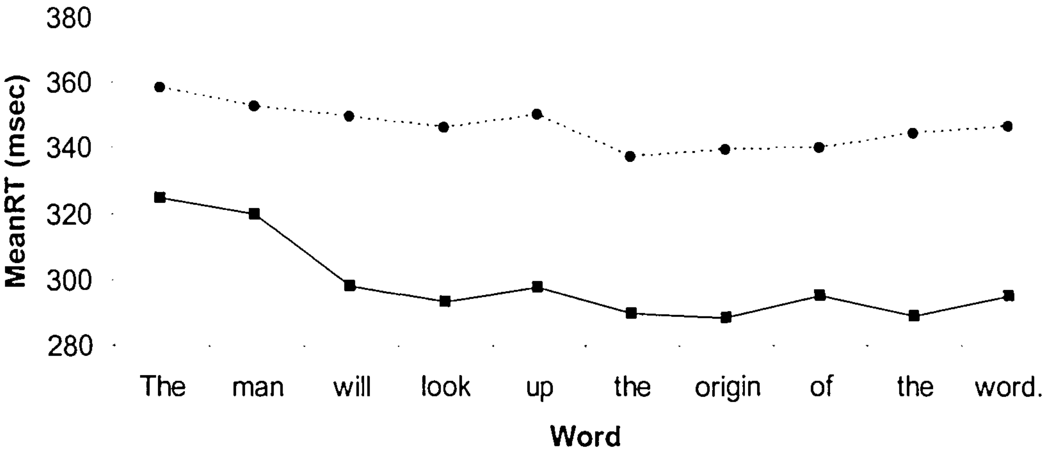
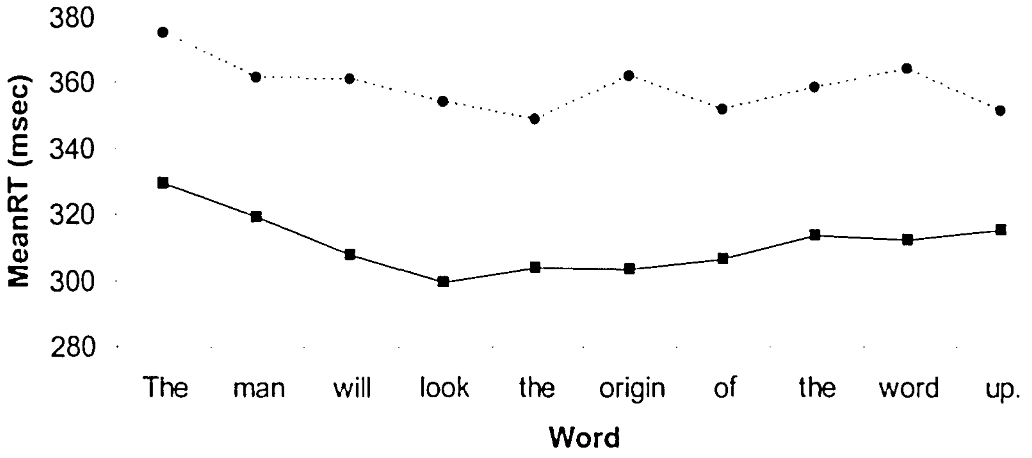


Figure 5f. Particle-Shifted Long Sentences



Figures 5e-5f. Study 1: Mean word by word reading times (msec) for the low and high WM groups reading particle *adjacent* (Figure 5e, left) and *shifted* (Figure 5f, right) sentences with *long* direct object noun phrases.

Figure 6a. Low WM Group

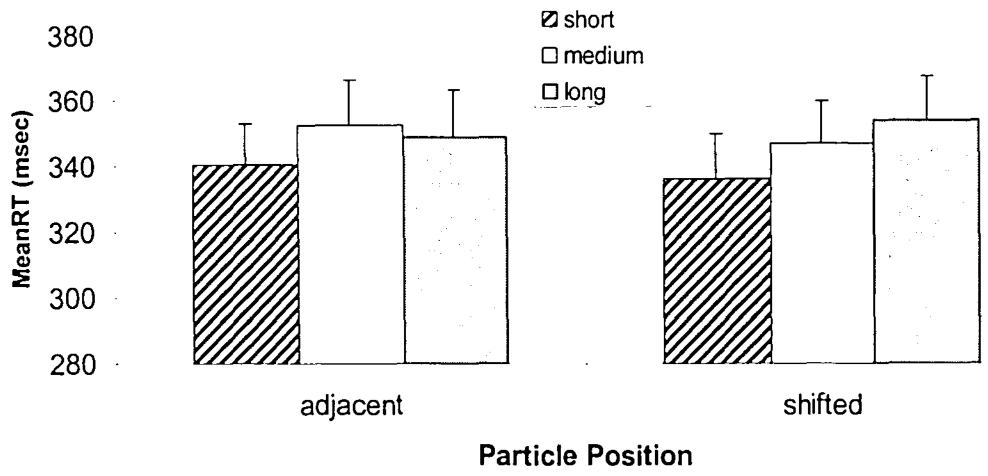
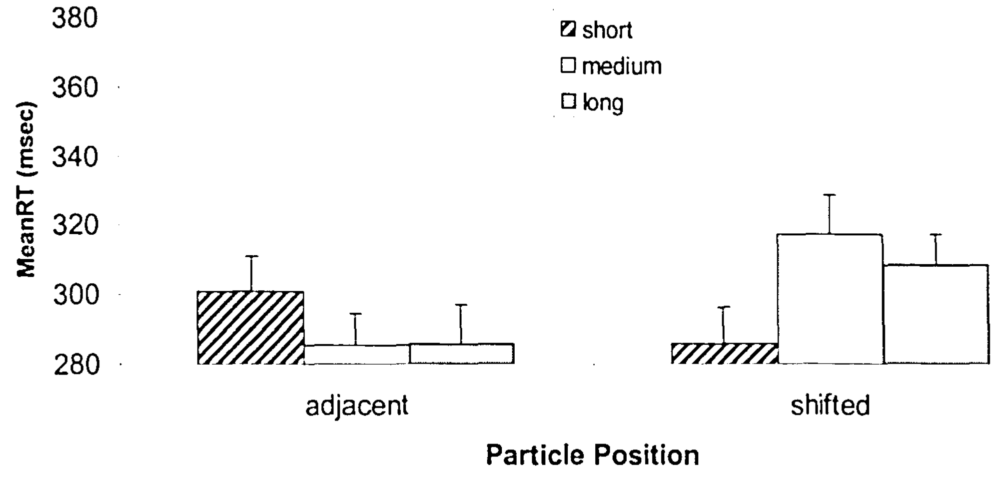


Figure 6b. High WM Group



Figures 6a and 6b. Study 1: Mean particle reading times (msec) for the *low* (6a, top) and *high* (6b, bottom) WM groups reading sentences that vary in verb-particle adjacency (adjacent or shifted) and direct object NP length (short, medium, or long).

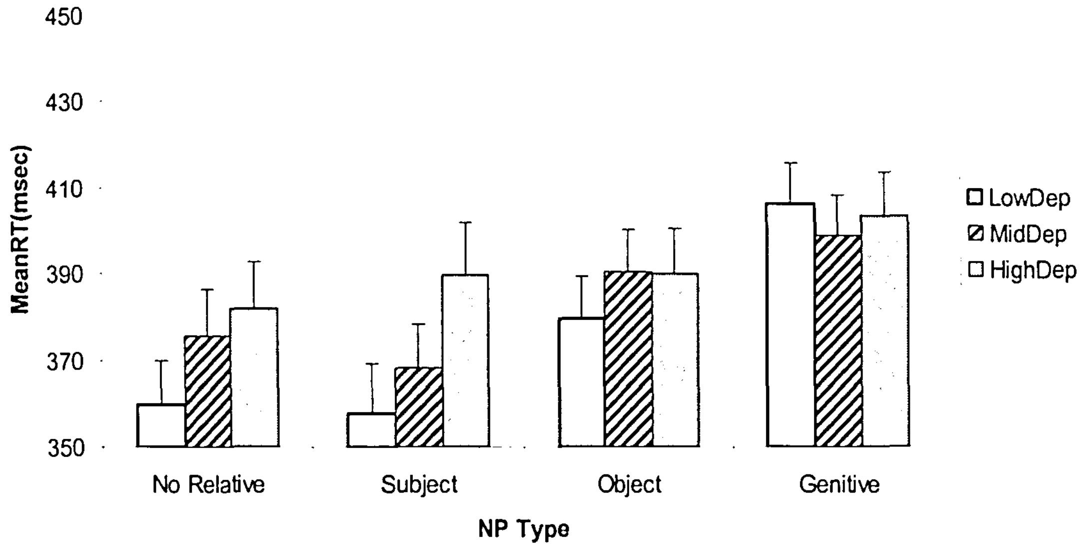


Figure 7. Study 2: Mean reading times (msec) for the shifted particle in sentences that varied in verb-particle dependency (low, middle, or high) and NP complexity (no relative, subject relative, object relative, or genitive relative).

Figure 8a. Particle-Adjacent No Relative Clause

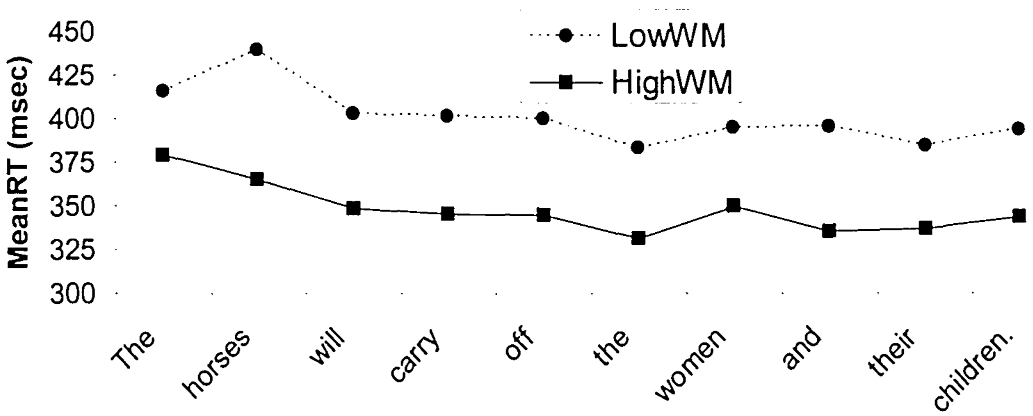
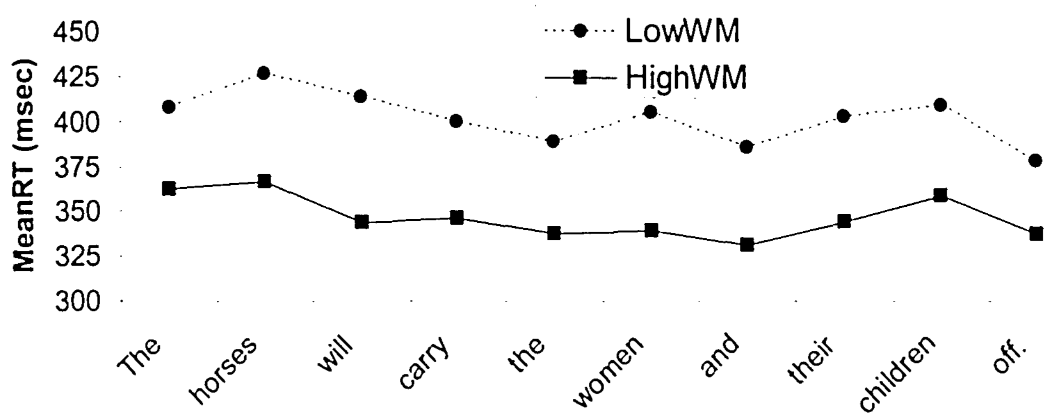


Figure 8b. Particle-Shifted No Relative Clause



Figures 8a-8b. Study 2: Mean word by word reading times (msec) for the low and high WM groups reading particle *adjacent* (Figure 8a, top) and *shifted* (Figure 8b, bottom) sentences with *no relative clauses* in the direct object noun phrases.

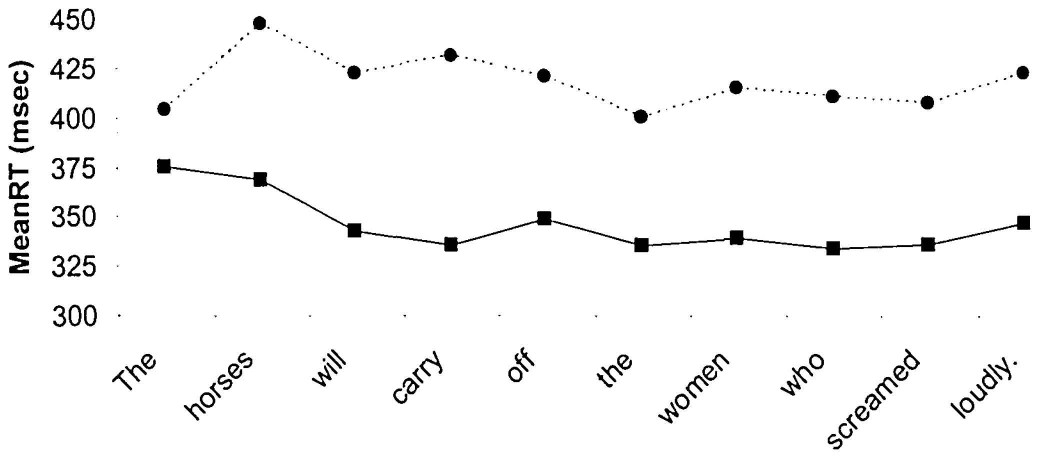


Figure 8c. Particle-Adjacent Subject Relative

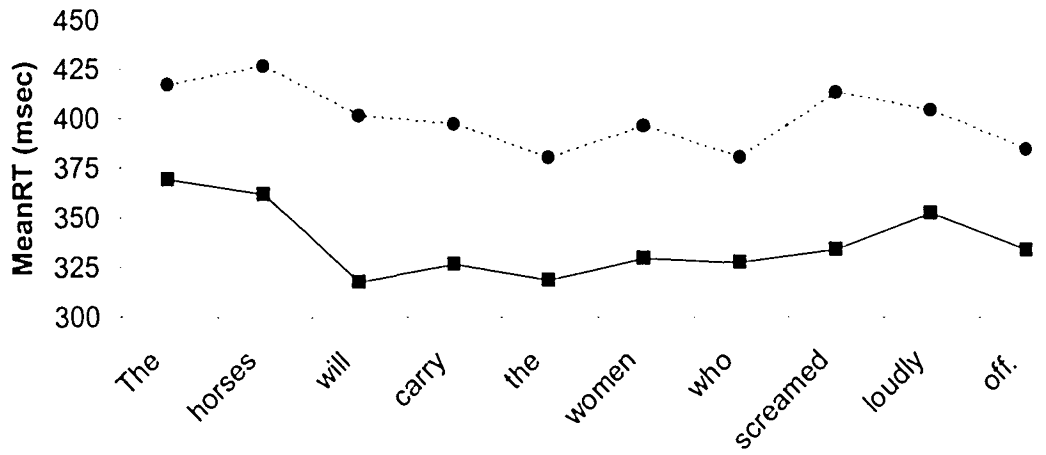


Figure 8d. Particle-Shifted Subject Relative

Figures 8c-8d. Study 2: Mean word by word reading times (msec) for the low and high WM groups reading particle *adjacent* (Figure 8c, top) and *shifted* (Figure 8d, bottom) sentences with *subject relative clauses* in the direct object noun phrases.

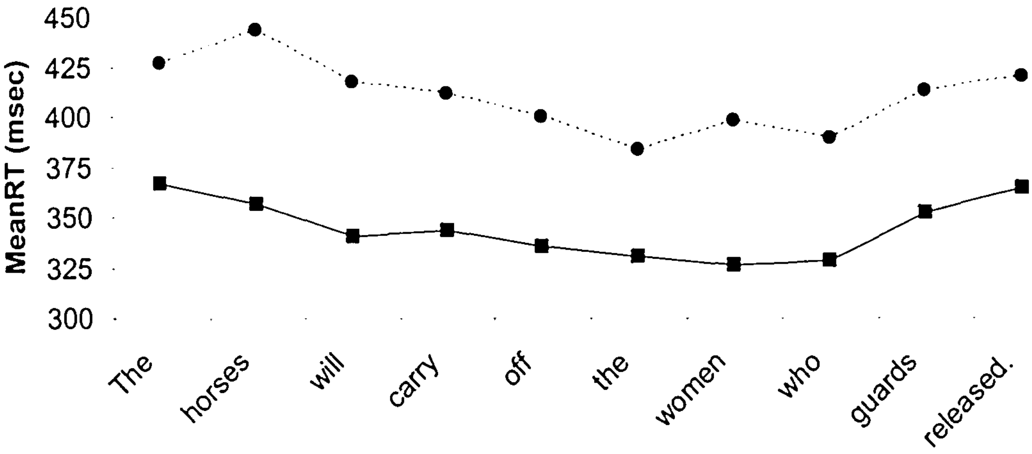


Figure 8e. Particle-Adjacent Object Relative

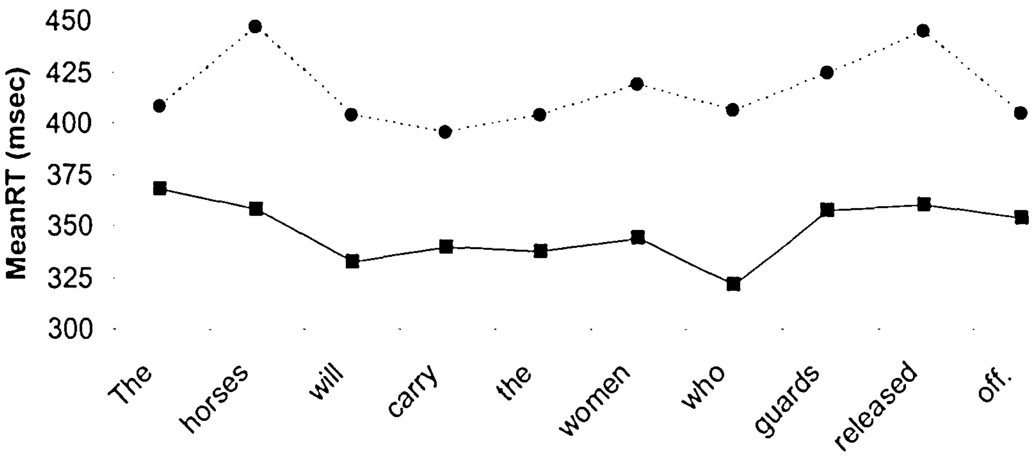


Figure 8f. Particle-Shifted Object Relative

Figures 8e-8f. Study 2: Mean word by word reading times (msec) for the low and high WM groups reading particle *adjacent* (Figure 8e, top) and *shifted* (Figure 8f, bottom) sentences with *object relative clauses* in the direct object noun phrases.

Figure 8g. Particle-Adjacent Genitive Relative

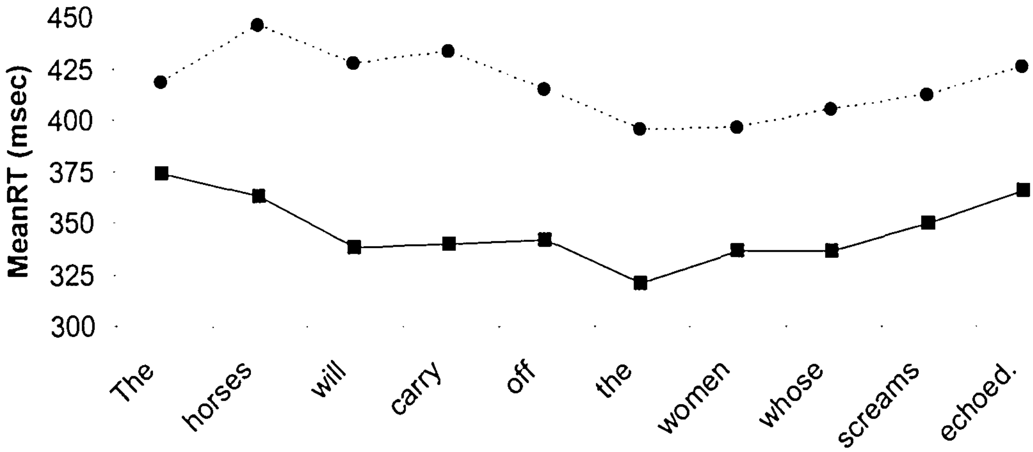
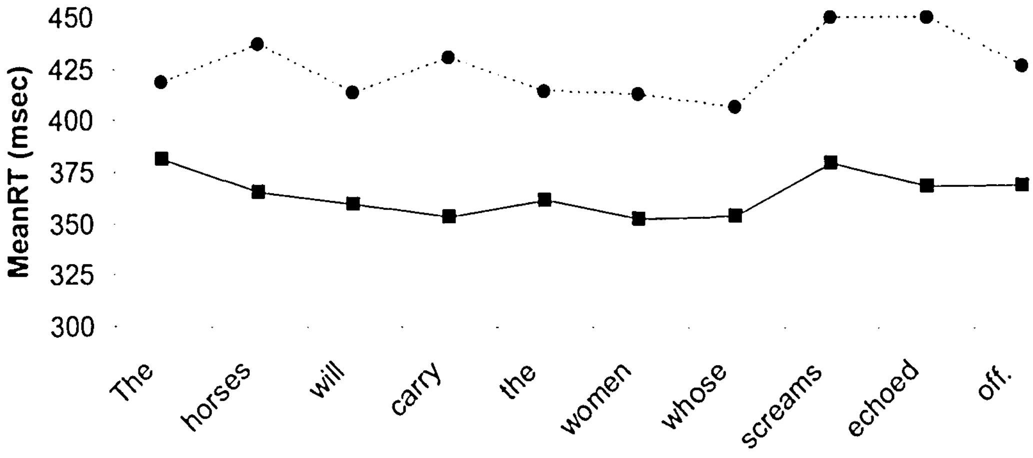


Figure 8h. Particle-Shifted Genitive Relative



Figures 8g-8h. Study 2: Mean word by word reading times (msec) for the low and high WM groups reading particle *adjacent* (Figure 8g, top) and *shifted* (Figure 8h, bottom) sentences with *genitive relative clauses* in the direct object noun phrases.

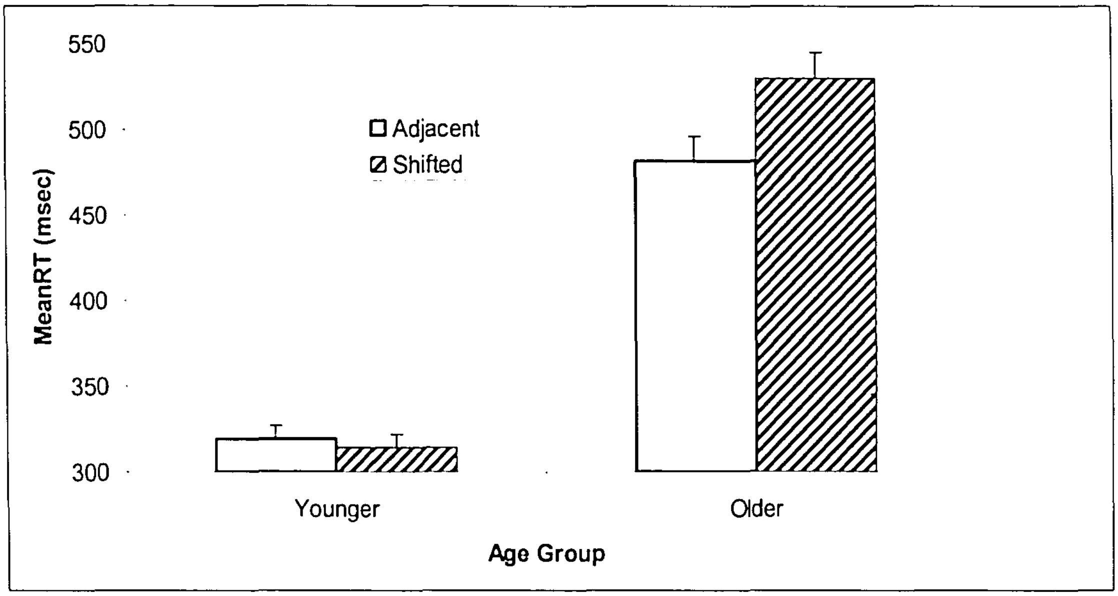


Figure 9. Study 3: Mean reading times (msec) for adjacent or shifted particles in sentences with *low* dependency verb-particle constructions and *short* direct object NP's read by younger and older age groups.

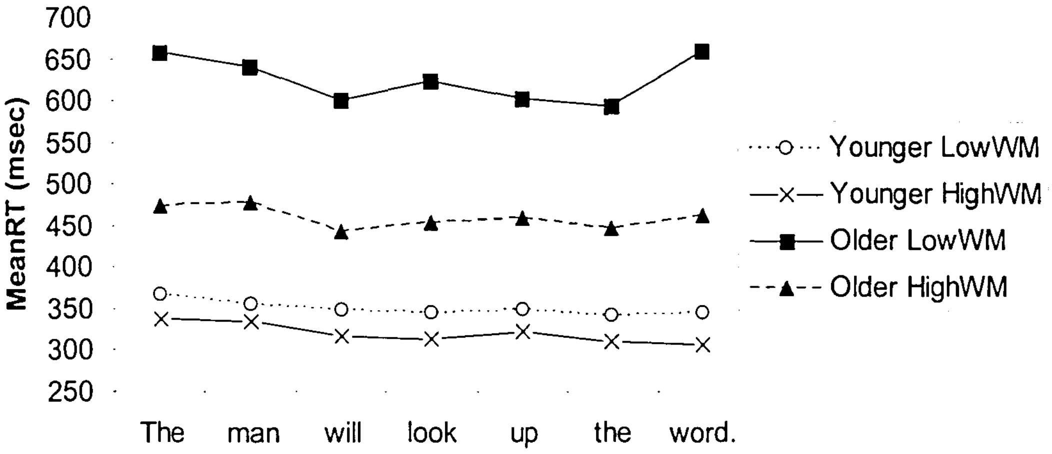


Figure 10a. Particle-Adjacent Short NP

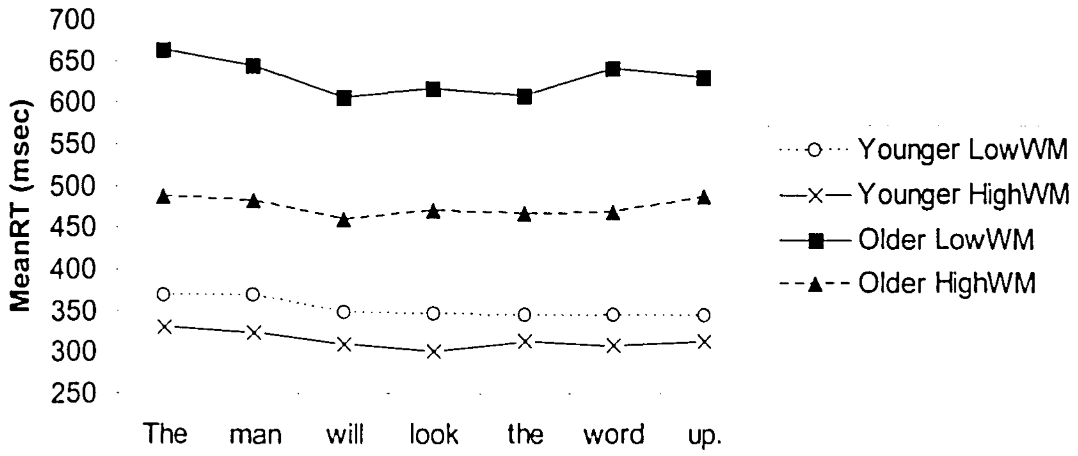


Figure 10b. Particle-Shifted Short NP

Figures 10a-b. Study 3: Mean word by word reading times (msec) for younger and older adults in the low and high WM groups reading particle *adjacent* (Figure 10a, top) and *shifted* (Figure 10b, bottom) sentences with *short* direct object noun phrases.

Figure 10c. Particle-Adjacent Medium NP

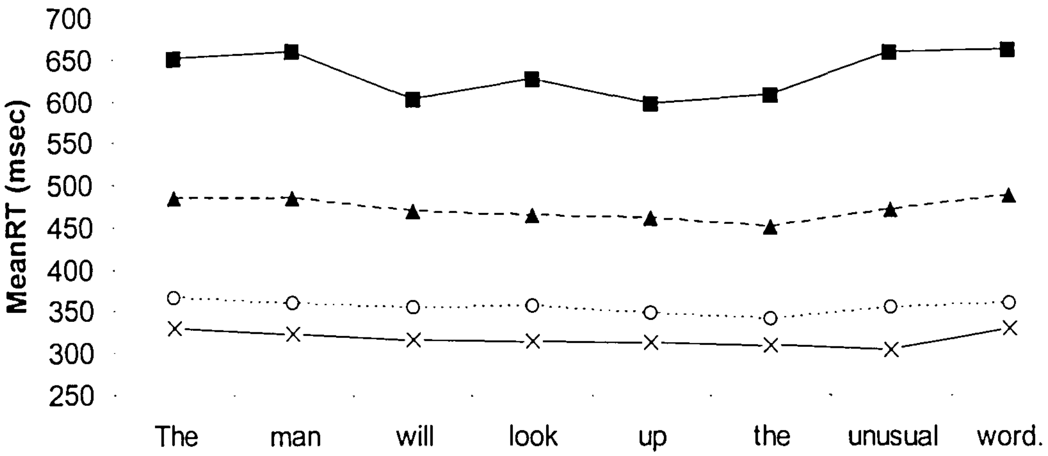
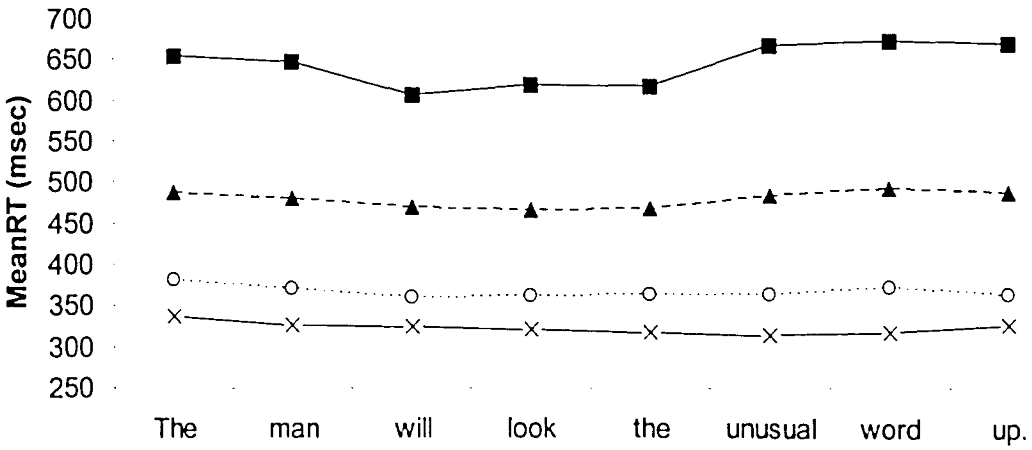


Figure 10d. Particle-Shifted Medium NP



Figures 10c-d. Study 3: Mean word by word reading times (msec) for younger and older adults in the low and high WM groups reading particle *adjacent* (Figure 10c, top) and *shifted* (Figure 10d, bottom) sentences with *medium* direct object noun phrases.

Figure 10e. Particle-Adjacent Long NP

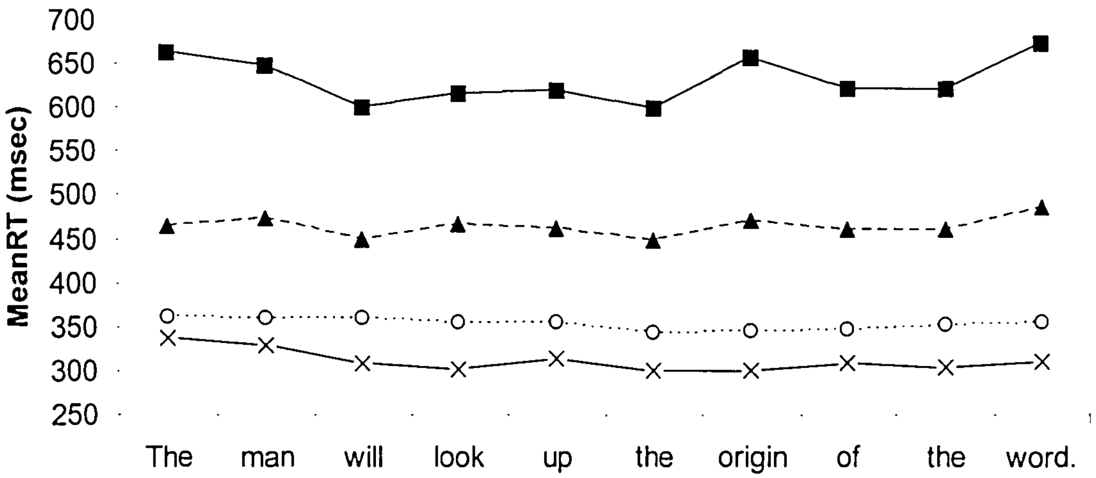
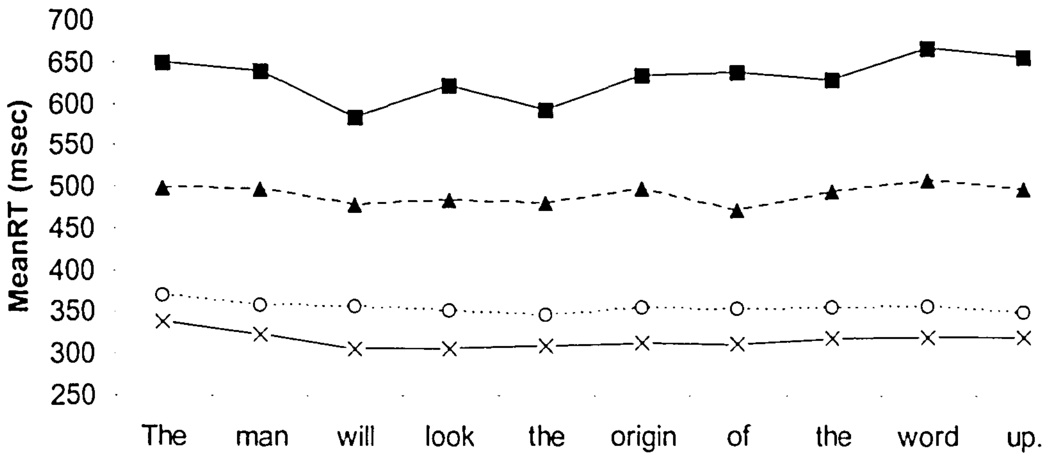


Figure 10f. Particle-Shifted Long NP



Figures 10e-f. Study 3: Mean word by word reading times (msec) for younger and older adults in the low and high WM groups reading particle *adjacent* (Figure 10e, top) and *shifted* (Figure 10f, bottom) sentences with *long* direct object noun phrases.

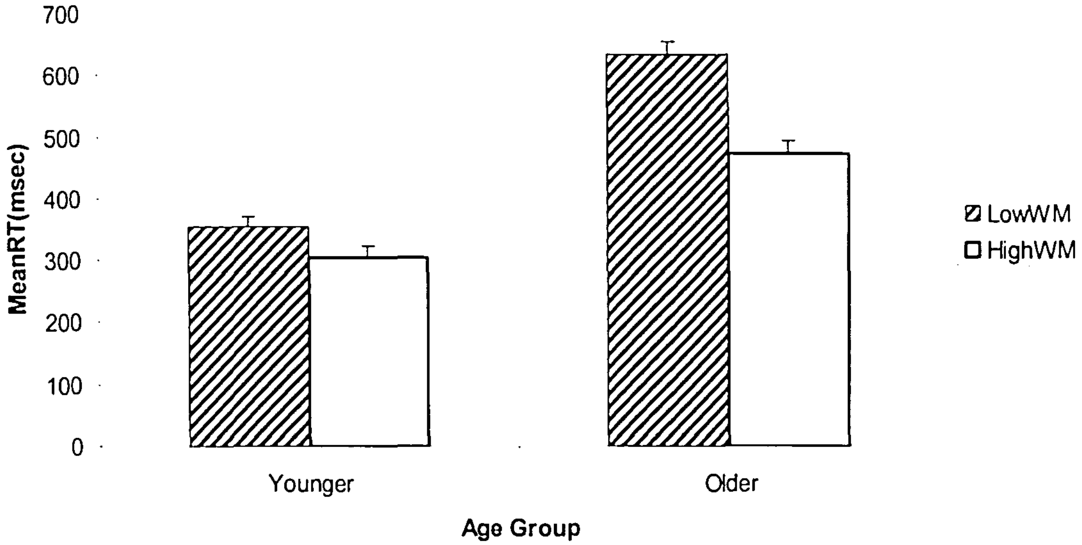


Figure 11. Study 3: Mean reading times per word (msec) across the direct object NP for older and younger adults in the low and high WM group.

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Curriculum Vitae

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EDUCATION

August, 2005- May, 2007 (expected)	M.S. in Cognitive Psychology, Lehigh University, Bethlehem, PA
May, 2006- December, 2006	Pre-SLP Program, LaSalle University, Philadelphia, PA
May, 2004	B.S. in Psychology, Lehigh University, Bethlehem, PA Graduated summa cum laude with departmental honors *Honors Thesis: Dependency and Length as Processing Constraints on Word Order in Particle Constructions* Advisor: Dr. Laura Gonnerman

HONORS AND AWARDS

May, 2004	Donald T. Campbell Social Science Research Prize, Lehigh University
April, 2004	Williams Writing and Performance Award, Lehigh University

RESEARCH EXPERIENCE

September, 2005- January, 2007	**Research Assistant,** Language and Thought Lab, Department of Psychology, Lehigh University Assisted Dr. Barbara Malt with multiple research projects which investigated the conceptual and perceptual knowledge of objects in complex scenes. Tasks include: assisting in the design of research projects, collecting data, analyzing data, and managing undergraduate research assistants
September, 2005- February, 2006	**First Year Project Research,** Department of Psychology, Lehigh University Examined performance factors that affect sentence comprehension, specifically how syntactic and semantic factors interact to affect processing difficulty. In addition, how noun phrase complexity affects processing ease and how ease of processing reflects grammaticalized structures in languages of the world.
September, 2002- May 2005	**Research Assistant/Lab Manager,** Language Acquisition and Processing Lab, Lehigh University Assisted Dr. Laura Gonnerman with several projects, including, word and morpheme acquisition in toddlers and sentence processing and working memory ability in college students and older adults. Tasks included: formulating

projects; collecting, coding, and evaluating data; training and supervising undergraduate research assistants; and conducting literature searches.

TEACHING EXPERIENCE

August, 2004- **Teaching Assistant,** Lehigh University

May, 2005 Course: Introduction to Psychology

Tasks included: reviewing material with students, conducting review sessions, proctoring exams, and assisting in test formulation and preparation.

January, 2003- **Apprentice Teacher,,** Lehigh University

May, 2003 Course: Mind and Brain

Tasks included: creating class materials and grading students' homework.

PUBLICATIONS

Gonnerman, L. M., & Hayes, C.R. (2005). The professor chewed the students... out: Effects of dependency, length, and adjacency on word order preferences in sentences with verb particle constructions. In Proceedings of the Twenty-Seventh Annual Conference of the Cognitive Science Society. (p. 785-790). Mahwah, NJ: Erlbaum.

CONFERENCE PRESENTATIONS

Gonnerman, L. M., & Hayes, C.R. (2005, July). *The professor chewed the students... out: Effects of* *dependency, length, and adjacency on word order preferences in sentences with verb particle constructions.* Poster presented at the Proceedings of the Twenty-Seventh Annual Conference of the Cognitive Science Society, Stresa, Italy.

Gonnerman, L. M. & Hayes, C. R. (2005, April). *The relationship between processing difficulty and grammaticalization: Effects of relative clause type on word order preferences.* Poster presented at the 18th Annual CUNY Sentence Processing Conference, Tucson, AZ.

Gonnerman, L. M. & Hayes, C. R. (2004, March). *Dependency and length as processing constraints on word order in particle constructions.* Poster presented at the 17th Annual CUNY Sentence Processing Conference, College Park, MD.

ACADEMIC SERVICE

September, 2005- May, 2006	**Brown bag seminar organizer,** Department of Psychology, Lehigh University

BIOGRAPHY

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Parents: Bart and Deborah Hayes

END OF TITLE