Language and Linguistics Compass 6/4 (2012): 193–211, 10.1002/lnc3.330

Memory Interference as a Determinant of Language Comprehension

Julie A. Van Dyke* and Clinton L. Johns
Haskins Laboratories

Abstract

The parameters of the human memory system constrain the operation of language comprehension processes. In the memory literature, both decay and interference have been proposed as causes of forgetting; however, while there is a long history of research establishing the nature of interference effects in memory, the effects of decay are much more poorly supported. Nevertheless, research investigating the limitations of the human sentence processing mechanism typically focus on decay-based explanations, emphasizing the role of capacity, while the role of interference has received comparatively little attention. This paper reviews both accounts of difficulty in language comprehension by drawing direct connections to research in the memory domain. Capacity-based accounts are found to be untenable, diverging substantially from what is known about the operation of the human memory system. In contrast, recent research investigating comprehension difficulty using a retrieval-interference paradigm is shown to be wholly consistent with both behavioral and neuropsychological memory phenomena. The implications of adopting a retrieval-interference approach to investigating individual variation in language comprehension are discussed.

1. Introduction

One of the most fascinating properties of natural language is the fact that related pieces of information need not be adjacent. For instance, the subject of a sentence (*athlete*) may be separated from its verb (*ran*) by just a few words (1), or by many words, phrases, or even clauses (2–4):

(1) The *athlete* in the training program *ran* every day.
(2) The *athlete* in the training program that was designed by an Olympic gold-medal winner *ran* every day.
(3) The *athlete* who the Olympic gold-medal winner in the training program coaches *ran* every day.
(4) The *athlete* who the Olympic gold-medal winner who the coach hired trained *ran* every day.

The ability to process non-adjacent dependencies of this sort suggests a fundamental role for memory processes in language comprehension. Nevertheless, linguistic theory has generally not made close contact with memory research. For example, although configurational properties and formal construction rules (e.g., c-command) have been proposed to explain why certain types of dislocation lead to comprehension difficulty, as in (3), or failure, as in (4), there has been no systematic attempt to determine whether such configurations can actually be maintained in active memory. This is particularly problematic because most processing accounts of comprehension breakdown rely on the concept of memory *capacity* to define the bounding constraints for long distance dependencies. This approach holds that the amount of information that can be actively maintained is limited, and that comprehension failure arises when that limit is exceeded. The obvious next step is to determine the means through which the language processing mechanism might regain access to this lost information; however, despite decades of research exploring the relation between memory and language processes, a clear understanding of the factors that influence availability of information during language processing is still lacking.

In this review we approach this problem by seeking answers from the domain of memory research, in which the issues of information storage, maintenance, and retrieval are the central concerns. We take seriously the idea that the memory system that subserves language processing has properties that are (at least) functionally equivalent to those that serve other memory-dependent tasks. From this perspective, research in the memory domain becomes an important resource for generating predictions about how comprehension processes may be limited. One of the most consistent findings to arise from this research is that *interference* is a primary source of memory failure, affecting both the ability to maintain active information and to restore inactive information into the focus of attention. This is in contrast to *decay*, which has played a prominent role in certain accounts of forgetting, and has been the most frequently suggested explanation for comprehension difficulty. We first review the notion of decay, and explore the roots of its influence on models of language processing. We then summarize evidence from the memory literature that interference constrains the availability of information; discuss research that extends this finding to sentence processing; and suggest an alternative neural architecture for language comprehension. Finally, we review the role that memory capacity and interference have played in explaining individual differences in reading ability, concluding with a discussion of areas in which future research can further elucidate the role of interference in language comprehension.

2. Forgetting

2.1. DECAY AND CAPACITY APPROACHES TO COMPREHENSION

The concept of decay was one of the earliest explanations for memory failure. Simply put, the strength of a memory trace fades with the passage of time, becoming increasingly difficult to retrieve. The only way to avoid decay is to actively maintain the critical information in memory. The classic demonstrations of decay are the Brown–Peterson studies (Brown 1958; Peterson and Peterson 1959), in which articulatory suppression was used to block rehearsal during a memory task where participants were supposed to remember a three-consonant trigram (e.g., *TWF*). Memory performance declined as the length of the suppression task increased from three to eighteen seconds (i.e., as the delay between study and test increased), until only about 10% of studied trigrams could be recalled. The apparent conclusion is that, absent rehearsal, information will be almost completely lost within about 18 seconds.

The ideas that active maintenance is achieved via rehearsal, and that information that is not rehearsed is vulnerable to time-based decay, are incorporated into one of the most prominent accounts of memory function: the Baddeley Working Memory model (Baddeley 2003; Baddeley and Hitch 1974). This model also formalizes the role of *capacity* as central to memory access. The architecture of the model includes three fixed-capacity ‘‘slave’’ systems that store phonological information (the ‘‘phonological loop’’), visuo-spatial information (the ''visuo-spatial sketchpad''), and integrated episodic information. These stores are coordinated via a separate executive control mechanism, which is also responsible for directing attention during task completion and managing encoding and retrieval processes. This working memory model was originally developed to account for a number of experimental findings arising out of memory recall paradigms, where the task is to remember lists of words (or patterns of objects) in the face of a variety of distracting conditions (e.g., Baddeley 1966; Conrad 1964; Murray 1967; Wickelgren 1965). This research showed that information is lost from memory unless it is rehearsed.

The immense popularity and influence of the Baddeley Working Memory model is largely responsible for the focus on fixed capacity in many theories of language processing. To illustrate, consider the oft-replicated finding that sentences in which grammatical heads are separated from their dependents are more difficult to process than those with heads that are adjacent (e.g., Grodner and Gibson 2005; McElree et al. 2003). This is true of unambiguous sentences like (5) and (6), as well as ambiguous sentences like (7) and (8) – in both cases the shorter sentence is more easily processed than the longer one.

(5) The *book ripped*.
(6) The *book* that the editor admired *ripped*.
(7) The boy understood the *man was afraid*.
(8) The boy understood the *man* who was swimming near the dock *was afraid*.

A number of prominent theories have accounted for these results by appealing to working memory capacity. The common conclusion is that the unattached constituent (the grammatical subjects *book* and *man* in these examples) cannot be actively maintained while processing the intervening material because doing so exceeds the comprehender's processing capacity. This inattention to necessary constituents results in their loss from memory through decay and displacement. Thus, as the distance between the unattached constituent and its associated dependent increases, so does comprehension difficulty, because more information will be lost and the likelihood that the distal constituent in particular will be displaced is much higher. The chief question, then, is how much intervening material is ''too much'', after which capacity is exhausted and critical information is rendered inaccessible? Some have suggested that the relevant metric is the number of words (Ferreira and Henderson 1991; Warner and Glass 1987) or discourse referents (Gibson 1998, 2000). Others have focused on the hierarchical nature of dependencies, suggesting that difficulty depends on the number of embeddings (Miller and Chomsky 1963), or the number of incomplete dependencies (Abney and Johnson 1991; Gibson 1998; Kimball 1973). The intuitive appeal of this approach was further enhanced by the development of simple, easy-to-administer tasks designed to index capacity (e.g., the Reading Span task; Daneman and Carpenter 1980). The result has been hundreds of studies adopting a capacity approach to language processing over the past three decades, in which decay effectively emerges as the de facto arbiter of successful comprehension.

The attempt to link language processing to the body of research on decay suffers from a fundamental weakness; however, the evidence supporting decay is equivocal. One of the chief problems for tests of the decay hypothesis is that it is nearly impossible to rule out interference as an alternative explanation for retrieval failure. For example, the classic Brown–Peterson evidence for decay was quickly called into question. In a modified analysis of data from the Brown–Peterson task, Underwood and Keppel (1962) found that trials at the beginning of the experiment were more easily recalled than those from the later stages, regardless of time between study and test: accuracy on the first trial was nearly 100% even after a delay of 18 minutes, thereafter declining on each successive trial. This finding directly contradicts the conclusion of the original studies, suggesting that the evidence of decay was an artifact of the analysis method (in which the experimenters aggregated data over all individual trials). Underwood and Keppel concluded that the likely source of retrieval difficulty was interference, rather than decay: the residual activation of items from earlier trials persisted as the experiment progressed, such that recall on later trials suffered. That is, as the number of items in memory that were similar to the target increased, they interfered with participants' ability to discriminate the correct target from the other distracting information. Waugh and Norman (1965) mounted an additional challenge to the decay account, demonstrating, contrary to the decay hypothesis, that the passage of time affected recall performance only minimally, if at all. They varied the presentation rate of 16-digit study lists, at the end of which subjects were asked to recall the digit that followed a target probe. Presentation was either fast (four digits/second, recall in 4 seconds) or slow (one digit/second, recall in 16 seconds). Despite the greater length of time between study and test in the latter condition, there was no difference in recall performance as a function of presentation rate.

More recently, Berman et al. (2009) directly compared effects of interference and decay using an item recognition task introduced by Sternberg (1966). Participants are shown four target words to remember for a brief retention interval followed by a probe word and must judge whether or not the probe word occurred as one of the four target words. Interference trials are created via negative trials, in which the probe word did not occur as one of the four target words in the current trial, but did occur in the previous trial. In such a design, the amount of interference can be manipulated by varying how many trials back the probe word had occurred. Berman and colleagues contrasted three types of negative trials. The first type had probes taken from the two-back set, thus having one full trial separating the appearance of the probe word in a memory set from its occurrence as a probe. The second type of negative trial had the probe word taken from the one-back set, but with an inter-trial interval (ITI) equated to the time that an additional trial would have taken (10 seconds). This contrast provides a direct test of the effect of interference, while keeping the passage of time between the first occurrence of the probe word constant. The third type negative trial had the probe word taken from the one-back set with an ITI of only 1 second. Contrasting this trial with the second type provided a test of the effects of decay, controlled against confounding effects of intervening information. Berman et al. found significantly lower response times for the two-back condition (type 1) as compared to the one-back condition with a blank 10 seconds ITI (type 2), attesting to an effect of interference; however, they found no significant difference between the two-one-back trials with varying it is (types 2 and 3), suggesting no effect for decay. This, together with six additional experiments in which they probed for possible effects of decay over various ITIs and found none, further contributes to the now large body of work suggesting that it is interference, and not the mere passage of time, that contributes to reduced memory performance.

2.2. INTERFERENCE, RETRIEVAL CUES, AND CUE-OVERLOAD

While decay is concerned with the lack of attention focused on the contents of memory, interference is concerned with precisely the opposite. That is, it is concerned with the attention devoted to processing the seemingly irrelevant items in memory, which cause the target to become unavailable. Focusing on interference as the factor constraining memory access suggests a memory-language interface that is quite different from that inspired by the Baddeley model. The emphasis shifts from the *quantity* of information that can be maintained, to *the specific content* of that information, and the question of whether it can be retrieved. Shifting the focus away from capacity and towards retrieval makes moot the question of how much intervening material is tolerable. Instead, the reliability of retrieval cues for discriminating targets among distracting information in memory (including the relation of the cue and the content of the distracting information) is the parameter that determines successful memory access. This is consistent with the long history of research indicating that the presence of similar items in memory results in the retrieval of unwanted items, thus decreasing the probability of retrieving the correct target – possibly to the extent that it appears to be entirely lost from memory (e.g., Nairne 2002; Öztekin and McElree 2007; Watkins and Watkins 1975).

Reliable retrieval cues are associated with a single target item in memory, thus minimizing the probability that other distractor items in memory will interfere with retrieval operations. When retrieval cues are associated with multiple items in memory, the cue is said to be ''overloaded'' (Watkins and Watkins 1975). Two varieties of cue-overload have been extensively investigated in memory tasks: the case where similar items precede the target, creating proactive interference (PI), and the case were similar items follow the target, creating retroactive interference (RI). To illustrate, consider the memory items X, Y, and Z, which we assume have an underlying feature structure as represented in brackets (see Figure 1). The item α will serve as a retrieval probe intended to restore item Y back into active memory; at issue is the content of the feature structure associated with α that specifies the retrieval cues used to access item Y. If α is associated only with feature *d*, then it will be a reliable cue for accessing item Y, as no other memory item is associated with that feature. However, if α is also associated with either *c* or *e* it becomes an overloaded cue; that is, while it will elicit Y in some non-zero proportion of trials, it will do so much less often because *c* and *e* are associated with other items in the list. As shown in the figure, the association of *c* with X creates PI for accessing Y and the association of *e* with Z creates RI. Cue-overload (and, consequently, both PI and RI) can result from both semantic and contextual features of studied items.

Evidence for contextual cue-overload comes from experiments using paired-associate learning paradigms, in which participants are trained to criterion on lists of word pairs,

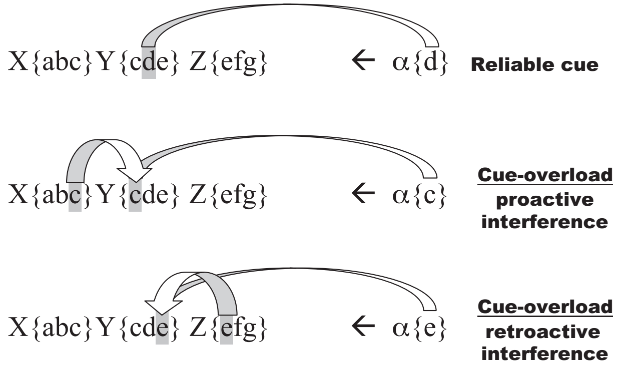

Fig 1. Graphical illustration of proactive and retroactive interference during retrieval of item Y. Feature structures are exemplified as discrete values in brackets, however, this is only for illustrative purposes. The assumption is that memory representations are comprised of continuous feature bundles and are matched via a global matching process (e.g., Clark & Gronlund, 1996), which simultaneously takes all features into account. See Van Dyke and McElree (2011) for further discussion.

and retrieval is tested by presenting one member of a pair as a cue for producing its associate. In A-B/A-C lists, word A (*paper*) is a retrieval cue associated with word B (*string*) and word C (*watch*), as in the pairs *paper-string* and *paper-watch*. This contrasts with A-B/C-D lists, where A is a unique retrieval cue for its associate, unconnected to the C-D word pair (e.g., *foam-iron*). The result is that performance is worse when A appears in multiple pairs; further, performance declines in direct relation to the number of associates A has in the list (Anderson 1974). Here, interference is the result of incidental properties of the list in which the word appears, rather than pre-existing semantic associations.

Evidence for semantic cue-overload comes from experiments that manipulate the semantic overlap among studied items. For example, Öztekin and McElree (2007) presented participants with a series of six-item study lists, each of which contained items from the same semantic category (e.g., fruit: banana, kiwi, apple, lime, orange, pear). The semantic category of the trial list changed after participants studied three lists containing items from the same category; for instance, after three lists containing fruit items, participants might receive a list of animal items (e.g., sheep, lion, deer, hamster, dog, lizard). Each list was followed immediately by a recognition probe. Consistent with other studies using this paradigm, participants' ability to correctly verify the test probe declined over the course of trials with items drawn from the same semantic category (see also Dillon and Bittner 1975; Gardiner et al. 1972; Watkins and Watkins 1975; Wickens 1970; cf. Crowder 1976). That is, they were most accurate after the first fruit list, less accurate after the second, and least accurate after the third. The semantic overlap among items in a particular category means that each new fruit item creates competition for retrieving the memory trace for any particular fruit, making it difficult for participants to reliably determine whether a test probe (e.g., pear) actually appeared. In addition, participants were released from PI (see also Wickens 1972) immediately upon switching categories, thus further highlighting the semantic nature of the retrieval interference; the efficacy of the retrieval cue was enhanced once it no longer shared features with items from the previous lists, and memory performance improved.

3. Forgetting during Language Comprehension

3.1. INTERFERENCE

3.1.1. Evidence for proactive interference during sentence comprehension

Effects of PI on sentence processing have been observed in a number of recent studies. Gordon et al. (2002) used a memory load paradigm in which participants were required to memorize a list of words prior to reading a sentence and then recall the words after reading. This technique has the advantage of permitting a direct manipulation of the contents of memory during comprehension. While the length of the memory list was held constant at three items across conditions, they manipulated the similarity of the items in the load vis-à-vis the noun phrases in the sentence to be comprehended. For example, memory load was either a list of three proper names or three role descriptions (e.g., banker), and the NPs in the sentence were either names or roles (different from those in the memory load). In this paradigm, potential for interference comes from the match between the type of nouns in the memory load and the type of nouns in the sentences (see 9 and 10).

(9) Matched memory load: Joel-Greg-Andy
Sentence: It was Tony that [liked Joey\Joey liked] before the argument began.

(10) Mismatched memory load: Joel-Greg-Andy
Sentence: It was the dancer that [liked the fireman\the fireman liked] before the argument began.

Gordon et al. (2002) observed a clear match effect on accuracy to comprehension questions, in which participants produced significantly higher error rates when the nouns in the load lists matched the category of the sentential nouns, as in (9). Further, they found an interaction indicating that the match effect was stronger in constructions where the two noun phrases had to be held in memory before they can be integrated with their verb (i.e., *It was Tony that Joey liked…* and *It was the dancer that the fireman liked…*). This suggests that the content of the memory list had a direct effect on comprehension processes, contra suggestions that memory and language processes may draw on separate memory systems (e.g., Caplan and Waters 1999). Fedorenko et al. (2006) extended these results using the same paradigm to measure effects of low and high memory load (1-word vs. 3-word lists) on reading times for subject-relative (11) and object-relative (12) clause constructions.

(11) The physician <u>who consulted the cardiologist</u> checked the files in his office.
(12) The physician <u>who the cardiologist consulted</u> checked the files in his office.

They reported reliably slower reading times for embedded material in object-relative clauses under high load conditions. Consistent with Gordon et al. (2002), these findings indicate that similarity-based interference induced by the prior contents of memory is an important determinant of comprehension difficulty.

A significant limitation of these studies, however, is that they do not establish whether interference effects arise during the *encoding* of subsequent NPs or during *retrieval* of the required constituent. Specifically, if the effect were purely an encoding effect (due to the presence of same-NP-type distractors in memory), then processing difficulty should occur at the point when the similar item is first encountered (i.e., in the region containing *It was the NP that…* in sentences (9) and (10), or at the reading of *physician* in sentences (11) and (12). Slower reading times in this region are difficult to uniquely attribute to either encoding or retrieval, however, as the slowdown may arise either because the quality of the memory representations are diminished, or because the retrieval cues are insufficient due to cue-overload.

Van Dyke and McElree (2006) aimed to distinguish between these two accounts by explicitly manipulating the retrieval cues available to the reader. They used the memory load paradigm as in Gordon et al. (2002) and manipulated the relationship between the memory load items and the semantic cues used to identify the target subject. Thus, in a sentence like (13) they assumed it was necessary to retrieve the subject *boat* upon reading the verb *sailed* so that it could be integrated as a direct object.

(13) Memory load: TABLE-SINK-TRUCK
It was the *boat* that the guy who lived by the sea <u>*sailed*</u> after 2 days.

This condition was presumed to be a low interference trial because *boat* is the only noun in the sentence that is "sail-able." Semantic interference was manipulated by varying the critical (underlined) verb, so that the memory list items were or were not suitable potential objects of the verb (e.g., substituting *fixed* for *sailed*). Van Dyke and McElree observed longer reading times at the manipulated verb when the memory list items could serve as objects; for example, in (13), all memory list items are "fixable", than when they could not, an effect that disappeared when subjects read these sentences without first memorizing the memory set. Van Dyke and McElree interpreted this as evidence of PI from the presence of items in memory that fit the retrieval cues of the verb, making it difficult for readers to uniquely identify which of the recently encountered nouns actually occurred in the sentence. Moreover, since the encoding conditions were constant, the effect could be clearly assigned to retrieval processes, pointing to the importance of cue-based retrieval as the mechanism through which interference effects arise. This is consistent with studies in the memory domain which suggest that interference has its primary effect on retrieval processes, with little or no effect on memory encoding or storage (Dillon and Bittner 1975; Gardiner et al. 1972; Tehan and Humpreys 1996).

3.1.2. Evidence for retroactive interference during sentence comprehension

Retroactive interference has also been observed in the language domain. Van Dyke and Lewis (2003) investigated contextual interference by contrasting various syntactic constructions occurring in the region between two grammatically dependent constituents, such as *man* and *was paranoid*, as in (14) and (15).

(14) The frightened boy understood that the *man* who was swimming near the dock *was paranoid* about dying.
(15) The frightened boy understood that the *man* who said the townspeople were dangerous *was paranoid* about dying.

The amount of interference is measured with respect to the retrieval cues from the verb phrase *was paranoid*, which is assumed to contain cues that will identify a grammatical subject with which it can be associated, and consequently integrated into a coherent interpretation of the sentence. Thus, sentence (15) is considered to have more interference than sentence (14) because the intervening noun phrase *the townspeople* shares grammatical encoding characteristics with the target constituent: both are grammatical subjects. The retrieval cues from the verb will therefore match both *the townspeople* and *the man* as potential subjects. In contrast, sentence (14) is a low interference condition because it does not have a subject intervening between the verb phrase and the target noun phrase; rather, the intervening noun phrase *the dock* is the object of a prepositional phrase. In addition, note that sentences (14) and (15) are matched on the distance dimension (both have six intervening words). Van Dyke and Lewis added an additional condition without intervening material, as in (16), which afforded an estimate of the distance effect by contrasting the long, non-interfering condition in (14) with (16).

(16) The frightened boy understood that the *man was paranoid* about dying.

They observed that interference had a significant effect on both reading times and acceptability judgments, but distance did not. This is consistent with the view that the critical factor for making constituents unavailable for retrieval is not the *amount* of information in memory, but rather how *similar* the intervening information is to the target.

In an extension of this paper, Van Dyke (2007) showed that interference from semantically similar distractors could arise as well, even when they are not in a syntactically similar position. Van Dyke used the same constructions as in (14) and (15) but manipulated the suitability of the intervening nouns as subjects of the main verb. Thus, (17) is identical to (14) except for the object of the intervening preposition phrase, where the word *dock* in (14) has been replaced with the word *girl* in (17). When readers process the semantic cues of the verb phrase *was paranoid*, retrieval is impaired in (17) because the intervening noun fits the retrieval cue as well as the intended target. Both *the man* and *the girl* can be paranoid, but *the dock* cannot. This result was also replicated when an adverbial occurs between the distractor *girl* and the critical verb phrase, and in constructions such as (15) when *townspeople* is substituted for *dock*, thus ruling out an explanation for these effects based on adjacency or local coherence (cf. Tabor et al. 2004).

(17) The frightened boy understood that the *man* who was swimming near the girl *was paranoid* about dying.

Another variety of semantic interference was observed by Gordon et al. (2001, 2004), who investigated the well-documented difficulty processing sentences containing object relative as compared to subject relative constructions (e.g., King and Just 1991; Staub 2010; Traxler et al. 2002). For example, *The banker that praised the barber climbed the mountain* is more easily processed than *The banker that the barber praised climbed the mountain.* The typical explanation for this subject-object difference appeals to the different demands each construction makes on memory. Gordon and colleagues sought to pinpoint the contribution of interference to the subject-object difference by manipulating the referential status of the second noun phrase in each type of clause. In several experiments, they contrasted the sentences above with versions that substituted an indexical pronoun (*you* or *everyone*) or a proper name (*Joe*) for *barber*, and found that the processing advantage for subject-relative clauses over object-relative clauses was reduced or eliminated. Gordon and colleagues reasoned that common nouns like *barber* and *banker* refer indirectly by virtue of their description, while pronouns and proper names refer directly, singling out specific entities in the current discourse representation. Thus, interference is reduced in sentences with one descriptive noun and one direct reference, because the two nouns can be more easily distinguished by virtue of their differing referential status.

3.1.3. Proactive vs. Retroactive Interference Effects

Although the investigations discussed above suggest that both RI and PI effects may be present in sentence processing, a recent article suggests that the former may play a greater role. Van Dyke and McElree (2011) compared sentence constructions in which semantic distractors occurred prior to the target, as in (18), with those where the distractor occurred after the target as in (19). In both cases, interference was created by replacing *motion* with *witness*, thus establishing a distractor which fits both the syntactic and semantic cues of the verb *compromised*, which must be integrated with an animate grammatical subject (*attorney*).

(18) The judge who had declared that the *motion* was inappropriate realized that the attorney in the case *compromised*.
(19) The attorney who the judge realized had declared that the *motion* was inappropriate *compromised*.

Using both a speed-accuracy tradeoff (SAT) paradigm (e.g., McElree et al. 2003) and eye tracking, they observed a main effect of semantic interference, with a numerically greater effect in retroactive contexts, as in (16), as compared with proactive contexts like (15), although the interaction was significant in only early eye-movement measures. Martin and McElree (2009) also observed that RI constructions were more difficult to process than PI constructions, focusing on the resolution of verbal ellipsis, as in (20) and (21).

These constructions are particularly interesting because there is no way to predict that a retrieval is upcoming, whereas in (18) and (19) the noun *attorney* remains "unattached" until it can be integrated with its verb, thereby supporting the prediction that a retrieval is imminent.

(20) Even though Claudia did not write an angry letter, she filed a complaint. Ron did too.
(21) Claudia filed a complaint. Even though he did not write an angry letter, Ron did too.

In (20), the clause *even though Claudia did not write an angry letter* fits the *did* cue supplied in the elliptical phrase, and thus serves as PI for the actual target verb phrase *filed a complaint*. Similarly, in (21) the clause *even though he did not write an angry letter* serves as an intervening distractor, producing RI for the target. The greater difficulty in processing RI constructions may be due to the recency of the distractor, which may be more salient at the time of retrieval relative to the target. In contrast, the PI constructions have the target in most recent position, making it more easily identifiable.

3.2. DECAY

We do not claim that decay is absent from, or has no effect on, sentence comprehension processes. Yet, just as it is difficult to disentangle decay and interference in memory studies, it is also difficult to unambiguously demonstrate effects of decay in sentence comprehension. Van Dyke and Lewis (2003) achieved this by holding the content of the intervening (interfering) information constant across conditions, and manipulating the presence of decay by relying on ambiguous verb constructions. For example, sentence (22) is the ambiguous version of (16), differing only by the omission of the word *that*. This creates an ambiguous sentence up to the appearance of *was*, wherein the verb *understood* can be interpreted either as a verb that takes a direct object (e.g., *The boy understood the question and answered it*) or as a verb that takes a sentential complement (e.g., *The boy understood the question was difficult*).

(16) The frightened boy understood that the *man was paranoid* about dying.
(22) The frightened boy understood the *man was paranoid* about dying.

Effects of decay may be observed if the less preferred interpretation is not pursued *but turns out to be correct*, because the syntactic features licensing the sentential complement – which were assumed to decay after having been abandoned – must be re-accessed to complete the reanalysis. Van Dyke and Lewis ensured that participants would adopt the preferred interpretation by choosing ambiguous verbs that were strongly biased towards a direct object construction, and by including a large number of direct object sentences as filler items. Thus, sentence (23) is the ambiguous version of (14), and its initial interpretation could be consistent with the sentence *The boy understood the man who was swimming near the dock and smiled at him*.[1]

(14) The frightened boy understood that the *man* who was swimming near the dock *was paranoid* about dying.
(23) The frightened boy understood the *man* who was swimming near the dock *was paranoid* about dying.

A similar relationship between *understood* and *the man* would be adopted prior to the occurrence of *was paranoid* for the ambiguous version of the high interference sentence (15), given here as (24).

(15) The frightened boy understood that the *man* who said the townspeople were dangerous *was paranoid* about dying.
(24) The frightened boy understood the *man* who said the townspeople were dangerous *was paranoid* about dying.

Crucially, at the point when *was paranoid* must be processed, the sentential complement features must be reactivated in order to integrate the verb phrase into the sentence. The prediction was that any difficulty in reactivating the sentential complement features arises as a result of how much these features decayed while the incorrect interpretation was pursued. Consistent with this view, the distance effect on the ability to reanalyze the ambiguous sentence was significant, suggesting decay of the less preferred interpretation. There was no additional effect of interference during reanalysis, however, which is consistent with the fact that the interfering material in the unambiguous sentences is identical to that in the ambiguous sentences. The strong implication of this work is that interference is the primary factor contributing to the difficulty of integrating associated constituents during unambiguous sentence comprehension, with a more specialized role arising for decay in situations where sentence constructions must be deliberately restructured.

4. An Alternative Memory Architecture for Language Comprehension

The appearance of interference effects in language comprehension points to a unification of memory mechanisms operating in the domains of both memory and language. Support for this approach is also apparent in neuroimaging research investigating the brain regions responsible for memory retrieval. Evidence from fMRI suggests that the retrieval of recent items recruits the left inferior frontal gyrus (LIFG) (Öztekin et al. 2008, 2010), and this region has also been repeatedly implicated in resolution of memory interference (for a review, see Jonides and Nee 2006). In addition, clinical (e.g., Thompson-Schill et al. 2002) and repetitive transcranial magnetic stimulation investigations (e.g., Feredoes et al. 2006) provide converging evidence for a direct role of LIFG in successfully resolving interference. Significantly, this brain region has a long history of being associated with language processing (for a review, see Rogalsky and Hickock 2011). In particular, subregions of LIFG – the pars opercularis (Brodmann Area 44) and the pars triangularis (Brodmann Area 45), which together comprise Broca's Area – have been repeatedly implicated in the processing of syntactically interfering sentence constructions (e.g., Cooke et al. 2001; Fiebach et al. 2004; Makuuchi et al. 2009; Stowe et al. 1999). Further, attempts to specify the functional role of the subregions of LIFG during memory retrieval, in which participants were required to select among competing alternatives (Badre and Wagner 2007; Badre et al. 2005), point to a unique role for the pars triangularis in interference resolution. This result complements a recent fMRI study extending Van Dyke (2007), which found semantic interference effects in the pars triangularis region (Guo et al. 2010).

Taken together, these separate streams of research in the memory and language domains provide converging evidence that the primary factor limiting accurate sentence comprehension is interference (both contextual and semantic), which arises as a consequence of insufficiently distinct cues available at retrieval. This has strong implications for the type of memory system that may support sentence comprehension. As discussed above, the dominant capacity approach has suggested that sentences (reproduced here for ease of reference) such as (14) and (15) are difficult to process because *the man* must be ''held'' in working memory while processing the intervening material, which consumes memory resources because of its length.

(14) The frightened boy understood that the *man* who was swimming near the dock *was paranoid* about dying.
(15) The frightened boy understood that the *man* who said the townspeople were dangerous *was paranoid* about dying.
(16) The frightened boy understood that the man *was paranoid* about dying.

Contra this, Van Dyke and Lewis (2003) found that (14) was not significantly more difficult than the shorter (16), and only became so when the intervening region contained interfering content, as in (15). Thus, the distance effects that were previously thought to occur because of decay (as a result of memory resources being insufficient to actively maintain the unattached noun phrase while processing the intervening material) can be attributed to retrieval interference (either contextual or semantic). This emphasis on retrieval means that an individual's ability to identify appropriate cues and execute efficient retrieval processes is more important than the size of an individual's working memory capacity – a non-trivial assertion, given the prevalence of capacity-based accounts of language processing. However, this claim is fully consistent with recent research suggesting the size of active memory may be severely limited – perhaps to only 1–4 items even for skilled readers (see McElree 2006; Cowan 2006 for reviews of this literature). In addition, it provides a means of resolving the puzzling findings that patients who have extremely limited working memory spans nevertheless show preserved comprehension of quite complex grammatical constructions (e.g., Caplan and Hildebrandt 1988; Caplan and Waters 1999; Martin and Feher 1990).

The possibility of such a highly restricted capacity invites a new conceptualization of the architecture that supports language comprehension, where the cue-based retrieval process provides the computational power necessary to create dependencies in real time (see Lewis et al. 2006; for a computational implementation of such a system). The plausibility of this approach is supported by mathematical analyses of reaction time distributions (Ratcliff 1978) and evidence from the SAT paradigm (McElree 2001), which suggest that humans can restore items into active memory in approximately 80–90 ms. Retrieval speeds that are this fast enable the parsing mechanism to compensate for the severe limit on the size of active memory, while still enabling parsing decisions to be made in approximately 200 ms, which is typical for real-time language processing. The result is a model in which accurate and efficient language comprehension can occur even in the face of a highly restricted memory capacity.

The central role of retrieval in comprehension has already been acknowledged in models aimed at explaining certain aspects of higher-level text processing. For example, the Resonance Model, proposed by O'Brien, Myers, and colleagues (e.g., Myers and O'Brien 1998) adopts the resonance metaphor popularized by Ratcliff (1978) to describe the procedure for creating inferences and resolving anaphoric reference during comprehension. According to this approach, incoming text information serves as a retrieval probe to all of long-term memory, including discourse memory and general world knowledge. Related information *resonates* in response to these retrieval signals, as a function of both the conceptual overlap between, and the number of features shared by, the retrieval probe and the to-be-retrieved information. As in cue-based retrieval, whether particular resonating information is successfully accessed or integrated into an inference is dependent on the distinctiveness of that information in memory; as with the sentence-level studies already discussed here, interference effects are predicted when competing information (i.e., that sharing some, but not all features of the retrieval probe) is present. Thus far, direct explorations of interference effects at the discourse level have not been conducted, and this is an important direction for future research.

5. Implications for Individual Differences

This view presents a strong challenge to the large body of work that has emphasized reduced capacity as the source of comprehension difficulty. Just and Carpenter (1992) provides an influential example of such a theory. They observed differences in college students' ability to interpret particularly difficult sentences, such as those containing complex grammatical constructions or ambiguities. They attributed these differences to variability in the quantity of neural processing resources the students were able to apply to sentence comprehension. Those with ''low'' processing capacity were more significantly impaired, while those with greater capacity performed well, presumably because their greater capacity provided them with additional resources to process the complex properties of the sentence (e.g., simultaneously maintain multiple interpretations for extended periods of time), as compared with those with a more limited capacity, who could keep only the most likely interpretation active. Thus, if the ultimately correct interpretation was not the most likely one, low capacity readers would fail to comprehend because the correct interpretation had been ''pushed out'' of memory. Just and Carpenter indexed individual capacity using the Reading Span task (Daneman and Carpenter 1980), which requires participants to read (or, in the auditory version of the task, listen) to an increasingly large group of sentences, and report back only the last words of each sentence in the set. The task of processing the sentence (and in some cases answering questions about it), together with the requirement to store the final words, is thought to assess the efficiency with which the central executive can allocate resources to both maintain and process linguistic information. Indeed, the task mirrors the functional demand of processing complex linguistic constructions (e.g., long-distance dependencies) discussed in the introduction, where substantial information is situated in between two linguistic constituents that must be associated.[2]

Yet a memory architecture such as that described above, which enables skilled language comprehension even with a sharply circumscribed capacity limit, orphans this research; if skilled readers succeed with a highly restricted capacity, then the source of difficulty for unskilled readers must be found elsewhere. The research surveyed in this article points to a possible alternative locus: individual variation in the efficiency of retrieval processes, including sensitivity to interference. Indeed, a number of findings in the memory literature have already suggested that differences in susceptibility to interference may provide a more veridical characterization of individual differences in age-related changes in memory ability (Hasher and Zacks 1988; Stoltzfus et al. 1996). Importantly, current approaches to language deficits in clinical populations have also moved toward explanations that implicate interference; for example, comprehension deficits in patients with Parkinson's disease have been linked to an inability to inhibit irrelevant information (Hochstadt et al. 2006). A similar deficit has been observed in adults with poor comprehension ability as compared to good comprehenders, with the former displaying more intrusion errors from memory items which have been processed but which now must be suppressed during a verbal memory task (De Beni et al. 1998). However, a limitation of these various strains of research is that, although they demonstrate the existence of interference effects, they have so far not incorporated a detailed explanation of the memory mechanisms that gives rise to these effects.

In contrast, our approach has been to view interference effects as an inevitable consequence of a cue-based retrieval mechanism. Thus, the issue is not simply how individuals vary in sensitivity to interference, but more broadly, how well individuals use retrieval cues to retrieve target information. We have begun to pursue this issue with a community-based sample of college-aged, non-college-bound readers, which has the advantage of incorporating a much broader range of reading ability than that usually investigated in studies that utilize university subject pool populations. Our work has two primary goals: first, to determine if reading ability is related to sensitivity to retrieval interference; and second, to better understand the role of working memory capacity as an index of comprehension ability. We took as our starting point the paper by Van Dyke and McElree (2006), described earlier (see Section 3.1.1., example conditions given here for ease of reference).

(13) Memory load: TABLE-SINK-TRUCK
It was the *boat* that the guy who lived by the sea *sailed* after 2 days.
(25) Memory load: TABLE-SINK-TRUCK
It was the *boat* that the guy who lived by the sea *fixed* after 2 days.

In addition to performing the same reading task as in the original study, participants in this experiment completed an extensive battery of individual differences measures. We replicated the original result, finding that comprehension scores were impaired when the memory list items could be taken as objects of the sentence's main verb (Van Dyke et al. 2010). In addition, we found that readers with high sensitivity to interference also scored poorly on a number of ability measures, including the working memory measure (listening span). Interpreting this result was complicated by the observation that listening span was significantly correlated with 16 other individual differences measures, including indices of decoding ability, phonological processing, simple memory span, rapid naming, vocabulary knowledge, reading fluency, and spoken language ability. Moreover, these correlations were high, ranging from .30 to .63 ($p < .01$ for $|r| > .30$).

The size and extent of these correlations suggests that the utility of the working memory span task as a tool to index individual differences in sensitivity to interference is low; the relation of span to performance may simply be related to the complexity of the task itself, or its close association with fluid intelligence (e.g., Kane et al. 2005), providing no conclusive diagnostic information about the underlying source of comprehension difficulty. In an attempt to achieve some additional insight into the source of these interference effects, Van Dyke and colleagues conducted analyses partialling out variance shared between the battery measures and participants' general cognitive ability (indexed by IQ), and found that the sentence span measure no longer accounted for any unique variance in the comprehension task. Instead, comprehension performance was predicted only by readers' receptive vocabulary knowledge. The strong influence of vocabulary knowledge in predicting retrieval interference is consistent with other recent research focusing on vocabulary – and not working memory measures – as key determinants of both online sentence processing (e.g., of syntactic ambiguity resolution; Traxler and Tooley 2007) and assessments of overall comprehension ability (Braze et al. 2007). It is important to emphasize here that the conclusion of this work is *not* the trivial suggestion that comprehension fails because readers don't know the meanings of words in a sentence. Rather, the suggestion is that retrieval success depends on qualitative aspects of lexical representations. This is consistent with research in the memory domain (e.g., Dosher, 1976, 1981; McElree and Dosher, 1989; Ratcliff 1978; Wickelgren 1977), which has established that the probability of retrieving particular items depends on the strength or distinctiveness of the representation itself. Thus, it follows that the determining factor for comprehension is the robustness of the lexical representations themselves. If the to-be-retrieved representations are noisy, then the probability of accessing target items is reduced and comprehension will suffer.

This is particularly apparent in the case of poor reading ability, where high quality lexical representations would be characterized by highly automatic associations of precise orthographic forms to the phonological representations learned during oral language acquisition; automatic associations of these same phonological representations to semantic representations; and a highly elaborated semantics, encompassing the full variety of syntactic and semantic contexts for the word (Perfetti 2007). Individuals with diminished ability to discriminate either phonological or semantic features, as is characteristic of poor reading ability, will necessarily have lower quality lexical representations overall, characterized by lower-dimension feature structures which omit important discriminations. Moreover, during comprehension an activated lexical representation that is of poor quality may spread spurious activations to neighboring representations, by virtue of their inexact semantics. This would result in activated but irrelevant information – essentially noise – which will interfere with retrieval and comprehension. Evidence for this phenomenon has been observed by Gernsbacher and colleagues (e.g., Gernsbacher 1990; Gernsbacher and Faust 1991, 1995; see also Long et al. 1999), who showed that poor readers were less able than skilled readers to inhibit the context-irrelevant meanings of ambiguous words during sentence comprehension. Thus, retrieval operations on low-quality lexical representations will necessarily be less efficient, and more subject to interference, resulting in poor comprehension in general, and greater difficulty when comprehension requires retrieving distal structures to complete grammatical dependencies in particular.

The main thrust of this approach, then, is to shift the emphasis away from questions of *how much* can be held in active memory towards questions related to the specific *content and quality* of the individual representations held there. We believe that research adopting this perspective has the most potential for revealing new insights into the causes of comprehension difficulty for both skilled and less skilled readers. Crucial issues for future research, some of which are currently being pursued in our lab, will be the extent to which variation in sensitivity to interference, ability to identify and use retrieval cues, and the efficiency of retrieval processes constrain comprehension.

6. Conclusion

The ubiquitous presence of non-adjacent dependencies in language attests to the crucial role that memory processes must play for language comprehension. Unfortunately, a clear understanding of how the two are linked has thus far not been produced, either at the sentence- or discourse-level, with little agreement on the issue of how much information can be maintained in active memory. In this review we argue that a promising perspective for investigating this relationship is to sidestep the issue of capacity altogether, especially in light of suggestions that even skilled language comprehension can occur with a highly limited memory capacity. Rather, we suggest that a focus on interference and retrieval as the determining factors for successful language comprehension serves to reorient both investigations of processing complexity and individual differences, as well as provide an important framework for developing novel questions for future research.

Short Biographies

Julie A. Van Dyke is a Senior Research Scientist at Haskins Laboratories in New Haven, CT. Her research is supported by the NIH/National Institute of Child Health and Human Development and aims to elucidate the computational properties of the memory mechanisms that support language comprehension in both skilled and unskilled readers, as well as those with acquired language deficits and other clinical disorders. A particular focus of her research is to examine a broad range of reading and language ability as found in non-college-bound adults, a population which is not typically investigated in mainstream psycholinguistic research. She utilizes eye-tracking methods to investigate natural reading behaviors and the speed-accuracy tradeoff technique to precisely characterize the dynamics of word retrieval and linguistic processing. Her current research involves adapting the latter technique for use with clinical populations. She received her PhD in Cognitive Psychology from the University of Pittsburgh in 2002, and her MSc in Computational Linguistics from Carnegie Mellon University in 1996. She completed postdoctoral training at New York University and at Haskins Laboratories in the areas of Cognitive Psychology and Reading Disability. She has taught cognitive psychology, psycholinguistics, and cognitive science at Yale University, Pace University and the University of Pittsburgh.

Clinton L. Johns obtained his PhD from the University of California, Davis, in 2009. He is now a postdoctoral fellow at Haskins Laboratories in New Haven, Connecticut. His primary research interests center on the memory processes that underlie language comprehension. Recent research has focused on encoding and retrieval processing during coreference. Current research investigates individual differences in memory function and sentence comprehension in non-college bound young adults. He has taught at the University of California, Davis, at Southern Connecticut State University, and at the University of Connecticut.

Acknowledgement

This work was supported by the following grants from the NIH National Institute of Child Health and Human Development: HD 058944 to Julie Van Dyke (PI), HD 056200 to Brian McElree (PI), HD 040353 to Donald Shankweiler (PI). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

Notes

* Correspondence address: Julie A. Van Dyke, 300 George Street, New Haven, CT 06511, USA. Email: jvandyke@haskins.yale.edu

[1] The continuation *and smile at him* is included here only to emphasize that *the man* is interpreted as the direct object of *understood*. The experiment did not include continuations such as these.

[2] There are now a plethora of similar tasks – so called ''complex span'' tasks that index the same processing capacity, both in reading and non-reading, and verbal and non-verbal modalities (e.g., Turner and Engle 1989).

Works Cited

Abney, S. P., and M. Johnson. 1991. Memory requirements and local ambiguities of parsing strategies. Journal of Psycholinguistic Research 20. 233–50.

Anderson, J. R. 1974. Retrieval of propositional information from long-term memory. Cognitive Psychology 6. 451–74.
Baddeley, A. D. 1966. The capacity for generating information by randomization. Quarterly Journal of Experimental Psychology 18. 119–29.
——. 2003. Working memory: looking back and looking forward. Nature Reviews Neuroscience 4. 829–39.
——, and G. J. Hitch. 1974. Working memory. Recent advances in learning and motivation, Vol. 8, ed. by G. A. Bower, 47–89. New York, NY: Academic Press.
Badre, D., R. A. Poldrack, E. J. Paré-Blagoev, R. Insler, and A. D. Wagner. 2005. Dissociable controlled retrieval and generalized selection mechanisms in ventrolateral prefrontal cortex. Neuron 47. 907–18.
——, and A. D. Wagner. 2007. Left ventrolateral prefrontal cortex and the control of memory. Neuropsychologia 45. 2883–901.
Berman, M. G., J. Jonides, and R. L. Lewis. 2009. In search of decay in verbal short-term memory. Journal of Experimental Psychology: Learning, Memory, and Cognition 35. 317–33.
Braze, D., W. Tabor, D. P. Shankweiler, and W. E. Mencl. 2007. Speaking up for vocabulary: reading skill differences in young adults. Journal of Learning Disabilities 40(3). 226–43.
Brown, J. 1958. Some tests of the decay theory of immediate memory. Quarterly Journal of Experimental Psychology 10. 12–21.
Caplan, D., and H. Hildebrandt. 1988. Disorders of syntactic comprehension. Cambridge, MA: MIT Press.
——, and G. S. Waters. 1999. Verbal working memory and sentence comprehension. Brain & Behavioral Sciences 22. 77–126.
Clark, S. E., and S. D. Gronlund. 1996. Global matching models of recognition memory: how the models match the data. Psychonomic Bulletin and Review 3. 37–60.
Conrad, R. 1964. Acoustic confusions in immediate memory. British Journal of Psychology 55. 75–84.
Cooke, A., E. B. Zurif, C. DeVita, D. Alsop, P. Koenig, J. Detre, J. Gee, M. Piñango, J. Balogh, and M. Grossman. 2001. Neural basis for sentence comprehension: grammatical and short-term memory components. Human Brain Mapping 15(2). 80–94.
Cowan, N. 2006. Working memory capacity. New York, NY: Psychology Press.
Crowder, R. G. 1976. Principles of learning and memory. Hillsdale, NJ: Erlbaum.
Daneman, M., and P. A. Carpenter. 1980. Individual differences in working memory and reading. Journal of Verbal Learning and Verbal Behavior 19. 450–66.
De Beni, R., P. Palladino, F. Pazzaglia, and C. Cornoldi. 1998. Increases in intrusion errors and working memory deficit of poor comprehenders. Quarterly Journal of Experimental Psychology 51(2). 305–20.
Dillon, R. F., and L. A. Bittner. 1975. Analysis of retrieval cues and release from proactive inhibition. Journal of Verbal Learning and Verbal Behavior 14. 616–22.
Dosher, B. A. 1976. The retrieval of sentences from memory: a speed-accuracy study. Cognitive Psychology 8. 291–310.
——. 1981. The effect of delay and interference: a speed-accuracy study. Cognitive Psychology 13. 551–82.
Fedorenko, E., E. Gibson, and D. Rohde. 2006. The nature of working memory capacity in sentence comprehension: evidence against domain specific resources. Journal of Memory and Language 54(4). 541–53.
Feredoes, E, G. Tononi, and B. R. Postle. 2006. Direct evidence for a prefrontal contribution to the control of proactive interference in verbal working memory. Proceedings of the National Academy of Science of the United States of America 103. 19530–4.
Ferreira, F., and J. M. Henderson. 1991. Recovery from misanalyses of garden-path sentences. Journal of Memory and Language 30. 725–45.
Fiebach, C. J., S. H. Vos, and A. D. Friederici. 2004. Neural correlates of syntactic ambiguity in sentence comprehension for low and high span readers. Journal of Cognitive Neuroscience 16. 1562–75.
Gardiner, J. M., F. I. M. Craik, and J. Birstwistle. 1972. Retrieval cues and release from proactive inhibition. Journal of Verbal Learning and Verbal Behavior 11. 778–83.
Gernsbacher, M. A. (1990). Language comprehension as structure building. Hillsdale, NJ: Erlbaum.
——, and M. Faust. 1991. The mechanisms of suppression: a component of general comprehension skill. Journal of Experimental Psychology: Learning, Memory, and Cognition 17. 245–62.
——, and ——. 1995. Skilled suppression. Interference and inhibition in cognition, ed. by F. N. Dempster and C. J. Brainerd, 295–327. San Diego, CA: Academic Press.
Gibson, E. 1998. Linguistic complexity: locality of syntactic dependencies. Cognition 68. 1–76.
——. 2000. The dependency locality theory: a distance-based theory of linguistic complexity. Image, language, brain: Papers from the first mind articulation project symposium, ed. by A. Marantz, 94–126. Cambridge, MA: MIT Press.
Gordon, P. C., R. Hendrick, and M. Johnson. 2001. Memory interference during language processing. Journal of Experimental Psychology: Learning, Memory, and Cognition 27. 1411–23.
——, ——, and ——. 2004. Effects of noun phrase type on sentence complexity. Journal of Memory and Language 51. 97–114.

——, ——, and W. H. Levine. 2002. Memory-load interference in syntactic processing. Psychological Science 13. 425–30.

Grodner, D., and E. Gibson. 2005. Consequences of the serial nature of linguistic input. Cognitive Science 29(2). 261–90.

Guo, Y., R. Martin, J. Van Dyke, and C. Hamilton. 2010. Interference effects in sentence comprehension: an fMRI study. Proceedings of the 32nd Annual Conference of the Cognitive Science Society, ed. by S. Ohlsson and R. Catrambone, 1429–34. Austin, TX: Cognitive Science Society.

Hasher, L., and R. T. Zacks. 1988. Working memory, comprehension, and aging: a review and a new view. The psychology of learning and motivation, Vol. 22, ed. by G. H. Bower, 193–225. New York, NY: Academic Press.

Hochstadt, J., H. Nakano, P. Lieberman, and J. Friedman. 2006. The roles of sequencing and verbal working memory in sentence comprehension deficits in Parkinson's disease. Brain & Language 97. 243–57.

Jonides, J., and D. E. Nee. 2006. Brain mechanisms of proactive interference in working memory. Neuroscience 139. 181–93.

Just, M. A., and P. A. Carpenter. 1992. A capacity theory of comprehension: individual differences in working memory. Psychological Review 99. 122–49.

Kane, M.J., D. Z. Hambrick, and A. R. A. Conway. 2005. Working memory capacity and fluid intelligence are strongly related constructs: comment on Ackerman, Beier, and Boyle (2005). Psychological Bulletin 131(1). 66–71.

Kimball, J. 1973. Seven principles of surface structure parsing in natural language. Cognition 2. 15–47.

King, J., and M. A. Just. 1991. Individual differences in syntactic processing: the role of working memory. Journal of Memory and Language 30(5). 580–602.

Lewis, R. L., S. Vasishth, and J. A. Van Dyke. 2006. Computational principles of working memory in sentence comprehension. Trends in Cognitive Science 10(10). 447–54.

Long, D. L., B. J. Oppy, and M. R. Seely. 1999. The strategic nature of less skilled readers' suppression problems. Discourse Processes 27. 281–302.

Makuuchi, M., J. Bahlmann, A. Anwander, and A. D. Friederici. 2009. Segregating the core computational faculty of human language from working memory. Proceedings of the National Academy of Sciences of the United States of America 106(20). 8362–7.

Martin, A. E., and B. McElree. 2009. Memory operations that support language comprehension: evidence from verb-phrase ellipsis. Journal of Experimental Psychology: Learning Memory & Cognition 35. 1231–9.

Martin, R. C., and E. Feher. 1990. The consequences of reduced memory span for the comprehension of semantic versus syntactic information. Brain and Language 38(1). 1–20.

McElree, B. 2001. Working memory and focal attention. Journal of Experimental Psychology: Learning, Memory and Cognition 27. 817–35.

——. 2006. Accessing recent events. The psychology of learning and motivation, Vol. 46, ed. by B. H. Ross, 155–200. San Diego: Academic Press.

——, and B. A. Dosher. 1989. Serial position and set size in short-term memory: time course of recognition. Journal of Experimental Psychology: General 118. 346–73.

——, S. Foraker, and L. Dyer. 2003. Memory structures that subserve sentence comprehension. Journal of Memory and Language 48(1). 67–91.

Miller, G. A., and N. Chomsky. 1963. Finitary models of language users. Handbook of mathematical psychology, Vol. 2, ed. by R. D. Luce, R. R. Bush and E. Galanter, 419–91. New York, NY: Wiley.

Murray, D. J. 1967. The role of speech responses in short-term memory. Canadian Journal of Psychology 21. 263–76.

Myers, J. L., and E. J. O'Brien. 1998. Accessing the discourse representation during reading. Discourse Processes 26. 131–57.

Nairne, J. S. 2002. Remembering over the short-term: the case against the standard model. Annual Review of Psychology 53. 53–81.

Öztekin, I., L. Davachi, and B. McElree. 2010. Are representations in working memory distinct from those in long-term memory? Neural evidence in support of a single store. Psychological Science 21. 1123–33.

——, and B. McElree. 2007. Retrieval dynamics of proactive interference: PI slows retrieval by eliminating fast assessments of familiarity. Journal of Memory and Language 57. 126–49.

——, ——, B. P. Staresina, and L. Davachi. 2008. Working memory retrieval: contributions of left prefrontal cortex, left posterior parietal cortex and hippocampus. Journal of Cognitive Neuroscience 21. 581–93.

Perfetti, C.A. 2007. Reading ability: lexical quality to comprehension. Scientific Studies of Reading 11(4). 357–83.

Peterson, L. R., and M. J. Peterson. 1959. Short term retention of individual verbal items. Journal of Experimental Psychology 58. 193–8.

Ratcliff, R. 1978. A theory of memory retrieval. Psychological Review 85. 59–108.

Rogalsky, C., and G. Hickock. 2011. The role of Broca's area in sentence comprehension. Journal of Cognitive Neuroscience 23(7). 1664–80.

Staub, A. 2010. Eye movements and processing difficulty in object relative clauses. Cognition 116(1). 71–86.
Sternberg, S. 1966. High-speed scanning in human memory. Science 153(3736). 652–4.
Stoltzfus, E. R., L. Hasher, and R. T. Zacks. 1996. Working memory and aging: current status of the inhibitory view. Working memory and human cognition, ed. by J. T. E. Richardson, W. W. Engle, L. Hasher, R. H. Logie, E. R. Stoltzfus and R. T. Zacks, 66–88. Oxford, England: Oxford University Press.
Stowe, L. A., A. M. J. Paans, A. A. Wijers, F. Zwarts, and G. M. W. Vaalburg. 1999. Sentence comprehension and word repetition: a positron emission tomography investigation. Psychophysiology 36. 786–801.
Tabor, W., B. Galantucci, and D. Richardson. 2004. Effects of merely local syntactic coherence on sentence processing. Journal of Memory & Language 50(4). 355–70.
Tehan, G., and M. S. Humpreys. 1996. Creating proactive interference in immediate recall: building a DOG from a DART, a MOP, and a FIG. Memory & Cognition 26(3). 477–89.
Thompson-Schill, S. L., J. Jonides, C. Marshuetz, E. E. Smith, M. D'Esposito, I. P. Kan, R. T. Knight, and D. Swick. 2002. Effects of frontal lobe damage on interference effects in working memory. Cognitive, Affective, and Behavioral Neuroscience 2. 109–20.
Traxler, M. J., R. K. Morris, and R. E. Seely. 2002. Processing subject and object relative clauses: evidence from eye movements. Journal of Memory and Language 47. 69–90.
——, and K. M. Tooley. 2007. Lexical mediation and context effects in sentence processing. Brain Research 1146. 59–74.
Turner, M. L., and R. W. Engle. 1989. Is working memory capacity task dependent? Journal of Memory and Language 28. 27–154.
Underwood, B. J., and G. Keppel. 1962. An evaluation of two problems of method in the study of retention. American Journal of Psychology 75. 1–17.
Van Dyke, J. A. 2007. Interference effects from grammatically unavailable constituents during sentence processing. Journal of Experimental Psychology: Learning, Memory, and Cognition 33(2). 407–30.
——, C. L. Johns, and A. Kukona. 2010. Individual difference in sentence comprehension: a retrieval-interference approach. New York, NY: Talk presented at the 23rd CUNY Conference on Human Sentence Processing.
——, and R. L. Lewis. 2003. Distinguishing effects of structure and decay on attachment and repair: a retrieval interference theory of recovery from misanalyzed ambiguities. Journal of Memory and Language 49. 285–413.
——, and B. McElree. 2006. Retrieval interference in sentence comprehension. Journal of Memory and Language 55. 157–66.
——, and ——. 2011. Cue-dependent interference in comprehension. Journal of Memory and Language 65. 247–63.
Warner, J., and A. L. Glass. 1987. Context and distance-to-disambiguation effects in ambiguity resolution: evidence from grammaticality judgment of garden path sentences. Journal of Memory and Language 26. 714–38.
Watkins, O.C., and M. J. Watkins. 1975. Build-up of proactive inhibition as a cue overload effect. Journal of Experimental Psychology: Human Learning and Memory 104. 442–52.
Waugh, N. C., and D. A. Norman. 1965. Primary memory. Psychological Review 72(2). 89–104.
Wickelgren, W. A. 1965. Acoustic similarity and intrusion errors in short-term memory. Journal of Experimental Psychology 70. 102–8.
Wickelgren, W. 1977. Speed-accuracy tradeoff and information processing dynamics. Acta Psychologica 41. 67–85.
Wickens, D. D. 1970. Encoding categories of words: an empirical approach to meaning. Psychological Review 77. 1–15.
——. 1972. Characteristics of word encoding. Coding processes in human memory, ed. by A. W. Melton and E. Martin, 191–215. Washington, D.C.: Winston & Sons.