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Short Term Memory, Working Memory, and Syntactic Comprehension in Aphasia

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Abstract

Sixty one people with aphasia were tested on ten tests of short term memory (STM) and for the ability to use syntactic structure to determine the meanings of eleven types of sentences in three tasks – object manipulation, picture matching and picture matching with self-paced listening. Multilevel models showed relationships between measures of the ability to retain and manipulate item and order information in STM and accuracy and RT, and a greater relationship between these STM measures and accuracy and RT for several more complex sentence types in individual tasks. There were no effects of measures of STM that reflect the use of phonological codes or rehearsal on comprehension. There was only one effect of STM measures on self-paced listening times. There were double dissociations between performance on STM and individual comprehension tasks, indicating that normal STM is not necessary to perform normally on these tasks. The results are most easily related to the view that STM plays a facilitatory role in supporting the use of the products of the comprehension process to accomplish operations related to tasks.

The fact that linguistic stimuli arrive at sensory receptors over time requires that language comprehension utilize a memory system. One aspect of language comprehension that requires memory is the construction of the syntactic structure of a sentence (parsing) and the use of this structure to determine aspects of meaning (interpretation) (which we will call “syntactically based comprehension”). Even adjacent words must be assigned a syntactic relationship, requiring a memory system. In addition, syntactic relations often span many words. For instance, in (1), the arguments of *grabbed* and the reference of *his* must be retrieved at the point at which *grabbed* and *his* are encountered (or later, if parsing and interpretation is deferred):

1. The boy who the girl who fell down the stairs grabbed lost his balance

The memory system that supports sentence comprehension, including syntactically based comprehension, is therefore an important area of study. Several memory systems and mechanisms have been suggested as supporting the memory requirements of these processes. Neuropsychological cases are relevant to these suggestions because deficits in the memory system that supports an aspect of comprehension should lead to deficits in the comprehension function that it supports. This paper presents new neuropsychological data regarding the relationship of memory and sentence comprehension. We begin with a brief review of suggestions regarding the memory systems that support syntactically based comprehension.

Because the time frame over which many aspects of syntactic comprehension operate is short, often not more than seconds, many researchers have looked to models of short-term

memory (“STM”) for mechanisms that might support the memory needs of parsing and interpretation. However, this is not always the case, and we begin with two suggestions about other memory systems that support syntactically based comprehension.

The first of these is procedural memory. Ullman (2004) has suggested that the application of parsing rules is a skill that utilizes procedural memory. Lewis, Vasishth and their colleagues (cf., Lewis and Vasishth, 2005) have modeled syntactically based comprehension in ACT-R (Anderson, 1993), which contains a procedural memory, where partially analyzed structures are maintained and operations are performed, and a long term declarative memory, where information about syntactic structure and the syntactic features of incoming words are maintained and accessed. Caplan and Waters (2013) have proposed that sentence comprehension involves two types of processes -- a skilled parser that incrementally assigns structure and meaning in most situations and a controlled processor that contributes to comprehension when the skilled parser fails to yield a meaning that satisfies the comprehender's needs. Caplan and Waters suggested that the skilled parser utilizes long-term working memory (“LT-WM,” Ericsson and Kintsch, 1995), an aspect of procedural memory that applies to cognitive skills, and the controlled processor utilizes STM.

The claim that syntactically based comprehension utilizes procedural memory/LT-WM is attractive because syntactically based comprehension has many features that are found in tasks that utilize procedural memory/LT-WM. LT-WM was postulated to explain memory behavior in skilled tasks such as chess playing, abacus use, waiters' memory for orders, and comprehension of discourse. Four features of memory in these functions led to the postulation of LT-WM -- a large capacity for memory of items; domain specific knowledge; a high degree of familiarity with the specific task on the part of performers; relative imperviousness of memory to interruption of performance of the task. Syntactically-based comprehension clearly has the first three of these features. Though syntactic structures have some general features that overlap with representations in other cognitive domains (e.g., hierarchical structure), they constitute a largely separate type of knowledge (e.g., the semantic values associated with relations between nodes in syntactic structures, and the relations between nodes that determine these semantic values, are unique to syntax), and their processing is one of the most over-practiced cognitive skills humans engage in. The few available results suggest that syntactically-based comprehension is quite robust despite interruption (e.g., Wanner and Maratsos, 1978). LT-WM is distinguished from STM by the formation and use of complex domain-specific cues to the structure of the input. The retrieval cues that have been proposed in retrieval-based parsing have exactly this quality (Vasishth and Lewis, 2005). Procedural memory/LT-WM also is distinguished from STM by its unconscious mode of operation, which is also a feature of syntactically based comprehension.

Evaluation of the claim that syntactically based comprehension utilizes procedural memory/LT-WM is difficult because of the lack of information about how procedural memory/LT-WM works. For instance, as we will review immediately below, there is considerable information about features of STM such as how information is retrieved, but there is no comparable information about these features of procedural memory/LT-WM. This makes it hard to formulate predictions about how individual differences or deficits in specific aspects of the operation of procedural memory/LT-WM would affect syntactically based comprehension. There is also a methodological challenge that arises from the fact that skills are highly domain-specific (great waiters are not necessarily great chess players; Ericsson and Kintsch, 1995). To the extent that procedural memory/LT-WM is domain-specific (i.e., that specialization in these memory systems support specific skills), it not possible to measure a general “procedural memory/LT-WM” capacity or even features of such a capacity, to correlate with performance in syntactically based comprehension.

Given these constraints on direct psychological evidence for the claim that syntactically based comprehension utilizes procedural memory/LT-WM, researchers have sought other evidence for a relation between the two. Ullman (2004) argues that overlap of brain areas that support other tasks that involve procedural memory and tasks that require syntactic processing supports the view that syntactically based comprehension utilizes procedural memory, but the data and their implications are disputed (e.g., Joanisse and Seidenberg, 1999). Lewis and Vasishth's model receives support from predictions it makes about reaction times and eye fixations that are confirmed (Vasishth and Lewis, 2006), and experiences difficulty when these predictions are not confirmed (Caplan and Waters, 2013, discuss one such possible case).

The second non-STM memory system that has been proposed to support the memory needs of syntactically based comprehension is long term memory (LTM). McElree is the major proponent of this view (see McElree, 2006, for an overview). McElree argues that only one "chunk" of information is maintained in the focus of attention and all other information is accessed from long-term memory; this model does not have a "STM" system in the sense of a temporally- and/or capacity-limited store other than the focus of attention. The focus of attention in McElree's model cannot support the memory needs of parsing and interpretation because the memory processes that apply in sentences necessarily relate at least two items ("chunks" in McElree's terminology) to each other (see Lewis, 1996, for discussion), and therefore require more than a focus of attention that only contains one chunk. Consistent with this view, McElree and his colleagues have argued that many studies using the speed-accuracy trade-off paradigm have shown that information is retrieved in parsing and interpretation by content-addressable retrieval of information in long term memory ("LTM") (McElree 2000; McElree and Griffith, 1995, 1998; McElree et al, 2003; Foraker and McElree, 2007; Van Dyke and McElree, 2011).

Turning to STM, a considerable number of models postulate that STM supports syntactically based comprehension. These models have adopted various models of STM and maintain different positions about the STM mechanisms and components that are involved in comprehension.

Most models of STM postulate a capacity-limited store of multidimensional representations; differences arise regarding the capacity of such a store. Cowan (2000) postulates both a focus of attention limited to one chunk and a capacity- and temporally-limited store of multidimensional representations (his "Central Store (CS)"). The CS contains four to five "chunks" of information. Verhaeghen and his colleagues (Verhaeghen and Basak, 2005; Verhaeghen et al., 2004, 2007) postulate a focus of attention that varies in capacity as a function of factors such as age and practice; in such models, an expanded focus of attention can be seen as a STM system. Baddeley's (2000b, 2001) "working memory (WM)" model of STM contains a Central Executive (CE) and an Episodic Buffer (EB) that also consist in part of capacity- and temporally-limited stores of multidimensional representations. Baddeley's CE contains both a storage mechanism and a mechanism to allocate attention, and his EB "binds together information to form integrated episodes (Baddeley, 2003, p. 836)" rather than store unrelated items. Despite their differences, all these postulated stores -- the CS, CE, EB and an expanded focus of attention -- are similar in that they contain multidimensional representations and are capacity- and, in most models, temporally-, limited.

A large number of studies have considered the possibility that a capacity-limited component of a STM system, such as Baddeley's Central Executive, supports parsing and interpretation (see Just and Carpenter, 1992, for review). However, a number of empirical results create problems for this view. Patients with Alzheimer's Disease and severely limited STM, whose

STM limitations were attributed to Central Executive limitations (Baddeley et al, 1986, 1991), have been shown to be able to understand syntactically complex sentences (Rochon, et al, 1994; Waters et al, 1991, 1995) and to have normal on-line syntactic processing, as measured by increases in self-paced listening times at points of increased syntactic complexity (Almor et al, 1999; Kempler et al, 1998; Caplan et al, 2007a). Concurrent memory loads did not lead to increases in effects of syntactic complexity more in these patients than in neurologically intact controls (Waters et al, 1995). In many studies of neurologically intact individuals, individual differences in on-line measures of syntactic processing have not been correlated with individual differences in measures of “working memory” that are weighted towards the CE (Baum, 1991; Caplan et al, 2007a; DeDe et al, 2004; Caplan et al, 2011a; Kemtes, 1999; Kemtes and Kemper, 1997; Stine, 1990; Traxler et al, 2002, 2005; Waters and Caplan, 1996b, 2001b, 2003b, 2005; Waldstein & Baum, 1992; for discussion of apparently discrepant results such as King and Just, 1991, see Waters and Caplan, 1996a, and Caplan and Waters, 1999). In normals, concurrent memory loads have not led to disproportionate increases in on-line measures of processing at syntactically demanding points in sentences compared to less demanding points (Waters et al, 2003). Aphasic patients with impairments of syntactically based comprehension attributable to a reduction in processing resources do not show further decrements in comprehension of syntactically complex sentences when required to retain a concurrent digit load, despite the absence of a floor effect (Caplan and Waters, 1996). These data are hard to reconcile with the view that parsing and interpretation utilize a capacity-limited store or multidimensional representations such as the CE.

A different approach to the relation of a capacity limited multidimensional store and parsing than to claim that individual differences in the capacity of such a store correspond to individual differences in the efficiency of parsing and interpretation, is to invoke capacity limitations of STM as the source of limitations in parsing and interpretation. This position dates at least to Chomsky and Miller (1963) and we cannot review all the proposals that link parsing limitations to memory capacity limitations here. We will illustrate this work with the model developed by Lewis (1996). Lewis (1996) invokes capacity limits of STM as one reason to set the limit of two on the number of items of the same type that the buffer can contain. He was able to explain a number of complexity effects after making this assumption. However, this number does not correspond to any suggestion about a capacity-limited portion of ST-WM, which, as we have seen, has been estimated as one by McElree and 4 -5 by Cowan. In addition, the “chunks” in buffers in Lewis's model can be accessed by ongoing operations, which differs sharply from the conceptualization of chunks in the STM literature, where they are treated as being opaque (cf. Halford et al., 2007). These differences between Lewis' model and models of the CS make it unclear to what extent invoking the limitations of the Central Store accounts for what may be capacity limits in parsing and interpretation. Caplan and Waters (2013) argue that problems of similar sorts arise in all models that attribute capacity limits in parsing to capacity limits in STM.

In addition to a capacity- and possibly temporally-limited store of multidimensional representations, many models that postulate STM include a rehearsal process. The role of this process differs in different models. Baddeley and his colleagues have argued that rehearsal reactivates decaying representations in a temporally-limited store of phonological representations (the “phonological store (PS)”). Some models that do not recognize the existence of a purely phonological store nonetheless view rehearsal as an important mechanism in supporting STM. For instance, Page and Norris (1998, 2003) present a “primacy model” in which serial order is coded as a primacy gradient in which multidimensional items decay with a half life of about 2 seconds and are reactivated by cumulative rehearsal (see also Burgess and Hitch, 1999, for a model that includes rehearsal without a purely phonological store). The role of rehearsal may be more important in recall,

or serial recall, tasks than in recognition tasks. However, there is near universal agreement that it can support memory at short temporal intervals. Cowan (2000), for instance, points out that it is necessary to eliminate effects of both perceptual after-images and rehearsal to estimate the capacity of the CS.

At this time, there appears to be a broad consensus that rehearsal and phonological storage are not involved in supporting parsing and interpretation (see Caplan and Waters, 1990, for review, and Just and Carpenter (1992) for a rejection of a relation between Baddeley's Phonological Loop and parsing and interpretation). However, this conclusion may be premature. Data from both normal individuals and neuropsychological cases are mixed regarding phonological effects in syntactically based comprehension. Correlational data in neurologically normal individuals are inconclusive. Performance on tasks that require immediate serial recall, such as span tasks, is not highly correlated with performance on many tasks that require language comprehension (Danemann and Carpenter, 1980). However, these verbally mediated tasks are ones such as the verbal IQ measurements of the Wechsler IQ test, which involve many abilities other than sentence comprehension and therefore may rely on the Central Executive. Experimental results are also contradictory. Tongue twister effects (McCutcheon and Perfetti, 1982; McCutchen et al, 1991; Keller et al, 2003; Ayres, 1984; Baddeley & Hitch, 1974; Perfetti & McCutchen, 1982; Zhang & Perfetti, 1993) suggest interference among items maintained in a phonological store, but may arise during encoding rather than during storage (Haber & Haber, 1982). This has been tested by the use of concurrent verbal loads, which affect phonological coding of orthography and therefore should reduce tongue twister effects if they arise during encoding. There have been effects of shared initial consonants in the load and sentences on comprehension of tongue twister sentences in some studies (McCutchen et al, 1991) but not others (McCutchen & Perfetti, 1982). Effects of phonological similarity on self-paced reading times are also contradictory. Kennison (2004) found main effects of initial consonant similarity and syntactic ambiguity, but no interaction of these variables, on reading times for disambiguating and post-disambiguating words in "early closure" syntactic ambiguities (*After Dana/Lea and David/Michael definitely decided/finally agreed) to drive(,) the Datsun/Nissan) (with the damaged door/rusted hood) began to show signs of mechanical problems*), suggesting no role for phonological codes in retrieving information need to recover from initial misinterpretation of these structures. In contrast, Acheson and McDonald (2011) found an increase in self paced reading times for the noun phrase and verb of object, but not subject, relatives clauses in tongue twister compared to non-tongue twister sentences. A third experimental approach has been to measure effects of homophones in sentences with elided elements, such as *The children sleighed in the park and the murderer in cold blood* (Coltheart et al, 1994; Waters et al, 1992). This work demonstrates a role for phonology in comprehension, but fails to determine whether the phonology is maintained in STM or re-accessed from print at the point of the elided element.

The neuropsychological data regarding a role for phonological codes and rehearsal in syntactically based comprehension are also contradictory. Some patients with disorders of the articulatory rehearsal/phonological storage slave system have shown deficits in some aspects of sentence and discourse comprehension (Caramazza et al, 1981; Vallar and Baddeley, 1984; Baddeley, Vallar, & Wilson, 1987; Romani, 1994; Papagno, Cecchetto, Reati, & Bello, 2007), but others have not (Martin, 1993; Martin & Romani, 1994; Waters, Caplan, & Hildebrandt, 1987; Gvion and Freidmann, 2012). Similarly, some studies of children with Specific Language Impairment have shown evidence of correlations between phonological and grammatical performance (Bishop, 1997; Joanisse & Seidenberg, 1998; Leonard, 1997) and others have not (van der Lely, 2005).

Other mechanisms have been postulated to apply in STM, such as retrieval based on temporal cues that include Weber-compressed temporal intervals from a retrieved item to a retrieval cue or a response (Brown et al, 2007), positional activation gradients measured from both list-initial and list-terminal items (Henson, 1998), temporal oscillators that estimate list length (Brown et al, 2000; Henson and Burgess, 1997), and others (for review, see Henson, 1998). Most of these mechanisms, like some of those mentioned above (primary gradients), have been developed to account for serial order effects in immediate serial recall. Of the mechanisms postulated in these models, not all have been explored for their possible relevance to the memory utilized in parsing and interpretation. Arguably, some of them -- such as positional activation gradients measured from both list-initial and list-terminal items and temporal oscillators that estimate list length -- are not plausible candidates for mechanisms that support the memory requirements of these functions. Also, it is not clear that parsing and interpretation requires retrieval of order as well as item information (Lewis and Vasishth, 2005).

A final memory mechanism to consider is a “short term semantic store” (Martin et al, 1994; Acheson et al 2010; Hamilton et al, 2010), which Martin and her colleagues have suggested plays a role in sentence comprehension by maintaining items that are not assigned propositional meaning in memory, such as pre-nominal sequences of adjectives (*the old, rusty, twisted ... N*) (Martin and He (2004) (an anonymous reviewers suggested this might be the case for NPs in English object relative clauses *The boy who the girl ...*). Given the incremental nature of parsing and the structure of most sentences, semantic STM would play a minor role in comprehension.

We conclude this introduction with our own view of the memory system that underlies parsing and interpretation. Based on results cited above, we have previously suggested that the memory requirements of parsing and interpretation are not supported by the Phonological Loop or Central Executive of Baddeley's WM model (Caplan and Waters, 1990, 1999; Waters and Caplan, 1996a). We argued that the memory system that underlies parsing and interpretation was a specialized memory system that is at least partially separate from the memory system that supports such tasks and that probably supports performance on the many verbally-mediated task with which both simple and complex span performance correlates. On the other hand, we recognized that there is evidence that the mechanisms that support performance in STM tasks play a role in aspects of what may be called an “expanded” comprehension process. In many studies, end-of-sentence performance has been significantly correlated with WM capacity (King and Just, 1991; MacDonald et al, 1992; Just and Carpenter, 1992; Stine-Morrow et al., 2000; Kemper and Kemtes, 1999; see Waters and Caplan, 1996a and Caplan and Waters, 1999, for additional references). To account for this, Caplan and Waters (1999) argued that the postulated specialized memory system supported the initial, preferred, discourse congruent interpretation of a sentence (what we called “interpretive processing”), and that revisions of this structure and interpretation and the use of the product of the comprehension process to perform a task (what we called “post-interpretive processing”) could make use of mechanisms that support performance in STM tasks. We maintain essential aspects of this view, but would now put matters in a different framework.

First, as noted above, we view the postulated specialized memory system as supporting skilled parsing and interpretation, and suggest that it is a form of procedural memory – an aspect of long term working memory (LT-WM). Second, we suggest that our previous formulation of when the skilled parser/interpreter operates was too narrowly focused on what structures it could assign. We now suggest that, although skilled parsing and interpretation has its limits, whether these limits trigger use of comprehension mechanisms that utilize STM depends on the comprehenders' goals (Caplan and Waters, 2013). If the

criteria for task performance are set low, the comprehender may choose to accept some aspects of the meaning of a sentence as the basis for a response even if the skilled parser/interpreter fails to yield a wellformed syntactic structure and a coherent, unambiguous, complete semantic interpretation. For instance, if a comprehender only needs to know who participated in an action and not what thematic role each participant played, comprehension may be incrementally successful even if the parser/interpreter does not assign an unambiguous set of thematic roles. On the other hand, a comprehender may choose to review a sentence even if the parser/interpreter has produced a wellformed, coherent, unambiguous semantically interpreted representation, as is seen in “wrap up” effects at ends of clauses and sentences (Just and Carpenter, 1980) and occasionally within sentences (Traxler et al, 2002). This view has much in common with Ferreira's “good enough” comprehension framework (Ferreira and Patson, 2007, Ferreira et al, 2009) and Lewis' view on bounded optimality (Howes et al, 2009). It requires that we specify empirical measures of points of incremental comprehension success, where the skilled parser/interpreter operates alone, and those of incremental comprehension failure, where controlled comprehension processes that use STM are engaged. Caplan and Waters (2013) suggest several behavioral markers of these two postulated modes of comprehension.

The present study examines the relation between mechanisms that support STM performance and syntactic comprehension in 61 people with aphasia. The logic behind the study is as follows. If mechanisms that support STM are required for syntactic comprehension, patients with deficits in these mechanisms should have deficits in syntactic comprehension, and there should be a relation between the magnitude of the STM disorder and the disorder of syntactic comprehension. Conversely, the absence of a relation between STM and syntactic comprehension, and/or dissociations of STM and comprehension performance, would provide evidence that the two performances are functionally unrelated. Last, if there is a relation between STM and comprehension performance, individual exceptions to the pattern are relevant to whether the relation is a necessary one or an optional one. We examined performances for these patterns.

Methods

Participants

Sixty-one aphasic patients (mean age 64.2 years (sd: 12.9; range: 28 - 96); mean education, 15.3 years (sd: 3.2; range: 7 - 22); M:F = 44:17) who met entry criteria were tested. Patients were required to be aphasic as determined by a physician or speech-language pathologist, right handed, have a single left hemisphere stroke, be able to perform the tests, and be judged to have adequate single word comprehension to not fail because of lexical semantic disturbances. Patients were tested for disturbances of phoneme discrimination, auditory lexical decision and spoken word-picture matching using the Psycholinguistic Assessment of Aphasia, a test developed in our lab (see Caplan, 1992, for description). Patients were tested for their ability to match the nouns in the sentences to pictures, and trained as necessary until they achieved 100% correct matches. Forty-six age and education matched controls (mean age 64.2 years sd: 11.3; (range: 38 - 87); mean education, 16.3 years (sd: 2.3; range: 8 - 28); M:F = 20:26) were also tested.

Materials and Procedures

Syntactic Comprehension

The ability to parse and interpret passives, object extracted clefts, object extracted relative clauses, and sentences with reflexives and pronouns was tested by having patients respond to pairs of sentences in which the baseline sentence did not contain the construction/element in question or could be interpreted on the basis of a heuristic and the experimental sentence

contained the structure/element and required the assignment of a complex syntactic structure to be understood. In addition, the ability to combine operations was tested by presenting sentences with relative clauses and either a reflexive or a pronoun. Table 1 presents a list of sentence types used in this study. Twenty examples of each sentence type were presented.

Subjects were tested in object manipulation (OM) and picture matching (SPM) tasks, the latter with both whole sentence (Full SPM) and self-paced listening (auditory moving windows – AMW-SPM) presentation conditions, using digitized computer-delivered auditory stimuli. Accuracy was measured in OM and accuracy and end-of-sentence reaction time were measured in Full SPM and AMW-SPM. Procedures were as in previous studies (Caplan et al, 1985, 1996, 2006, 2007b; Caplan and Hildebrandt, 1988; Caplan and Waters, 2003) and will be summarized briefly. All sentence stimuli were recorded by one of the authors (DC) at a normal, but slow, speaking rate, and digitized using SoundEdit software. The files were edited for the auditory moving window task as follows. A marker (referred to as a “tag”) was placed in the waveform at each word boundary. In order to make word-to-word transitions smooth, tags were placed in the waveform at areas of low signal amplitude, as indicated by auditory and visual inspection, whenever possible. When word boundaries did not coincide with areas of low signal amplitude, the tags were placed so as to maximize the intelligibility of the words. Segments (tag to tag portions of the waveform) were saved as individual audio files. Pictures were created as JPEG files. Auditory and visual stimuli were used to create experiments in Superlab, which were presented on Macintosh iBook computers, with auditory files presented over headphones. In all studies, sentences were presented in a pseudo-randomized order, so that three or more examples of the same sentence type never occurred in succession.

Object Manipulation (OM)—In the object manipulation task, participants indicated thematic roles and co-indexation by manipulating paper dolls corresponding to nouns in auditorily presented sentences. Patients were told that the purpose of the experiment was to test their abilities to understand “who did what to whom” in the sentences. They were instructed to indicate “who did what to whom” by acting out the sentence using the items provided. The experimenter emphasized that the patient did not need to show details of the action of the verb, but had to clearly demonstrate which item was accomplishing the action and which item was receiving it. A practice session was given, during which some easy and some difficult sentence types were presented. During the practice session, the experimenter did not correct errors that a patient made, but did ask for repetitions and revisions of responses in which it was not clear which item initiated and which item received an action. Practice continued until the participant's actions could be clearly interpreted. Previous work has shown that inter-observer reliability is high for scoring these responses (Caplan et al., 1985; Caplan & Hildebrandt, 1988). The experimenter then proceeded with the digitized sentences and videotaped the participant's responses. See Caplan et al. (1985) and Caplan and Hildebrandt (1988) for a fuller description of the task.

Sentence-Picture Matching with uninterrupted auditory presentation (Full SPM)—In this test, each sentence was played auditorily with two black and white line drawings in full view of the participant, and the participant was required to choose the drawing that matched the sentence by pressing one of two keys on the computer keyboard using fingers on the non-paretic hand. Drawings depicted the thematic roles in the sentence and a reversed set of thematic roles and syntactically licensed and syntactically unlicensed antecedents of pronouns and reflexives. Correct and incorrect pictures were displayed equally frequently on the right and left side of the computer screen; order of presentation on each side was randomized within sentence type. A practice session consisting of ten sentences of different sentence types preceded the task. Incorrect responses were again not corrected by the experimenter. Responses were scored for accuracy and reaction time (RT).

Sentence-Picture Matching with auditory self paced (auditory moving window) presentation (AMW SPM)

The method was based on Ferreira et al. (1996a, b) and identical to that used in Caplan and Waters (2002) and Caplan et al (2007b). On each trial, a participant heard a sentence that had been digitized and segmented as described above, and saw a pair of pictures as in Full SPM. The participant's task was to pace his/her way through the sentence as quickly as possible, by pressing a computer key for the successive presentation of each segment (the tag-to-tag portion of the waveform corresponding to each word), and to select the picture corresponding to the meaning of the sentence at the end of the sentence. If a participant pressed the button before the end of a segment, the segment was truncated at the point of the button press in order to discourage participants from pressing the button before they had heard and processed each segment. Inter-response times between successive button presses, as well as response time and accuracy on the SPM task, were recorded. Segment durations were subtracted from inter-response times to eliminate effects of length, and regression analyses in which frequency was regressed onto self-paced listening times were performed for all words for each subject to obtain residual self-paced listening times. Analyses were performed on residuals of corrected self paced listening times for words at which processing load differed in the experimental and baseline sentences, shown in Table 1. We also examined one point in which the elements were the same in the experimental and baseline sentences -- the main verb of relative clauses -- to look for spillover effects of points of load in relative clause and because there is empirical evidence that this point is also a point of load (Traxler et al, 2002).

STM

Ten tests of STM were administered. Six were simple tests of immediate serial recall: Digit Span, Word Span; Span for Phonologically Similar Words; Span for Phonologically Dissimilar Words; Span for Long Words; Span for Short Words. The contrast between performance on Span for Phonologically Similar and Dissimilar Words is a measure of the Phonological Similarity Effect, an indication of the preservation of the Phonological Store in Baddeley's model. The contrast between performance on Span for Long and Short Words is a measure of the Word Length Effect, an indication of the preservation of the rehearsal mechanism in Baddeley's model. Four tests required both retention and manipulation of items: Alphabet Span, Backwards Digit Span, Subtract-2 Span, and Sentence Span. These tests were considered to assess the Central Executive.

Materials for Digit Span, Backwards Digit Span and Subtract-2 Span consisted of the digits 0 – 9. Materials for the Word Span and Alphabet Span consisted of monosyllabic, medium frequency, semantically and phonologically unrelated words. Materials for Phonologically Similar Span consisted of eight monosyllabic, medium frequency, semantically unrelated, phonologically similar words. Materials for Phonologically Dissimilar Span consisted of eight monosyllabic, medium frequency, semantically unrelated, phonologically dissimilar words. Materials for Long Word Span consisted of eight trisyllabic, medium frequency, semantically and phonologically unrelated words. Materials for Short Word Span consisted of eight monosyllabic, medium frequency, semantically and phonologically unrelated words.

In all tasks except Sentence Span, participants listened to lists of words or digits presented over headphones at a rate of one stimulus per second. In Digit Span, Word Span, Phonologically Similar Span, Phonologically Dissimilar Span, Long Word Span and Short Word Span, participants reported the items in the list in the order in which they appeared. In Subtract-2 Span, they reported the result of subtracting two from each digit, in the order in which the digits were presented. In Alphabet Span, they reported the words in the stimulus list in alphabetical order. In Backwards Span, they reported the digits in the list in the reverse order of presentation. In Sentence Span (Waters and Caplan, 1996b), they listened to

a series of sentences in a simple syntactic form (cleft subject) and indicated whether the sentence was acceptable or not. After hearing all sentences in a set they reported the final words of all of the sentences in the set in the order they had occurred. RT and accuracy on the sentence processing component of the task as well as word recall were measured.

Because of speech production disorders in some aphasic participants, participants made pointing responses in all tasks. In Digit Span and Subtract-2 Span, the digits 0 through 9 were displayed on a computer screen. In Alphabet Span and Sentence Span, the stimulus words and two additional words drawn from the same pool of words were displayed on a computer screen. In Sentence Span, participants responded to the sentence plausibility judgment task with button presses on one of two computer keys (labeled “GOOD” and “BAD”) after each sentence. Because of this feature of this task, for span tests on the computer, the numbers or words from which a response could be chosen appeared after the subject had heard the last item in the list. In the remaining tests, participants pointed to pictures in a stimulus book. In Word Span, there was a new response page for each trial, displaying the stimulus items and two foil pictures. The materials used for Phonologically Similar and Dissimilar and Long and Short Word Span each had a separate single response page containing eight pictures. The pictures on the response pages for Word Span and Phonologically Similar and Dissimilar and Long and Short Word Spans were present while the subject listened to the list of items. Participants were required to point to stimuli in a specified order; if they did not recall the item that appeared at a particular point in that order, they were instructed to indicate that they did not know and that they were going on to the next position in the series. There were five trials at each list length in all tasks.

For both control participants and people with aphasia, each task began with a practice session consisting of three trials (five trials on Sentence Span) at Span 2. Following the practice session, for controls, the task began at list length 2 and continued to list length 8 (list length 6 on Sentence Span), regardless of performance on lower spans. For people with aphasia, the task began at list length 2 and continued to list length 5 (list length 6 on Sentence Span), regardless of performance on lower spans. The lower limit was selected because many people with aphasia performed at very low levels at list lengths 4 or 5 on several tasks, leading to concerns about attrition due to frustration, with potentially significant loss of participants in all aspects of the study. For people with aphasia who performed correctly on at least 3/5 trials at list length 5, 6 or 7, testing continued to the next list length.

Performance was scored for the number of items recalled in the correct serial position. The measure of performance was the total number of items each subject reported correctly in the correct order. The number of correct responses in the last list length tested in people with aphasia who were not tested to list length 8 was always less than 2, indicating that our measures of item and order recall did not significantly underestimate the performances of people with aphasia who were not tested at longer list lengths.

Results

Basic Aspects of Performance

Performance on the comprehension tests is shown in Table 2. Split-half reliability for both accuracy and RT for each sentence type in all tasks were high (Table 3). With the exception of one sentence type, reflexives, ANOVAs of percent correct showed significantly greater accuracy on experimental sentences than on baseline sentences in at least one task. Factor analysis of the accuracy results for each of the tasks showed first factors that accounted for about 90% of the variance, and Varimax rotation resulted in solutions in which two factors accounted for about 75% of the variance in each task. All sentence types loaded on the first

factors in the unrotated analysis in each task, and the loadings of sentences on the retained factors in the rotated analyses did not correspond to linguistic or psycholinguistic groupings of the sentence types.

Performance on the STM tests is shown in Table 4. Performance was greater on each of the “simple, forward” span tasks (Alphabet Span, Backwards Digit Span, Subtract-2 Span, and Sentence Span) than on each of the “demanding, complex” span tasks (Alphabet Span, Backwards Span, Subtract 2 Span, Sentence Span). There was a significant effect of phonological similarity, and the effect of word length was marginal ($p = .07$).

Relation of STM to sentence comprehension performances

The relation between STM and sentence comprehension was analyzed using mixed logistic regression models for accuracy (Jaeger, 2008) and linear mixed effects models for RT and reading time data (Baayen, Davidson, & Bates, 2008) with crossed random subject and item effects and fixed effects of comprehension (performance on the word picture matching test of the PAL), sentence type, STM, and the interaction of all variables. Sentence types were contrast coded with the baseline sentence treated as the base value against which the effect of the experimental sentence was estimated (baseline = 0; experimental = 1). Values of comprehension and STM were centered prior to analysis. Interactions and predictor variables were sequentially eliminated from initial models based on significance level and -2 log likelihood comparisons via a stepwise procedure. Analyses were conducted using R statistical software (R Development Core Team, 2007) and version 0.999375-37 of the lme4 package (Bates, 2005; Bates & Sarkar, 2007).

Both the sentence and STM performances were grouped to reduce the number of analyses. Four sets of sentence types were considered, grouping together sets of sentences with common linguistic elements:

1. Passive (P) vs Active (A).
2. Relative Clauses: Object extraction (CO, SO, SOREF and SOPRO) vs Subject extraction (CS, SS, SSREF and SSPRO)
3. Pronouns (PRO, SOPRO, SSPRO) vs Sentences with referential NPs (3NP, SO, SS)
4. Reflexives (REF, SO REF, SS REF) vs Sentences with referential NPs (3NP, SO, SS)

In the analyses of self-paced listening times, the critical words – those at which load was expected to differ in the baseline and experimental sentences -- consisted of the verbs of active and passive sentences (analysis 1 above); the relative clause verbs of CO, SO, SOREF, SOPRO and CS, SS, SSREF, SSPRO sentences (analysis 2 above); the pronoun and the third NP in PRO, SOPRO, SSPRO and 3NP, SO, SS sentences (analysis 3 above); and the reflexive and the third NP in REF, SO REF, SS REF and 3NP, SO, SS sentences (analysis 3 above). Spill-over effects of local demand were tested in the object/subject extraction contrast by examining for effects at the main verb of SO, SOREF, SOPRO vs SS, SSREF, SSPRO sentences.

Four measures of STM performances were utilized. Sentence Span was eliminated from these measures because of its overlap with the measures of comprehension.

1. “forward, simple” span (the summed item and order performance on Digit Span, Word Span, Phonologically Similar Span, Phonologically Dissimilar Span, Long Word Span and Short Word Span), taken as a measure weighted towards the

functioning of the mechanisms that support recall of item and order information in immediate serial recall.

2. “demanding, complex” span (the summed item and order performance on Subtract 2, Alphabet Span and Digits Backward Span), taken as a measure weighted towards the the mechanisms that support manipulation of item and order information in immediate serial recall, which are central to the functioning of the Central Executive in Baddeley's model.
3. The Phonological Similarity Effect (the difference between item and order performance on the Phonologically Similar Span and Phonologically Dissimilar Span tasks), taken as a measure weighted towards a store of phonological representations or the use of phonological cues in retrieval.
4. The Word Length Effect (the difference between item and order performance on the Long Word Span and Short Word Span tasks), taken as a measure weighted towards the use of rehearsal.

We here report main effects and interactions involving the sentence type and memory variables. The estimates of the sentence type and memory variables are independent of those of the comprehension measure, and main effects and interactions involving the comprehension measure are not reported for reasons of space. Results of all analyses are available from the authors.

There were no main effects or interactions involving the PSE or WLE measures in the models using end-of-sentence results (accuracy or RT). There was a main effect of WLE in self-paced listening in the model of relative clauses (longer self-paced listening times for individuals with lower WLE). There also were no effects at the main verbs of sentences with relative clauses.

Main effects and interactions of sentence type and memory measures in the most highly valued model in analyses involving the “forward, simple” span and “demanding, complex” span measures are summarized in Table 5. Details of significant interactions of sentence type and memory measures in the most highly valued model in each analysis are presented in Table 6.

There were effects of sentence type in all tasks. The estimates of the effect of sentence type were negative for accuracy for all contrasts except sentences with reflexives in object manipulation. These estimates were significant except for sentences with pronouns in object manipulation, sentences with reflexives in the analysis of object manipulation that included “forward, simple” span, and sentences with reflexives in sentence picture matching with auditory moving windows. The estimates of the effect of sentence type were positive for end-of-sentence RTs for all contrasts except sentences with reflexives. These estimates were significant except for sentences with pronouns in sentence picture matching with full sentence presentation. The estimates of sentence type were positive for corrected residual self-paced listening times in sentences with object relatives (not shown in Table 5).

There were significant effects of memory measures in the analysis of accuracy and end of sentence RTs in all analyses. In all cases, higher span (whether “forward, simple” span or “demanding, complex” span) was associated with higher accuracy and faster end of sentence RTs. There were no effects of STM on self-paced listening times.

There were fifteen significant interactions between a memory measure and a sentence type (Table 5). None involved passive sentences. There were four types of interactions involving

the other sentence types, shown in Figure 1 – 4. Patterns 1 and 2 occurred in the accuracy data and patterns 3 and 4 in the RT data.

Pattern 1 is shown in Figure 1. It consists of a negative sentence type effect, a positive memory effect, and positive interaction. The negative main effect of sentence type reflects the demands of the experimental sentence; the positive main effect of memory reflects better performance on the part of participants with greater memory capacity; the positive interaction term results from a greater sentence type effect in participants with lower memory capacity. This pattern was seen in sentence picture matching with full presentation for sentences with pronouns.

Pattern 2 is shown in Figure 2. It consists of a negative sentence type effect, a positive memory effect, and a negative interaction. The negative main effect of sentence type reflects the demands of the experimental sentence; the positive main effect of memory reflects better performance on the part of participants with greater memory capacity; the negative interaction term results from a greater sentence type effect in participants with higher memory capacity. This pattern was seen in all tasks for object relatives and in object manipulation for sentences with pronouns.

Pattern 3 is shown in Figure 3. It consists of a positive sentence type effect, a negative memory effect, and a negative interaction. The positive effect of sentence type (longer RTs) reflects the increased load of the experimental sentences; the negative effect of memory reflects the faster RTs for participants with higher memory function; the negative interaction term results from a greater sentence type effect in participants with lower memory capacity. This pattern was seen in sentence picture matching with auditory moving windows presentation for object relatives.

Pattern 4 is shown in Figure 4. It consists of a negative sentence type effect, a negative memory effect, and a positive interaction. This pattern is the same as that in Figure 3 with the effect of sentence type reversed – the baseline sentences produced longer RTs than the experimental sentences. This pattern was seen in sentence picture matching with full presentation for sentences with reflexives.

Comparing the effect of “demanding, complex” span to that of “forward, simple” span provides information about whether complex span measures add anything beyond that predicted by the simple span measures. The models that use “forwards, simple” and “demanding, complex” span are not nested and therefore cannot be compared using standard measures such as AIC and BIC. We therefore approached this question differently. In 16 of the 17 models in which “forwards, simple” or “demanding, complex” span interacted with sentence type, both STM measures showed the interaction. We re-ran these models with both “forwards, simple” and “demanding, complex” span in the same model. Both “demanding, complex” and “forwards, simple” span measures remained significant in these models and did not interact together with the sentence type measure.

Dissociations between STM and sentence comprehension performances

The data were examined for dissociations between performance on the sentence and STM measures. A dissociation was considered to be present if a patient performed below the normal range on the STM tests and within the normal range on the sentence comprehension tests, or *vice versa*. The normal range of performance was determined based on the mean percent correct and standard deviation of the control performances corrected for sample size as in Crawford and Howell (1998) and Crawford et al (2003). As above, we grouped the STM tests into a set of “forward, simple” tasks and a set of “demanding, complex” tasks. In these analyses, we further reduced the sentence comprehension data, grouping performance

on the sentences into two measures of comprehension – performance on baseline sentences and on experimental sentences. Results are shown in Tables 7 and 8.

Seven patients performed below the normal range on the “forward, simple” STM tasks and within the normal range on the baseline sentences in at least one task. Of these, four also performed within the normal range on the experimental sentences in at least one task. Four patients performed below the normal range on the “demanding, complex” STM tasks and within the normal range on the baseline sentences in at least one task. Of these, three also performed within the normal range on the experimental sentences in at least one task. One patient (case 54048) is represented in both groups, performing below the normal range on both sets of STM tasks and within the normal range on both sets of sentences in at least one task.

Three patients performed below the normal range on the baseline sentences in at least one task and within the normal range on the “forward, simple” STM tasks. Six patients, including two in the group just reported, performed below the normal range on the experimental sentences in at least one task and within the normal range on the “forward, simple” STM tasks. Seven patients performed below the normal range on the baseline sentences in at least one task and within the normal range on the “demanding, complex” STM tasks. Ten patients, including five in the group just reported, performed below the normal range on the experimental sentences in at least one task and within the normal range on the “demanding, complex” STM tasks.

Discussion

Performances of the individuals tested here on the tests of STM and comprehension replicate reports in the literature with respect to the effects of the features of both sets of tests. In STM, the requirement that items be reported in other than their presentation order or after some manipulation led to lower performance and there were effects of phonological similarity and word length. In sentence comprehension, the reliability of performance, the significant effects of syntactic elements and syntactic structure, and the factor structure of performance were similar to previous reports (Caplan et al, 1985, 1996, 2007b). As has been previously reported (Caplan et al, 2007b), not all sentence type effects were significant in all tasks, presumably due to the considerable variation in performance in people with aphasia. The absence of an effect for sentences with reflexives has also been observed previously (Caplan et al, 2007b; see discussion below). There was also an effect of object relativation on self-paced listening times for the verbs of relative clause, which has previously been seen in ANOVAs (Caplan and Waters, 2002; Caplan et al, 2007b). The absence of effects of other sentence types on on-line measures is likely due to the high variability of performance.

The absence of an effect for sentences with reflexives may be due to the processing load exerted by introducing a third entity into a discourse, which counteracts the load associated with connecting a reflexive to its antecedent. Sentences with reflexives and their baselines make different types of demands on the comprehension process – a reflexive requires retrieval of an NP that can serve as the antecedent of the reflexive and matching the reference of the reflexive to that of its antecedent, and a third NP requires introducing a new entity into the discourse model. The higher accuracy for sentences with reflexives than a third noun phrase in object manipulation suggests that the latter is more demanding than the former in this task, although this suggestion must be treated with caution because object manipulation was not timed and the lower accuracy and faster RTs for sentences with reflexives in sentence picture matching suggests a speed-accuracy trade off. Pronouns differ from reflexives in that the antecedent of a pronoun can be external to a sentence, making pronouns more like full noun phrases, and because the antecedent of a reflexive in these materials is always the immediately preceding noun phrase, allowing for a minimal distance

heuristic to yield the correct interpretation for reflexives but not for pronouns. These factors may be part of the reason for the better performance on sentences with reflexives, but not on sentences with pronouns, relative to baselines.

A novel analysis in this study is the use of multilevel models to assess the effects of sentence type, memory and their interactions. In these models, the main effect of sentence type was negative for accuracy and positive for RTs for passives, object relatives and sentences with pronouns, reflecting the increased load associated with these experimental sentences. The effect of sentence type on accuracy for sentences with reflexives was negative in sentence picture matching and positive in object manipulation, and the effect of reflexives was negative in the RT data.

Turning to the effects of memory, we first note that effects were only found for the measures of “simple, forward” and “demanding, complex” span, not the PSE or WLE (with one exception, which we cannot explain and will henceforth ignore). The absence of an effect of phonological similarity or word length is a null result. If we accept it as real, it provides evidence that the effect of these features of list composition on immediate serial recall does not result from mechanisms that support sentence comprehension. As noted, the PSE has been interpreted as a reflection of the capacity of a phonological store (Baddeley, 2000a, b; Shallice and Vallar, 1990); however, it is more likely to reflect the use of phonological codes as retrieval (Caplan et al, 2011b). We tentatively suggest that these results are evidence that stored phonological representations and phonological retrieval cues are not used in syntactically based comprehension. The WLE has been interpreted as a reflection of rehearsal (Baddeley et al, 1975; for discussion, see Caplan et al, 1992; Service, 1998; Tolan and Tehan, 2005; Zhang and Feng, 1990; Lovatt et al, 2000), and we tentatively suggest that these results are evidence that rehearsal is not widely used in syntactically based comprehension. The WLE also results from lexical neighborhood density effects (Jalbert et al, 2011), which leads us to suggest that lexical items are retrieved in syntactically based comprehension without activating their entire network of associations (Vitevitch et al, 2011).

The main effects of “forward, simple” and “demanding, complex” span performance were always in the expected direction – higher memory measures were associated with higher accuracy and faster RTs. This indicates that better STM function made for better performance on both the experimental and the baseline sentences in these tasks. The existence of these main effects on end-of-sentence but not on-line measures suggests that pwa use mechanisms that support recall of items in lists to reactivate words and word sequences in sentences in formulating and executing responses in these tasks.

Interactions of memory and sentence type can provide data regarding the role of STM in parsing and interpretation. Evidence for a role of an aspect of memory in syntactically based comprehension would come from the finding that the difference in performance between a more difficult experimental sentence type and a matched simpler, syntactically less complicated baseline sentence increases in individuals with lower memory function. This was the pattern found in three of the four patterns of interaction – pattern 1, for accuracy in sentences with pronouns in sentence picture matching with full presentation; pattern 3, for RT in object relatives in sentence picture matching with auditory moving windows; and pattern 4, for RT in baseline sentences compared to reflexives for picture matching with full presentation. Pattern 4 was unexpected, because the better performance on baseline sentences was unexpected. Given that the baseline sentences were more difficult than the experimental sentences in this contrast, this result is consistent with aspects of STM supporting the comprehension of the more difficult sentence type. As noted, in this contrast, operations that might be supported by memory are ones related to introducing and

maintaining a third entity in the discourse and considering this entity in formulating a response required by the task.

Pattern 2, seen in all tasks for object relatives and in object manipulation for sentences with pronouns, is not a pattern that would be expected if the memory measure reflected memory mechanisms that supported parsing and interpretive operations that are required to a greater extent in the experimental than in the baseline sentence. The pattern could arise from a floor effect in patients with low memory function, which created a lower bound to their accuracy on the experimental sentence.

Overall, therefore, although we cannot provide an account of why these effects were found in the specific combinations of sentence types, tasks, and dependent measures where they occurred, the patterns of effects of sentence type and memory function on accuracy and RT are all understandable. Patterns that would have challenged interpretation, such as patients with higher STM performing worse than those with lower STM, did not occur. The disproportional effects of sentence complexity on accuracy or RTs in patients with lower STM are consistent with a role of STM in supporting parsing and interpretation. However, they do not prove that STM supports parsing and interpretation. At least one alternative must be considered: that STM supports the use of the products of the comprehension process to perform a task. A brief consideration of how the tasks used here are performed illustrates where STM may play a role.

Picture matching requires participants to interpret visual scenes and to determine which of two interpretations best corresponds to the meaning of a sentence. Because the pictures appeared at the same time as the sentence began, participants had three options for scheduling sentence processing, scene analysis, and comparison operations. The first is to postpone visual analysis and comparing sentence meaning with scene interpretation until after the sentence was presented, which would require maintaining the meaning of the sentence in mind while interpreting the scenes and comparing them to the meaning of the sentence. Ferreira has shown that syntactically unlicensed interpretations are constructed and retained in memory, and that this occurs more often for semantically reversible sentences and sentences with non-canonical constituent orders (Ferreira and Patson, 2007, Ferreira et al, 2009). Review of the form of a sentence, maintained in STM, would therefore be useful if this option was exercised and would be expected to occur more for the more difficult sentences. The second option is the opposite – storing the ongoing sentence in memory without analyzing it while first interpreting the pictures. The obligatory and incremental processing of sentences makes it very unlikely that this occurred. The last option is doing both tasks incrementally. This requires dividing attention between sentence comprehension and visual analysis and therefore creates a need to retrieve portions of the sentence from memory. As with the first scheduling option, this can lead to more reliance on representations held in STM in more complex sentences.

In object manipulation, comprehension and motor planning must be scheduled. Unlike visual analysis in sentence picture matching, which in principle could be done before sentence comprehension, postponing sentence comprehension until motor planning is done is not an option. It is possible for sentence comprehension and motor planning to both be carried out incrementally, but times to initiate actions were almost always long (this is the reason they were not recorded), indicating that much of motor planning or execution was postponed until the sentence is understood. This could lead to increased use of STM to confirm sentence meaning when an action was planned for more complex sentences, for the same reasons that apply in sentence picture matching.

Interactions of sentence complexity and memory function in measures of task performance thus do not distinguish between use of STM to encode, maintain and/or retrieve information by the parser/interpreter and use of STM in encoding, maintaining and/or retrieving information to accomplish a task. Is it possible to distinguish between the use of STM for parsing and interpretation and for maintaining a representation of the sentence that is useful in accomplishing task demands? Three aspects of the results point towards the second interpretation. The first is the relative paucity of interactions of sentence type and STM measures. In fact, the number of these interactions may be even less than we have reported because, as an anonymous reviewer of this paper pointed out, the interaction involving sentences with pronouns in SPM is very small and may reflect a ceiling effect in high span participants (Fig 5). If STM was needed to assign and interpret syntactic structure, one would expect that there would be many effects of STM capacity on the ability to understand the more complex sentences, all of which involve increased memory loads. The second is the absence of an effect of the STM measures that affected end-of-sentence performance on on-line self paced listening, but this is a null result that cannot carry much weight. The third is the pattern of interaction of memory and sentence type in the sentences with reflexives. As we have noted several times, sentences with a third NP were more difficult than their corresponding sentences with a reflexive (a significant effect in the multilevel models but not the ANOVAs), which suggests that the demands made by introducing a third discourse referent outweigh those of finding an antecedent of a reflexive. As also noted, these additional demands may involve memory, but not memory required by the parser/interpreter. It is the determination of the antecedent of a reflexive that requires the parser/interpreter to retrieve information from memory, not the assignment of the structure and meaning of the baseline sentences with three NPs. The presence of a third NP requires memory for the syntactically licensed interpretation of the sentence. The fact that the effects of STM were seen in these sentence pairs is thus evidence that STM applies at a post-interpretive stage of processing. The interactions seen in the other sentence contrasts, and the main effect of STM, can also have arisen at this stage.

The second major aspect of the data are the double dissociations of performances, in which individual patients had deficits of STM and intact syntactic comprehension and others showed the opposite pattern. These cases are constituted about 8% of the group studied. Poor performance on the sentence task in the presence of normal STM shows that factors other than STM can lead to syntactic comprehension disorders. We here focus on the other half of the double dissociation – poor STM and normal comprehension -- which speaks to the necessity of the functions captured in the STM tasks for comprehension.

In many cases, the dissociation of below normal performance on STM and normal performance on sentence comprehension applied to only one sentence comprehension task (object manipulation, sentence-picture matching with uninterrupted auditory presentation, sentence-picture matching with auditory moving window presentation). Different patients with abnormal STM had preservation of comprehension in each of those tasks (Case 54008 in picture matching but not object manipulation; Case 54048 in object manipulation but not picture matching). We have previously emphasized the importance of task demands in determining performance (Caplan et al, 2006, 2007b, under review). The dissociations here reinforce their importance by showing that it is possible to selectively perform normally on either picture matching or object manipulation despite having an abnormal STM functional capacity. However, the present point is that it is possible to have abnormally low performance on STM tasks and still perform within the normal range on at least one task requiring comprehension of sentences with the syntactic structures and elements presented here. This shows that intact STM functions, as measured by our tasks, are not necessary to comprehend these sentences. Unless there is a way to understand these sentences without using normal parsing and interpretive operations, this leads to the conclusion that it is

possible to have abnormally low performance on STM tasks and perform these operations at a normal level of accuracy.

An interesting question is how limited STM can be and still allow an individual to perform normally, whether in object manipulation, picture matching, or other tasks (e.g., encoding into memory as tested in verification; matching meaning to information in semantic memory, as tested in plausibility judgment). The individuals who had abnormally low STM and normal comprehension in some task had spans between 2 and 4 on different measures. Patients with spans of zero (i.e., those who could not reliably report item and order information on 3/5 trials at list length 2) uniformly performed at chance on the comprehension tasks. It may be that there is a minimal memory function that is needed to perform normally, or above chance, on the comprehension tests used here that falls between these figures. Patients with Alzheimer's Disease with spans of 1 and 2 have shown normal performance on syntactically based comprehension tasks (Waters and Caplan, 1997), indicating that the capacity of the CE that is needed for normal performance is very low.

Overall, the results indicate that mechanisms that maintain, retrieval and manipulation of item and order information in STM support aspects of performance in tasks that require syntactically based comprehension. There is no evidence that phonological codes or rehearsal play a special role in this effect, but this does not imply that phonological features are not one aspect of multidimensional representations that are maintained in STM and utilized in the comprehension process. Some aspects of the data suggest that the role of STM is in mapping interpretations onto operations required to perform tasks. Dissociations between normal performance in sentence comprehension and below normal performance on STM indicates that normal STM is not needed to support either parsing and interpretation *per se* or the use of STM in mapping interpretations onto operations required to perform tasks.

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Fig 1. Characterization of effects of forward span on accuracy for sentences with pronouns in sentence picture matching with full sentence presentation. The main effect of sentence type is negative, the main effect of memory is positive, the interaction of sentence type and memory is positive.

Fig 2. Characterization of effects of forward span on accuracy for sentences with object relative clauses in object manipulation. The main effect of sentence type is negative, the main effect of memory is positive, the interaction of sentence type and memory is negative, and the effect of memory is more negative in the “reversed model” than in the original model.

Fig 3.

Characterization of effects of forward span on RT for sentences with object relative clauses in sentence picture matching with full sentence presentation. The main effect of sentence type effect is positive, the main effect of memory is negative, the interaction of sentence type and memory is negative.

Fig 4. Characterization of effects of forward span on RT for sentences with reflexives in sentence picture matching with full sentence presentation. The main effect of sentence type effect is negative, the main effect of memory is negative, the interaction of sentence type and memory is positive.

Table 1

Sentence Type	Example
Active (A)	The girl followed the boy.
Passive (P)	The girl was covered by the father.
Three Noun Phrases (3NP)	The niece said that the woman touched the girl .
Pronoun (PRO)	The daughter said that the woman held her .
Reflexive (REF)	The uncle said that the boy covered himself .
Cleft Subject (CS)	It was the boy who scratched the man.
Cleft Object (CO)	It was the man who the boy scratched .
Subject Object (SO)	The brother who the sister followed kissed the woman .
Subject Subject (SS)	The boy who hugged the girl chased the woman .
Subject Subject and Pronoun (SSPRO)	The nephew who touched the man washed him .
Subject Object and Pronoun (SOPRO)	The woman who the girl held touched her .
Subject Subject and Reflexive (SSREF)	The uncle who held the boy covered himself .
Subject Object and Reflexive (SOREF)	The nephew who the man touched scratched himself .

Table 2

A	Sentence Picture Matching with Auditory Moving Window Presentation												
	A	P	3NP	PRO	REF	CS	CO	SS	SO	SSPRO	SOPRO	SSREF	SOREF
PWA Mean	82.1	79.9	84.6	74.5*	86.3	83.4	74.3*	75.7	63.1*	75.2	63.7*	71.9	63.5*
PWA std	18.4	20.2	16	21	21	18.4	23	20.1	22.4	21	20.6	22.5	19.9
EC Mean	94.8	94.1	97.9	93.1	98.7	95.7	94.4	93.4	91	96.6	88.4	95.8	83.7
EC std	6.1	8.3	5.8	4.4	3.7	6.7	6.2	9.7	8.9	6.9	14.8	7.9	13.1
B	Sentence Picture Matching with Full Sentence Presentation												
	A	P	3NP	PRO	REF	CS	CO	SS	SO	SSPRO	SOPRO	SSREF	SOREF
PWA Mean	83.8	77.5*	81.7	74.5*	80.4	81.2	72.6*	70	66.5+	71.1	60.1*+	69.3	61.0*+
PWA std	15.3	18.4	17.3	21.9	23.8	18.6	20.4	17.8	14.8	19.8	20.5	20.5	17.7
EC Mean	95.1	93.6	97	96.3	97.2	95	92.6	92.1	82.3	95.1	82.4	94.2	83
EC std	3.6	6.5	5.5	5.7	4.8	4.5	6.6	8	13.4	6.1	14.1	8.9	12.7
B	Object Manipulation												
	A	P	3NP	PRO	REF	CS	CO	SS	SO	SSPRO	SOPRO	SSREF	SOREF
PWA Mean	88.1	77.6*	66.3	68.8	67	88.2	71.8*	56.2	33.5*	53.3	36.8*	60.4	37.1*
PWA std	16.9	27	35.6	32.9	39.9	18.3	28.8	41.5	37.8	42.6	33.3	39.5	37.7
EC Mean	100	99	97.2	97.4	95.4	100	98.8	99	84.2	91.8	83.4	96.4	87.9
EC std	0	6.7	14.9	13.4	17.8	0	6	2.7	21.2	25.6	24.2	15.1	22.9
B	Sentence Picture Matching with Auditory Moving Window Presentation												
	A	P	3NP	PRO	REF	CS	CO	SS	SO	SSPRO	SOPRO	SSREF	SOREF
PWA Mean	1178	1242	1016	1115	940	932	1038	1180	1472	1343	1522	1145	1383
PWA std	823	885	692	822	615	652	695	848	970	922	940	766	817
EC Mean	527	599	529	559	522	501	534	584	778	650	836	600	775
EC std	236	272	270	285	277	258	278	329	393	328	402	346	414
B	Sentence Picture Matching with Full Sentence Presentation												
	A	P	3NP	PRO	REF	CS	CO	SS	SO	SSPRO	SOPRO	SSREF	SOREF

A	Sentence Picture Matching with Auditory Moving Window Presentation												
	A	P	3NP	PRO	REF	CS	CO	SS	SO	SSPRO	SOPRO	SSREF	SOREF
PWA Mean	4944	5402	6480	6212	5486*	5762	6447*	7298	7927	7543	7996	7157	7789
PWA std	1674	1874	1911	1792	1430	1722	1868	2034	2215	2156	1940	1893	2204
EC Mean	3284	3591	4502	4465	4154	3990	4482	4831	4986	4795	5243	4565	4864
EC std	801	779	834	827	733	698	753	863	737	875	720	881	781

Table 3

SPM - AMW				SPM - Full				OM		
SentType	Accuracy		RT		SentType	Accuracy		SentType	Accuracy	
	Pearson r	p	Pearson r	p		Pearson r	p		Pearson r	p
3NP	0.66	<.0001	0.861	<.0001	3NP	0.697	<.0001	3NP	0.941	<.0001
A	0.63	<.0001	0.858	<.0001	A	0.595	<.0001	A	0.757	<.0001
CO	0.744	<.0001	0.863	<.0001	CO	0.779	<.0001	CO	0.855	<.0001
CS	0.662	<.0001	0.819	<.0001	CS	0.782	<.0001	CS	0.792	<.0001
P	0.63	<.0001	0.845	<.0001	P	0.574	<.0001	P	0.891	<.0001
PRO	0.712	<.0001	0.829	<.0001	PRO	0.741	<.0001	PRO	0.904	<.0001
REF	0.832	<.0001	0.871	<.0001	REF	0.857	<.0001	REF	0.956	<.0001
SO	0.725	<.0001	0.576	<.0001	SO	0.391	0.0029	SO	0.964	0.0029
SOPRO	0.66	<.0001	0.751	<.0001	SOPRO	0.653	<.0001	SOPRO	0.897	<.0001
SOREF	0.612	<.0001	0.795	<.0001	SOREF	0.469	0.0003	SOREF	0.911	0.0003
SS	0.619	<.0001	0.822	<.0001	SS	0.617	<.0001	SS	0.948	<.0001
SSPRO	0.765	<.0001	0.841	<.0001	SSPRO	0.786	<.0001	SSPRO	0.976	<.0001
SSREF	0.761	<.0001	0.764	<.0001	SSREF	0.691	<.0001	SSREF	0.93	<.0001

Table 4

		“Simple, Forwards” span tasks						“Complex, Demanding” span tasks				
		Digits F	Word	PSE NR	PSE R	WLE S	WLE L	Digits B	Alpha	Sub2	Sent	
EC	Mean	131.5	85.1	79.5	51.2	74.9	71.6	85.4	88.8	74.4	35.3	
EC	sd	35.4	23.9	29.2	23	17.6	22.2	39.5	36	36.1	20.7	
EC	Min	64	41	38	22	41	38	25	39	25	8	
EC	Max	175	158	161	118	121	124	167	159	168	96	
PWA	Mean	55.5	52.2	44.5	27.7	40.1	43.5	30.8	38.3	40.7	10.7	
PWA	sd	47.5	30.2	35.2	32.3	31.3	34.4	37.5	30.5	37.2	16.6	
PWA	Min	0	0	0	0	0	0	0	0	0	0	
PWA	Max	173	125	131	136	126	160	166	123	171	68	

Table 5

Accuracy				
Object Manipulation				
Main Effects				
Span Measure	P	Obj	Pro	Ref
Simple, Forward	POS*	POS*	POS*	POS*
Demanding, Complex	POS*	POS*	POS*	POS*
Interactions				
	P	Obj	Pro	Ref
Simple, Forward	ELIM	NEG*	NEG*	ELIM
Demanding, Complex	ELIM	NEG*	NEG*	ELIM

SPM-Full				
Main Effects				
Span Measure	P	Obj	Pro	Ref
Simple, Forward	POS*	POS*	POS*	POS*
Demanding, Complex	POS*	POS*	POS*	POS*
Interactions				
	P	Obj	Pro	Ref
Simple, Forward	ELIM	NEG*	POS*	ELIM
Demanding, Complex	ELIM	NEG*	POS*	ELIM

SPM-AMW				
Main Effects				
Span Measure	P	Obj	Pro	Ref
Simple, Forward	POS*	POS*	POS*	POS*
Demanding, Complex	POS*	POS*	POS*	POS*
Interactions				
	P	Obj	Pro	Ref
Simple, Forward	ELIM	NEG*	ELIM	ELIM
Demanding, Complex	ELIM	NEG*	ELIM	ELIM

RT				
SPM-Full				
Main Effects				
Span Measure	P	Obj	Pro	Ref
Simple, Forward	NEG*	NEG*	NEG	NEG*
Demanding, Complex	NEG*	NEG*	NEG*	NEG*
Interactions				
	P	Obj	Pro	Ref
Simple, Forward	ELIM	ELIM	ELIM	POS*

Demanding, Complex	ELIM	ELIM	ELIM	POS*
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SPM-AMW				
Main Effects				
Span Measure	P	Obj	Pro	Ref
Simple, Forward	NEG*	NEG*	NEG	NEG*
Demanding, Complex	NEG*	NEG*	NEG*	NEG*
Interactions				
	P	Obj	Pro	Ref
Simple, Forward	ELIM	NEG*	ELIM	POS*
Demanding, Complex	ELIM	NEG*	ELIM	ELIM

Table 6

OM accuracy, with "Forward" WM measure					
Obj. vs. Subj (CO, SO, SOREF and SOPRO vs. CS, SS, SSREF and SSPRO) contrast – REDUCED MODEL					
Fixed effects:					
(Intercept)	Estimate	Std. Error	z value	Pr(> z)	
	1.121e+00	6.327e-02	17.718	< 2e-16 ***	
ObjSubj	-1.342e+00	7.342e-02	-18.282	< 2e-16 ***	
Fwd	1.099e-02	4.061e-04	27.051	< 2e-16 ***	
Comp	2.015e-02	5.776e-03	3.489	0.000485 ***	
ObjSubj:Fwd	-3.259e-03	4.430e-04	-7.356	1.89e-13 ***	
Fwd:Comp	2.080e-04	2.954e-05	7.042	1.90e-12 ***	
Pronouns (PRO, SOPRO, SSPO vs. 3NP, SO, SS) contrast - REDUCED MODEL					
Fixed effects:					
(Intercept)	Estimate	Std. Error	z value	Pr(> z)	
	3.501e-01	6.553e-02	5.343	9.15e-08 ***	
Pro	-1.992e-02	7.769e-02	-0.256	0.797637	
Fwd	1.043e-02	4.288e-04	24.329	< 2e-16 ***	
Comp	9.217e-03	6.598e-03	1.397	0.162432	
Pro:Fwd	-1.793e-03	4.818e-04	-3.721	0.000198 ***	
Fwd:Comp	1.125e-04	3.468e-05	3.244	0.001180 **	
OM accuracy, with "Complex" WM measure					
Obj. vs. Subj (CO, SO, SOREF and SOPRO vs. CS, SS, SSREF and SSPRO) contrast - FULL MODEL					
Fixed effects:					
(Intercept)	Estimate	Std. Error	z value	Pr(> z)	
	1.122e+00	6.524e-02	17.196	< 2e-16 ***	
ObjSubj	-1.331e+00	7.998e-02	-16.640	< 2e-16 ***	
Comp	2.015e-02	8.496e-04	23.718	< 2e-16 ***	
Comp	2.305e-02	8.250e-03	2.794	0.005200 **	
ObjSubj:Comp	-4.223e-03	1.034e-03	-4.084	4.42e-05 ***	
ObjSubj:Comp	1.515e-03	9.921e-03	0.153	0.878620	

OM accuracy, with "Forward" WM measure				
Obj. vs. Subj (CO, SO, SOREF and SOPRO vs. CS, SS, SSREF and SSPRO) contrast – REDUCED MODEL				
Cmplx:Comp	3.035e-04	9.055e-05	3.351	0.000804 ***
ObjSubj:Cmplx:Comp	1.905e-04	1.084e-04	1.757	0.078921.
Pronouns (PRO, SOPRO, SSPRO vs. 3NP, SO, SS) contrast - FULL MODEL				
Fixed effects:				
(Intercept)	Estimate	Std. Error	z value	Pr(> z)
Pro	4.003e-01	6.987e-02	5.729	1.01e-08 ***
Cmplx	-5.017e-02	8.848e-02	-0.567	0.57073
Comp	2.067e-02	9.423e-04	21.936	<2e-16 ***
Pro:Cmplx	2.020e-02	8.935e-03	2.261	0.02378 *
Pro:Comp	-3.576e-03	1.165e-03	-3.069	0.00214 **
Cmplx:Comp	-9.452e-03	1.103e-02	-0.857	0.39154
Pro:Cmplx:Comp	2.356e-04	1.014e-04	2.324	0.02015 *
	2.289e-05	1.244e-04	0.184	0.85401
Full accuracy, with "Forward" WM measure				
Obj. vs. Subj (CO, SO, SOREF and SOPRO vs. CS, SS, SSREF and SSPRO) contrast - FULL MODEL, ALL INTERACTIONS SIGNIFICANT; MODEL NOT REDUCED				
Fixed effects:				
(Intercept)	Estimate	Std. Error	z value	Pr(> z)
ObjSubj	1.097e+00	6.323e-02	17.350	<2e-16 ***
Fwd	-4.893e-01	7.879e-02	-6.211	5.28e-10 ***
Comp	4.478e-03	3.488e-04	12.838	<2e-16 ***
ObjSubj:Fwd	2.355e-02	8.538e-03	2.759	0.00580 **
ObjSubj:Comp	-1.262e-03	4.189e-04	-3.014	0.00258 **
Fwd:Comp	-2.050e-02	1.034e-02	-1.982	0.04747 *
ObjSubj:Fwd:Comp	9.535e-05	4.282e-05	2.227	0.02596 *
	-1.150e-04	5.138e-05	-2.239	0.02518 *
Pronouns (PRO, SOPRO, SSPRO vs. 3NP, SO, SS) contrast - REDUCED MODEL				
Fixed effects:				
(Intercept)	Estimate	Std. Error	z value	Pr(> z)
	1.0942714	0.0565215	19.360	<2e-16 ***

OM accuracy, with "Forward" WM measure				
Obj. vs. Subj (CO, SO, SOREF and SOPRO vs. CS, SS, SSREF and SSPRO) contrast - REDUCED MODEL				
Pro	-0.1785103	0.0736550	-2.424	0.0154 *
Fwd	0.0039463	0.0003128	12.614	<2e-16 ***
Comp	0.0007144	0.0049650	0.144	0.8856
Pro:Fwd	0.0007784	0.0003653	2.131	0.0331 *
Full accuracy, with "Complex" WM measure				
Obj. vs. Subj (CO, SO, SOREF and SOPRO vs. CS, SS, SSREF and SSPRO) contrast - REDUCED MODEL				
Fixed effects:	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	1.113e+00	5.825e-02	19.105	<2e-16 ***
ObjSubj	-5.064e-01	6.446e-02	-7.856	3.97e-15 ***
Cmplx	8.838e-03	6.610e-04	13.371	<2e-16 ***
Comp	2.289e-02	7.093e-03	3.228	0.00125 **
ObjSubj:Cmplx	-3.059e-03	7.266e-04	-4.210	2.55e-05 ***
ObjSubj:Comp	-1.761e-02	6.611e-03	-2.664	0.00773 **
Cmplx:Comp	1.385e-04	6.127e-05	2.260	0.02385 *
Pronouns (PRO, SOPRO, SSPRO vs. 3NP, SO, SS) contrast - REDUCED MODEL				
Fixed effects:	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	1.1644993	0.0933528	12.474	<2e-16 ***
Pro	-0.1911858	0.1037060	-1.844	0.0653.
Cmplx	0.0075046	0.0008655	8.671	<2e-16 ***
Comp	0.0074956	0.0090810	0.825	0.4091
Pro:Cmplx	0.0015028	0.0007300	2.058	0.0395 *
AMW accuracy, with "Forward" WM measure				
Obj. vs. Subj (CO, SO, SOREF and SOPRO vs. CS, SS, SSREF and SSPRO) contrast - REDUCED MODEL				
Fixed effects:	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	1.434e+00	6.312e-02	22.711	<2e-16 ***
ObjSubj	-7.984e-01	6.422e-02	-12.433	<2e-16 ***

OM accuracy, with "Forward" WM measure					
Obj. vs. Subj (CO, SO, SOREF and SOPRO vs. CS, SS, SSREF and SSPRO) contrast – REDUCED MODEL					
Fwd	6.196e-03	3.767e-04	16.447		< 2e-16 ***
Comp	2.971e-02	6.755e-03	4.398		1.09e-05 ***
ObjSubj:Fwd	-2.244e-03	3.970e-04	-5.652		1.59e-08 ***
Fwd:Comp	1.854e-04	3.422e-05	5.417		6.07e-08 ***
AMW accuracy, with "Complex" WM measure					
Obj. vs. Subj (CO, SO, SOREF and SOPRO vs. CS, SS, SSREF and SSPRO) contrast - FULL MODEL					
Fixed effects:					
(Intercept)	Estimate	Std. Error	z value		Pr(> z)
ObjSubj	1.436e+00	6.626e-02	21.665		< 2e-16 ***
Cmplx	-7.612e-01	7.514e-02	-10.131		< 2e-16 ***
Comp	1.188e-02	8.064e-04	14.733		< 2e-16 ***
ObjSubj:Cmplx	4.211e-02	9.355e-03	4.501		6.75e-06 ***
ObjSubj:Comp	-4.125e-03	9.379e-04	-4.398		1.09e-05 ***
Cmplx:Comp	-1.760e-02	1.100e-02	-1.601		0.109
ObjSubj:Cmplx:Comp	4.161e-04	9.838e-05	4.230		2.34e-05 ***
	-1.478e-04	1.146e-04	-1.289		0.197
SPM-Full RTs, with "Forward" WM measure					
Reflexives (REF, SOREF, SSREF vs. 3NP, SO, SS) contrast - REDUCED MODEL					
Fixed effects:					
(Intercept)	Estimate	MCMCmean	HPD95lower	HPD95upper	pMCMC
Ref	5145.346	5134.524	4294.1592	5953.823	0.0000
Fwd	-702.453	-700.802	-1231.2677	-155.829	0.0120
Comp	-13.569	-13.577	-18.3287	-8.934	0.0000
Ref:Fwd	134.459	134.331	23.5959	244.456	0.0394
	1.607	1.609	0.3942	2.842	0.0102
SPM-Full RTs, with "Complex" WM measure					
Reflexives (REF, SOREF, SSREF vs. 3NP, SO, SS) contrast - REDUCED MODEL					
Fixed effects:					
	Estimate	MCMCmean	HPD95lower	HPD95upper	pMCMC
					Pr(> t)

OM accuracy, with “Forward” WM measure						
Obj. vs. Subj (CO, SO, SOREF and SOPRO vs. CS, SS, SSREF and SSPRO) contrast – REDUCED MODEL						
(Intercept)	5228.811	5227.251	4375.3935	6098.832	0.0001	0.0000
Ref	-707.586	-707.384	-1262.1629	-182.339	0.0082	0.0134
Cmplx	-20.614	-20.565	-29.3307	-11.630	0.0001	0.0001
Comp	93.137	93.069	-10.5528	212.452	0.1028	0.1643
Ref:Cmplx	2.472	2.466	0.2112	4.731	0.0374	0.0334
AMW RTs, with “Forward” WM measure						
Obj. vs. Subj (CO, SO, SOREF and SOPRO vs. CS, SS, SSREF and SSPRO) contrast – REDUCED MODEL						
Fixed effects:	Estimate	MCMCmean	HPD95lower	HPD95upper	pMCMC	
(Intercept) 0.0000	2027.4405	2026.2589	1726.352	2331.5901	0.0001	
ObjSubj 0.0000	331.4062	331.0674	230.412	429.1804	0.0001	
Fwd 0.0000	-4.8429	-4.8235	-6.600	-3.1224	0.0001	
Comp 0.7918	6.5745	6.4146	-37.851	48.4005	0.7710	
ObjSubj:Fwd 0.0148	-0.7004	-0.7031	-1.294	-0.1572	0.0140	
ObjSubj:Comp 0.0175	18.1648	18.2671	3.514	33.4297	0.0190	
Reflexives (REF, SOREF, SSREF vs. 3NP, SO, SS) contrast - REDUCED MODEL						
Fixed effects:	Estimate	MCMCmean	HPD95lower	HPD95upper	pMCMC	
(Intercept) 0.0000	2173.6382	2172.2446	1784.5043	2544.2757	0.0001	
Ref 0.0132	-191.5385	-189.5730	-336.3429	-33.3563	0.0140	
Fwd 0.0001	-4.7582	-4.7769	-6.9728	-2.6613	0.0001	
Comp 0.9674	1.3051	1.7908	-54.4635	56.9290	0.9480	
Ref:Fwd 0.0018	1.3725	1.3789	0.5190	2.2445	0.0022	
Ref:Comp 0.2824	-12.1739	-12.3705	-34.6486	9.7647	0.2744	
Fwd:Comp 0.7819	-0.0418	-0.0395	-0.2920	0.2302	0.7734	
Ref:Fwd:Comp 0.0430	-0.1088	-0.1102	-0.2147	-0.0023	0.0410	
AMW RTs, with “Complex” WM measure						

OM accuracy, with "Forward" WM measure						
Obj. vs. Subj (CO, SO, SOREF and SOPRO vs. CS, SS, SSREF and SSPRO) contrast – REDUCED MODEL						
Obj. vs. Subj (CO, SO, SOREF and SOPRO vs. CS, SS, SSREF and SSPRO) contrast - REDUCED MODEL						
Fixed effects:						
(Intercept) 0.0000	Estimate	MCMCmean	HPD95lower	HPD95upper	pMCMC Pr(> t)	
ObjSubj 0.0000	2051.215	2048.809	1718.582	2356.352	0.0001	
Cmplx 0.0002	333.635	332.673	236.406	434.061	0.0001	
Comp 0.7082	-7.331	-7.284	-10.699	-4.120	0.0002	
ObjSubj:Cmplx 0.0066	-9.558	-9.942	-53.039	33.549	0.6408	
ObjSubj:Comp 0.0145	-1.387	-1.395	-2.389	-0.409	0.0066	
	18.059	18.234	3.786	32.817	0.0156	

Table 7

Simple Forwards Tests						Simple Forwards Tests					
Subj	WM (Simple score)	OMsimple	AMWsimple	SPMsimple	Subj	WM (Simple score)	OMcomplex	AMWcomplex	SPMcomplex		
54004	305	96.3	85.9	87.5	54008	166	56.1	88.3	87.2		
54008	166	77.5	92.3	92.5	54015	250	64.4	84.4	85		
54009	274	95	87.5	86.1	54019	223	83.8	93.8	86.3		
54015	250	68.8	92.5	92.3	54022	324	93.3	85.6	73.3		
54019	223	83.8	93.8	86.3	54048	253	98.8	92.5	87.5		
54022	324	100	94.9	77.5							
54048	253	98.8	92.5	87.5							
EC mean	493.7	99	95.5	94.8	EC mean	493.7	92.8	92.9	90.8		
EC SD	104	4	5.4	3.6	EC SD	104	14	6.4	6.2		
1.6 SD cutoff	327.32	92.7	86.8	89.1	1.6 SD cutoff	327.32	70.4	82.7	80.8		
Complex Demanding Tests						Complex Demanding Tests					
Subj	WM (Complex Score)	OMsimple	AMWsimple	SPMsimple	Subj	WM (Complex Score)	OMcomplex	AMWcomplex	SPMcomplex		
54004	93	96.3	85.9	87.5	54008	87	56.1	88.3	87.2		
54008	87	77.5	92.3	92.5	54048	91	73.9	72.6	70.6		
54048	91	98.8	92.5	87.5	54057	103	76.1	80	76.1		
54057	103	98.8	96	87.5							
EC mean	248.6	99	95.5	94.8	EC mean	248.6	92.8	92.9	90.8		
EC SD	90.2	4	5.4	3.6	EC SD	90.2	14	6.4	6.2		
1.6 SD cutoff	104.28	92.7	86.8	89.1	1.6 SD cutoff	104.28	70.4	82.7	80.8		

Table 8

Simple Forwards Tests					Simple Forwards Tests				
Subj	WM (Simple score)	OMsimple	AMWsimple	SPMsimple	Subj	WM (Simple score)	OMcomplex	AMWcomplex	SPMcomplex
54023	336	62.5	89.5	80	54003	335	72.8	77.8	73.9
54057	335	98.8	96	87.5	54023	336	27.2	75.7	71.7
54059	354	97.5	94.7	88.8	54041	330	71.1	74.7	79.4
					54047	359	52.2	84.2	.
					54057	335	76.1	80	76.1
					54062	337	67.2	.	.
EC mean	493.7	99	95.5	94.8	EC mean	493.7	92.8	92.9	90.8
EC SD	104	4	5.4	3.6	EC SD	104	14	6.4	6.2
1.6 SD cutoff	327.32	92.7	86.8	89.1	1.6 SD cutoff	327.32	70.4	82.7	80.8

Complex Demanding Tests					Complex Demanding Tests				
Subj	WM (Complex Score)	OMsimple	AMWsimple	SPMsimple	Subj	WM (Complex Score)	OMcomplex	AMWcomplex	SPMcomplex
Subj	Demanding Tests	OM_simpl	AMW_simpl	Fullsimpl	Subj	WM (Complex Score)	OMcomplex	AMWcomplex	SPMcomplex
54009	123	95	87.5	86.1	54015	115	64.4	84.4	85
54015	115	68.8	92.5	91.3	54019	131	37.2	76.3	67.2
54022	164	100	94.9	77.5	54022	164	93.3	85.6	73.3
54023	149	62.5	89.5	80	54023	149	27.2	75.5	71.7
54041	156	98.8	87.5	81.3	54041	156	71.1	74.7	79.4
54045	124	92.5	77.8	82.3	54045	124	67.8	65.8	71.1
54059	190	97.5	94.7	88.8	54054	185	75.6	65.7	63.3

Simple Forwards Tests						Simple Forwards Tests					
Subj	WM (Simple score)	OMsimple	AMWsimple	SPMsimple	Subj	WM (Simple score)	OMcomplex	AMWcomplex	SPMcomplex		
					54062	124	67.2	.	.		
					54065	121	66.7	83.9	81.6		
EC mean	248.6	99	95.5	94.8	EC mean	248.6	92.8	92.9	90.8		
EC SD	90.2	4	5.4	3.6	EC SD	90.2	14	6.4	6.2		
1.6 SD cutoff	104.28	92.7	86.8	89.1	1.6 SD cutoff	104.28	70.4	82.7	80.8		