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Role for Memory Capacity in Sentence Comprehension: Evidence from Acute Stroke

Corinne Pettigrew and

Department of Neurology, Division of Cognitive Neuroscience Johns Hopkins University School of Medicine 1620 McElderry Street Baltimore, MD, 21205

Argye E. Hillis

Department of Neurology Johns Hopkins University School of Medicine 600 North Wolfe Street Baltimore, MD 21287 (410) 614-2381 argye@jhmi.edu

Abstract

Background—Previous research has suggested that short-term and working memory resources play a critical role in sentence comprehension, especially when comprehension mechanisms cannot rely on semantics alone. However, few studies have examined this association in participants in acute stroke, before the opportunity for therapy and reorganization of cognitive functions.

Aims—The present study examined the hypothesis that severity of short-term memory deficit due to acute stroke predicts the severity of impairment in the comprehension of syntactically complex sentences. Furthermore, we examined the association between damage to the short-term and working memory network and impaired sentence comprehension, as an association would be predicted by the previous hypothesis.

Methods & Procedures—47 participants with acute stroke and 14 participants with a transient ischemic attack (TIA; the control group) were included in the present study. Participants received a language battery and clinical or research scans within 48 hours of hospital admittance. The present study focused on the behavioral data from the short-term memory and working memory span tasks and a sentence-picture matching comprehension task included in this battery. Using regression analyses, we examined whether short-term and working memory measures explained significant variance in sentence comprehension performance.

Outcomes & Results—Consistent with prior research, short-term memory explained significant variance in sentence comprehension performance in acute stroke; in contrast, working memory accounted for little variance beyond that which was already explained by short-term memory. Furthermore, ischemia that included the short-term/working memory network was sufficient to cause sentence comprehension impairments for syntactically complex sentences.

Conclusions—The present study suggests that short-term memory resources are an important source of sentence comprehension impairments.

Corresponding author: Corinne Pettigrew (410) 502-9272 corinne.pettigrew@gmail.com.

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Keywords

acute stroke; short-term memory; working memory; sentence comprehension

Theoretical models of sentence processing have proposed several mechanisms that might account for aphasia-related sentence comprehension deficits (see, e.g., Caplan & Waters, 2007a). The present study examines one such mechanism – memory capacity accounts of comprehension – in participants with acute stroke. Capacity accounts of sentence processing propose that limited capacity systems, such as short-term or working memory, are critically involved in sentence processing (e.g., Caplan & Waters, 1999; Cecchetto & Papagno, 2011; Just & Carpenter, 1992; R. Martin, Shelton, & Yaffee, 1994), especially for sentences with increased processing load or length, such as syntactic complexity or distance, non-canonical word order, and reversible sentence types. In such accounts, capacity resources are allocated to different comprehension processes, serving to effectively store the intermittent sentence processing results until one arrives at a final interpretation. Here, we examined the hypothesis that impaired short-term memory capacity is one mechanism that can lead to impaired sentence comprehension in left hemisphere acute stroke, as determined by behavioral and neuroanatomical relationships.

One of the most broadly applied models describing limited-capacity retention and manipulation of information is Baddeley and Hitch's (1974) model of working memory (see Baddeley, 2012, for a recent review of this model). In its original description, this model included three primary components. The central executive was considered a supervisory system involved in attentional control and manipulating information. The other two components, the phonological loop and visuospatial sketchpad, were conceptualized as limited capacity systems responsible for the short-term retention of phonological and visual-spatial information, respectively. Under such a model, an important distinction can be drawn: whereas short-term memory (STM) refers to the temporary maintenance of information (for example, verbal or visual content), working memory (WM) refers to both the maintenance *and* manipulation of information, involving additional processing resources above and beyond simple information storage. Importantly, though closely related, STM and WM (and their associated tasks) are not equivalent (e.g., Engle Tuholski, Laughlin, & Conway, 1999).

While capacity accounts of comprehension tend to propose a critical role for the temporary maintenance of linguistic information in service of sentence comprehension, they differ in the specifics. For example, numerous neuropsychological case studies have suggested that deficits to domain-general STM mechanisms – that is, the short-term maintenance of verbal information – have consequences for sentence comprehension (e.g., R. Martin & Romani, 1994; R. Martin et al., 1994; Papagno, Cecchetto, Reati, & Bello, 2007; Vallar & Baddeley, 1984; cf. Butterworth, Campbell, & Howard, 1986). These accounts have placed different emphases on the type of linguistic representations that are maintained. Some have focused on the importance of the short-term retention of phonological information (e.g., Friedrich, R. Martin, & Kemper, 1985; Papagno et al., 2007; Vallar & Baddeley, 1984; cf. Caplan, Michaud, & Hufford, 2013), as might be measured by Baddeley and Hitch's (1974)

phonological loop. Phonological representations, for example, may be important when verbatim, ordered content or syntactic dependencies need to be maintained in order to parse a sentence (e.g., Papagno et al., 2007; Vallar & Baddeley, 1984; see Cecchetto & Papagno, 2011, for a review), as might be the case with, for example, center-embedded relative clauses. In contrast, others have focused on the importance of the short-term retention of lexical-semantic information (e.g., R. Martin & He, 2004; R. Martin & Romani, 1994; R. Martin et al., 1994). In sentence comprehension, lexical-semantic maintenance may play a role when several semantic representations must be maintained until they can be integrated into the corresponding syntactic structure (e.g., R. Martin & Romani, 1994; R. Martin et al., 1994), for example when more than one noun precedes a verb. That verbal STM might involve not only phonological representations, but also lexical-semantic representations, suggests that a purely phonological store (as proposed by Baddeley & Hitch, 1974) may be too restrictive (see also Caplan, Waters, & Howard, 2012). Accordingly, language-based models of STM have emphasized the contribution of multiple levels of linguistic representations, including both phonological and lexical-semantic codes (e.g., N. Martin & Ayala, 2004; N. Martin & Saffran, 1997; R. Martin & Romani, 1994).

Despite the differences in linguistic representations emphasized, the above-discussed accounts suggest that individual differences in verbal STM – as measured by traditional short-term memory tasks – play important roles in sentence comprehension. Because the present study was not designed to distinguish between different types of linguistic representations, we use the term “verbal STM” to refer to the retention of verbal representations more generally. Like language-based models of STM, we assume that verbal STM includes contributions from multiple levels of linguistic representations, including both phonological and lexical-semantic codes (see also N. Martin & Saffran, 1997; R. Martin & Romani, 1994), and can be measured by traditional span tasks. Furthermore, in line with the above accounts, we maintain that verbal STM supports sentence comprehension through the maintenance of linguistic representations (e.g., order of grammatical constituents, semantic information) until it can be integrated into a syntactic frame or sentential context.

Although they also propose a role for memory resources in sentence comprehension, Caplan and colleagues (e.g., Caplan, Michaud, & Hufford, 2013; Caplan & Waters, 1999) have taken a different perspective than the domain-general verbal STM accounts just discussed. Specifically, Caplan and colleagues have suggested that “interpretive processing” – which includes deriving syntactic structure and assigning meaning to that structure – is supported by a specialized pool of WM resources (Caplan & Waters, 1999), which they have more recently suggested to be a type of procedural memory (Caplan et al., 2013). Accordingly, this specialized WM system that underlies interpretive processing cannot be measured by standard WM tasks. In contrast, Caplan and Waters (1999) suggest that domain-general STM/WM resources may be used for “post-interpretive processes.” Post-interpretive processes refer to the ways in which one uses the results of interpretive processing, for example, in re-evaluating a misinterpreted sentence, or using the meaning of a sentence for specific purpose such as matching a parsed sentence to a corresponding picture in a sentence-picture matching task. As a result, Caplan and colleagues have proposed little role for domain-general capacity-limited memory system in sentence comprehension (i.e., parsing) *per se*. However, a domain-general capacity limited memory system such as STM

or WM is involved in retaining a sentence's meaning, for example, in order to apply it to another purpose.

Furthermore, individual difference approaches in non-brain damaged participants have also found a relationship between capacity-limited memory resources and sentence comprehension, though these studies have tended to emphasize WM (over STM). In regards to the sentence comprehension of non-brain damaged participants, for example, King and Just (1991) found individuals with high WM capacities performed better on more resource-demanding sentences (e.g., object relative sentences), relative to individuals with low WM capacities, though these two span groups performed similarly on less resource-demanding sentences (i.e., subject relative; see also Just & Carpenter, 1992; Daneman & Merikle, 1996; Miyake, Carpenter, & Just, 1994). In addition, dual-tasking studies have found that concurrent verbal memory loads interfere with sentence comprehension (e.g., Gordon, Hendrick, & Levine, 2002), suggesting that WM resource disruptions have detrimental effects on sentence processing. Importantly, it has also been suggested that similar reductions in WM capacity account for the sentence comprehension performance in participants with aphasia (Miyake et al., 1994; cf., R. Martin, 1995).

To summarize, research from multiple domains has provided support for the notion that limitations of one's memory capacity is one cognitive resource that can hinder sentence comprehension. However, although a fair amount of neuropsychological research from participants with chronic left hemisphere brain damage supports a STM capacity account of comprehension, it remains possible that this behavioral association results from patterns of functional brain reorganization, the development of heuristics that differentially favor sentence comprehension with low processing load, and/or differential practice effects of specific sentence types (e.g., in language therapy). The present study seeks to confirm the association between STM impairments and deficits in sentence comprehension in participants with acute stroke. By testing participants in the acute phase, within 48 hours of their stroke, we can assess the association between these cognitive processes before recovery occurs – i.e., shortly after deficit onset, making it unlikely that individuals have yet developed compensatory strategies. Despite the advantages of testing participants in the acute phase, very little work has directly examined the relationship between STM and sentence comprehension in these participants. One exception is a study by Race, Ochfeld, Leigh, and Hillis (2012), which sought to elucidate the brain regions involved in reversible versus nonreversible question comprehension (e.g., “Is a horse larger than a dog?” vs. “Do most people have 3 ears?”). Race et al. (2012) found that reversible question comprehension was associated with ischemia to the left inferior parietal cortex (BA 39, 40) as well as one left posterior frontal region (BA 6), whereas nonreversible question comprehension was associated only with volume of tissue dysfunction. Because BA 6 (premotor cortex) and BA 40 (supramarginal gyrus) are regions previously implicated in aspects of phonological STM (e.g., D'Esposito & Postle 1999; D'Esposito, Postle, Ballard, & Lease, 1999; Hickok & Poeppel, 2004; Romero, Walsh, & Papagno, 2006), Race et al. raised the possibility that impaired STM might account for the selective impairment in reversible questions in participants with lesions in these areas. These findings are consistent with neuropsychological and neuroimaging research suggesting that some of the left hemisphere regions that are involved in sentence comprehension (e.g., Caplan & Waters, 2007b;

Thompson, den Ouden, Bonakdarpour, Garibaldi, & Parrish, 2010; Thothathiri, Kimberg, & Schwartz, 2012) also support STM and/or WM, including the supramarginal gyrus (Henson, Burgess, & Frith, 2000; R. Martin, Wu, Freedman, Jackson, & Lesch, 2003; Paulesu, Frith, & Frackowiak, 1993; Race et al., 2012; Romero et al., 2006), Broca's area (Henson et al., 2000; Paulesu et al., 1993; Romero et al., 2006), dorsolateral prefrontal regions (Henson et al., 2000; Race et al., 2012), angular gyrus (Baldo, Karseff, & Dronkers, 2011; Race et al., 2012), and superior temporal gyrus (Baldo et al., 2012; Leff et al., 2009). The fact that multiple regions are associated with both STM/WM and impaired comprehension of syntactically complex sentences suggests that there should be a behavioral association even if there is not a causal relationship. Thus, the present study examines not only whether individual differences in STM/WM predict sentence comprehension performance in the acute stage of stroke, but also the association between impaired sentence comprehension and ischemia to the network of brain regions involved in STM and WM.

In line with memory resource accounts of sentence comprehension, our primary hypotheses are: (1) acute damage to areas of the brain critical for STM/WM (before the opportunity for therapy or reorganization of cognitive function) is associated with impairment in STM and in comprehension of syntactically complex sentences that cannot be understood on the basis of semantics alone, and (2) the severity of the STM deficit due to acute stroke predicts the severity of impairment in comprehension of syntactically complex sentences that cannot be understood on the basis of semantics alone. Furthermore, given the theoretical discrepancy concerning the involvement of STM vs. WM resources from neuropsychological vs. individual differences work (respectively), we also examined whether WM explains additional variance in sentence comprehension. It seems plausible that preserved WM (i.e., the processing or manipulation component) might permit the use of heuristics or other cognitive strategies in sentence-picture matching tasks to help compensate for subtle deficits in sentence processing. Thus, variability in WM might explain additional variance in sentence comprehension performance, above and beyond the variability explained by STM. Therefore, our secondary hypothesis is that the severity of impairment in WM after acute stroke, after adjusting for STM, predicts severity of impairment in comprehension of syntactically complex sentences in sentence picture matching tasks.

Method

Participants

A series of 47 acute stroke participants (45% female; 49% white) were enrolled in an ongoing research study, having being admitted to the hospital within 24 hours of their stroke; with one exception, all strokes were ischemic. In addition, 14 transient ischemic attack (TIA) participants (71% female; 57% white) were also enrolled to serve as a control group for group comparisons. TIA participants serve as a proper control group for various reasons, including demographic similarity (see Table 1), the availability of magnetic resonance imaging (MRI) for verifying that they had no lesions, and a similar cognitive and psychological testing environment (i.e., a hospital setting). Study exclusion criteria included the following: evidence of bilateral stroke on MRI; lack of premorbid English proficiency; known uncorrected hearing or visual loss; reduced level of consciousness, intubation, or

ongoing intravenous sedation; prior neurological disease, including dementia; presence of contraindication to MRI (e.g., any ferromagnetic implanted metal; pregnancy; severe claustrophobia; or allergy to Gadolinium contrast or renal failure (for perfusion weighted imaging)). Consent was obtained from all participants prior to behavioral testing and structural imaging according to procedures approved by the Johns Hopkins Institutional Review Board. Participants were enrolled in the study within 48 hours of being admitted to the hospital, at which point they were given a battery of language tasks and received an MRI. Where possible, testing was completed within the first 24 hours of stroke onset; however, some testing occurred within the first 48 hours of onset due to later admittance to the hospital (e.g., admittance close to the 24 mark). Following enrollment, participants were selected for the present study based on the following: presence of a left hemisphere infarct as indicated by structural imaging (diffusion weighted imaging) and full completion of either the sentence picture matching or a short-term memory task.

Over a period of 2 years, 516 individuals admitted to the stroke service failed screening for enrollment in our study of language deficits after stroke because they had one or more exclusion criteria (e.g., bilateral stroke on MRI or previous neurological disease). Of these, 7 individuals failed screening because of impaired attention, delirium, or inability to understand the tasks. Potential participants were screened with the auditory comprehension subtest of the Western Aphasia Battery (Kertesz, 2006) or Boston Diagnostic Aphasia Examination (Goodglass & Kaplan, 1972). While they could make errors, they needed to demonstrate reliable performance on the tasks (pointing to items in forced choice word/picture matching, yes/no responses to yes/no questions). We do not keep track of the number of patients who were not approached or screened because they were intubated or medically sedated. A very small percentage of acute ischemic hemispheric (non-brainstem) stroke patients are intubated or sedated in the first 24 hours.

Procedure

Both acute stroke and TIA participants were administered a battery of language tasks that took around 1.0-2.0 hours to administer, depending on participant severity. The present study reports a portion of this battery, including the Western Aphasia Battery-Revised (WAB; Kertesz, 2006), a sentence-picture matching task, and forward and backwards word and digit span tasks. Additional measures, not reported here, included the WAB's apraxia battery for older adults, a sentence enactment task, a telling of the Cinderella story as a measure of production, and the Trail Making Test (Parts A and B; Army Individual Test Battery, 1944). In addition to this language battery, a number of participants received additional behavioral testing, depending upon the research protocol being used at the time.

Sentence Picture Matching (SPM)—In this sentence comprehension task, participants saw two pictures on computer screen, while simultaneously hearing and seeing a written sentence (with the written sentence placed under the pictures). Participants pressed a key to indicate which of the two pictures matched the sentence. This task contained 80 trials that were randomized across participants, with 20 sentences in each of the following categories: active, passive, subject-cleft, and object-cleft. Furthermore, for each of these syntactic categories, half (10) of the picture pairs were semantically reversible (i.e., the foil picture

represented the reversal of the object and subject) and half (10) were irreversible (i.e., the foil picture contained a different object or agent). The dependent variable was accuracy.

Short-term and working memory span tasks—STM and WM were assessed with two span tasks: a forward and backwards digit span task, and a forward and backward word span task. The procedure for the digit and word span tasks was the same: participants heard a series of numbers or words that they recalled in the same order for the forward span tasks, and in backwards order for the backwards span tasks. Participants received two trials at each list length, starting at 2-items/list. Items were presented by an experimenter at an approximate rate of one word per second, with voice inflection dropped upon presentation of the last item. At recall, participants were encouraged to simultaneously say the correct items aloud and point to them on pointing response sheets, though one manner of responding was accepted in patients who were unable to speak or unable to point. Pointing response sheets consisted of 9 items that were organized in three scattered rows. For the digit span task, separate pointing response sheets were presented for each list length; the numbers 1-9 were always presented in consecutive order, starting at the top left, though the number of items/row varied across response sheets (see the Appendix for an example of four response cards). For the word span task, words were selected from a pool of 16 one-syllable concrete nouns. Separate pointing response sheets were presented for each trial; words were always presented in alphabetical order starting at the top left, with three words/row, though the actual words presented differed for each response sheet. Testing continued until a participant failed both items at a given list length, and span was calculated as the maximum list length for which a participant was successful on at least one trial. When participants had scores for both the digit and word span tasks, the word and digit measures were averaged together to form a STM composite score (i.e., both forward spans, tapping storage only) and a WM composite score (i.e., both backwards spans, tapping both storage and manipulation). Unsurprisingly, the two forward span measures – word and digit span – were highly correlated ($r = .65, p < .001$); additionally, the two backwards span measures were also highly correlated ($r = .79, p < .001$). If scores from only one of the span tasks were available, that participant's STM and WM measures were reflected by a single task (digit or word span).

Magnetic Resonance Imaging (MRI)—Participants received MRIs within 48 hours of being admitted to the hospital. The MRI protocol was obtained on either a Siemens 1.5T clinical scanner or a Philips 3T research scanner, and included the following: T1, T2, Fluid Attenuated Inversion Recovery, Diffusion-Weighted Imaging (DWI), and Apparent Diffusion Coefficient (ADC) maps; in addition, a subset of participants also received high-resolution magnetization-prepared rapid acquisition with gradient echo (MPRAGE) and dynamic-susceptibility contrast echo-planar Perfusion Weighted Imaging (PWI). PWI was Gadolinium-based (20 cc power-injection at 5 cc/second). All scans were acquired parallel to the anterior commissure-posterior commissure line.

To test Hypothesis 1 (as described in the Introduction), we identified whether or not participants with acute stroke had damage to areas critical for STM/WM. DWI and PWI scans were analyzed for dysfunction in left hemisphere frontal and temporoparietal regions

hypothesized to play a role STM/WM (i.e., the STM/WM network), including the supramarginal gyrus (BA 40; Henson et al., 2000; R. Martin et al., 2003; Paulesu et al., 1993; Race et al., 2012; Romero et al., 2006), angular gyrus (BA 39; Baldo et al., 2011; Race et al., 2012), Broca's area (BA 44 and/or 45; Henson et al., 2000; Paulesu et al., 1993; Romero et al., 2006), dorsolateral prefrontal regions (BA 6; Henson et al., 2000; Race et al., 2012), and superior temporal gyrus (BA 22; Baldo et al., 2012; Leff et al., 2009). Scans were analyzed on ImageJ (<http://rsb.info.nih.gov/ij/download.html>) using a standard atlas (Damasio & Damasio, 1989), without knowledge of language assessment results, in order to determine whether each participant's dysfunction covered at least part of (1) or none (0) of the area corresponding to each of the above-mentioned ROIs. For DWI scans (available for 100% of acute participants), dysfunction was indicated by infarct, which appears as bright on DWI images and dark on ADC. Using ImageJ, we traced each participant's lesion to get an estimate of lesion size (cubic centimeters, cc) to include as a covariate in statistical analyses. For PWI scans (available for 36% of acute participants), dysfunction was indicated by >4 second delay in time to peak (TTP) arrival of Gadolinium to an ROI, compared to the homologous region in the right hemisphere. Four seconds delay in TTP corresponds to dysfunctional tissue as defined by positron emission tomography (PET; Sobesky et al., 2004; Zaro-Weber et al., 2010).

Twenty-one participants had damage that included (but were not necessarily limited to) the STM/WM network. More specifically, 2 had damage to only one ROI, 7 had damage to two ROIs, 6 had damage to three ROIs, 1 had damage to four ROIs, 1 had damage to five ROIs, and 4 had damage to all six ROIs. Of the six STM/WM network ROIs, the supramarginal gyrus (BA40; $n = 18$) and inferior parietal (BA 39; $n = 15$) ROIs were the most frequently affected, followed by dorsolateral prefrontal (BA6; $n = 12$). For the remaining 26 participants with *no* infarcts to the STM/WM network, lesions encompassed a number of cortical and subcortical regions, including frontal ($n = 3$), parietal ($n = 3$), temporal ($n = 4$), and occipital ($n = 8$) cortices, as well as the cerebellum ($n = 3$) and subcortical areas such as the thalamus or basal ganglia ($n = 16$).

Results

Participant demographics, behavioral performance, and group comparisons (univariate ANOVA comparing acute stroke vs. TIA participants) are shown in Table 1. Relative to the TIA participants, acute stroke participants as a whole performed worse on the Auditory Verbal Comprehension subtest of the WAB, the STM and WM tasks, and on reversible sentence types in the SPM task.

Hypothesis 1

Acute damage to areas of the brain critical for STM/WM is associated with impairment in STM and in comprehension of syntactically complex sentences that cannot be understood on the basis of semantics alone.

Relative to the acute stroke participants with *no* infarcts to STM/WM ROIs, the acute stroke participants *with* infarcts to STM/WM ROIs performed significantly worse on the WAB

(and its subtests), STM and WM tasks, overall SPM performance, as well as a number of SPM sentence types, including passives, cleft objects, and reversibles (Table 2).

As an additional test of the relationship between lesions to the STM/WM network and sentence comprehension, we used Fisher's exact test to examine whether or not damage to the left hemisphere STM/WM network (BA 40, BA 39, BA 44, BA 45, BA 6, BA 22) among the acute stroke participants was significantly associated with impaired sentence comprehension (impaired, unimpaired). STM/WM network damage was indicated by a lesion that included damage to at least one network ROI in either DWI or PWI imaging. Of the 43 acute stroke participants with imaging *and* SPM data, 18 had lesions that included the STM/WM network. SPM was considered impaired if below the minimum obtained by the TIA control group, separately for the different sentence types. An association was considered significant if at an alpha level of $p < .007$ ($p < .05$, corrected for multiple comparisons).

Damage to the STM/WM network was significantly associated with impaired SPM performance across multiple sentence subtypes. There was an association between STM/WM network damage and impaired comprehension of reversible sentences (averaged over sentence types; $p = .003$), but this association was *not* present for irreversible sentences (averaged over sentence types; $p = .19$). Furthermore, the association between STM/WM network damage and impaired comprehension of cleft object sentences (averaged over reversible and irreversible sentence types) was not significant after correction for multiple comparisons ($p = .04$). Looking at reversible sentence subtypes, there was an association between STM/WM network damage and impaired performance on passive reversibles ($p = .006$), cleft object reversibles ($p = .003$), and active reversibles ($p = .001$), whereas the association for cleft subject reversibles ($p = .04$) did not survive the correction for multiple comparisons. In contrast, there was no association between STM/WM network damage and impaired performance on any of the irreversible sentence subtypes (all p 's $> .05$). These results suggest that in acute stroke, damage to the STM/WM network results in behavioral difficulties in sentence processing, specifically to sentence types that cannot be understood on the basis of semantics alone. In the present group of participants, we did not have enough power to examine individual STM/WM ROIs, though future research could examine whether individual ROIs play a greater role in some sentence subtypes than others.

Hypothesis 2

Severity of the STM deficit due to acute stroke predicts severity of impairment in comprehension of syntactically complex sentences that cannot be understood on the basis of semantics alone.

As shown in Table 1, acute stroke participants performed better on easier sentences types, including all active vs. passive sentences, $t(42) = 4.23$, $p < .001$; all cleft subject vs. cleft object sentences, $t(42) = 2.96$, $p = .005$; and all irreversible vs. reversible sentence types, $t(42) = 5.02$, $p < .001$. For the irreversible vs. reversible forms of individual sentence types, participants performed better on passive irreversibles vs. passive reversibles, $t(42) = 4.05$, $p < .001$, and cleft object irreversibles vs. cleft object reversibles, $t(42) = 4.89$, $p < .001$. The

performance differences between active irreversibles vs. active reversible and cleft subject irreversibles vs. cleft subject reversibles were not statistically significant, both $ps = .07$.

We used multivariate linear regression to examine the relationship between STM and sentence comprehension in the entire group of acute stroke participants. Specifically, we were interested in whether accuracy on difficult sentence types (the dependent variable (DV)) could be predicted by severity of STM deficit, independently of other variables, including age, lesion volume, and accuracy on the easier version of that sentence type (entered as covariates). Easier sentence types were included as covariates in each analysis to control for differences in basic sentence processing ability, in order to instead examine the contribution of STM/WM in difficult sentence types, defined as those with greater processing load (e.g., syntactic complexity, non-canonical word order, reversibility). Our specific regression analyses including the following:

- a) all passive sentences (covarying active sentences);
- b) all cleft-object sentences (covarying cleft-subject sentences);
- c) all reversible sentences (covarying irreversible sentences);
- d) active reversibles (covarying active irreversible sentences);
- e) passive reversibles (covarying passive irreversible sentences);
- f) cleft subject reversibles (covarying cleft subject irreversible sentences);
- g) cleft object reversibles (covarying cleft object irreversible sentences).

Regressions (a)-(b) collapse over reversible and irreversible sentences types in order to examine the overall effect of more difficult sentence types (i.e., (a) all passives (vs. actives); (b) all cleft-objects (vs. cleft-subjects)); regression (c) collapses over all reversibles (vs. irreversibles). Regressions (d)-(g) report the results from individual reversible sentence types (controlling for irreversible; i.e., uncollapsed). STM was considered significant predictor if significant at the alpha level of $p < .007$ ($p < .05$ after Bonferroni correction for multiple comparisons).

Of the 47 acute stroke participants, 36 had both SPM and STM data. Results from the 7 above-described regressions are shown in Table 3. STM was a significant predictor of multiple – but not all – sentence types. STM explained variance in the comprehension of cleft object sentences (regression (b), $p = .004$) and reversible sentences (regression (c), $p = .002$). Looking at the reversible form of individual sentence types, STM explained variance in the comprehension of passive reversibles (regression (e), $p = .004$) and cleft object reversibles (regression (g), $p = .002$), but not active reversibles (regression (d), $p = .03$, non-significant when corrected for multiple comparisons) or cleft subject reversibles (regression (f), $p = .80$). These results indicate that STM supports the interpretation of sentences that contain non-canonical word orders with greater syntactic-semantic integration demands (passive reversibles and cleft object reversibles). STM was predictive for passive constructions only when they could not be understood on the basis of semantics alone (e.g.,

passive reversibles). In contrast, STM was not significantly predictive of sentences that could be understood on the basis of semantics alone (active and passive irreversible) or reversible sentence types with canonical word orders (active reversibles, cleft subject reversibles).

One problem with the above STM/sentence processing associations is that they could be driven by deficits to other linguistic factors, such as lexical and/or semantic access, which could affect either STM or sentence processing in a number of ways (e.g., Caplan, Waters, & Howard, 2012; Caplan et al., 2007a; N. Martin & Saffran, 1997). As shown in Table 1, acute stroke participants showed a wide range of performance on language measures, as measured by WAB subtests. As a result, we ran a set of follow-up analyses to test whether the above-discussed associations were driven by STM deficits per se (as hypothesized), versus deficits to other factors such as lexical-semantic access. In these follow-up analyses ($n = 46$), we included an additional covariate to control for severity of lexical-semantic access. Given other background neuropsychological tests were not included in the design of the present study, this covariate was a composite score consisting of proportions of items correct on three WAB subtests: yes/no questions ($M = 0.96$, $SD = 0.06$, range = 0.75-1.0), auditory word recognition ($M = 0.94$, $SD = 0.14$, range = 0.37-1.0), and object naming ($M = 0.89$, $SD = 0.25$, range = 0-1.0). These three subtests were selected because they were hypothesized to measure aspects of language processing that were not redundant with sentence comprehension or STM. (For example, the WAB Aphasia Quotient was not used because it includes measures reflective of sentence comprehension and STM.) Yes/no questions and auditory word recognition were included as rough measures of lexical access, whereas object naming was included as a rough measure of semantic access. On average, participants had relatively high composite scores, though a fair amount of variability was present ($M = 2.79$ (/3.0), $SD = 0.43$, range = 1.1-3.0). Importantly, regression results were similar to those described above, even with the inclusion of this additional 'lexical-semantic access' covariate. Corrected for multiple comparisons, STM explained significant variance in the comprehension of cleft object sentences (regression (b), $p = .006$), reversible sentences (regression (c), $p = .006$), passive reversibles (regression (e), $p = .004$), and cleft object reversibles (regression (g), $p = .003$). As with the previous analyses, none of the other sentence types survived correction for multiple comparisons (all $ps > .03$).

Secondary Hypothesis

WM explains additional variance in sentence comprehension, beyond STM.

We also examined the extent to which the "manipulation" component of WM explains additional variance in sentence comprehension, above and beyond STM storage. To directly compare the influence of STM storage and WM manipulation, we extracted a residual measure of WM by regressing out STM and saving the residuals, then used these residuals as an additional predictor in regression models (a)-(g). With STM regressed out, this residual represents the "manipulation" or "processing" component of WM, independent of short-term storage. As shown in Table 4, WM showed only weak evidence of explaining additional variance in sentence comprehension performance, as none of these WM effects survived correction for multiple comparisons. This result suggests WM explains little

additional variance in sentence comprehension, above and beyond that which is explained by individual differences in STM during acute stroke. However, these results should be replicated in future studies with a larger number of participants, and therefore more power.

Examination of individual participants

Given that we were examining the specific hypothesis that STM/WM resource impairments lead to impaired sentence processing, we also examined participant performance at the individual level to identify dissociations that would be potentially problematic to this hypothesis (e.g., good STM/WM in the presence of poor SPM; poor SPM in the presence of good STM/WM). Most problematic to this hypothesis would be participants with impaired STM, but normal SPM. For these purposes, participants' STM was considered impaired if their average forward span was < 3.5 , and participants SPM was considered impaired if their overall accuracy was $< 85\%$ (as these values were outside the range of TIA participant performance).

Participant 1 demonstrated impaired STM and WM, as indicated by an average STM span of 3 (forward digit span = 5; forward word span = 1) and WM span of 3 (backwards digit span = 4; backwards word span = 2), in the presence of preserved SPM performance (overall accuracy, 93.75%), performing most poorly on passive reversibles and passive irreversibles (80% accuracy), but above 80% accuracy on all other sentence subtypes. His lesion included the basal ganglia and other subcortical regions within the middle cerebral artery territory, but no ischemia to STM ROIs on diffusion or perfusion imaging. Unlike most other participants (as indicated by the relatively high correlation between the digit and word span tasks reported above), Participant 1 had a word span of 1 item, but a digit span of 5 items. While the reason for this discrepancy between the two span tasks is unclear, his good digit span performance is consistent with this participant's relatively intact SPM performance. Retrospectively, it may have made more sense to use the higher of the two spans, digit or word span, as the measure of true short-term memory capacity. Thus, this participant does not seem to present a problem for the hypothesis that syntactically complex sentence comprehension depends on short-term memory capacity, given his digit span of 5.

Participant 2 also had impaired STM (average forward span = 2.5), and WM (average backwards span = 2) in the presence of ischemia to three STM ROIs, including BA 6, BA 22, and BA 44. In contrast to his impaired STM, this participant performed at an overall accuracy of 87.5% on SPM. Looking at sentence subtypes, however, this participant had the most difficulty on sentences containing reversible cleft phrases, performing at 60% accuracy on cleft object reversibles and 70% accuracy on cleft subject reversibles (despite performing $>80\%$ on the other reversible and irreversible subtypes, including passive reversibles). For this participant, the STM deficit might be driven at least in part by difficulty with production, potentially affecting subvocal rehearsal during STM tasks, with only subtle effects on comprehension. In accordance with this hypothesis, Participant 2 was classified as having Transcortical Motor aphasia according to the WAB, performing worst on the spontaneous speech (9/20 points) and naming/word finding (6.2/10 points) portions, relative to the auditory verbal comprehension (9.45/10 points) and repetition (8.6/10 points) portions. Alternatively, he may have just been lucky at guessing on the passive reversible

trials. Nonetheless, this dissociation raises the possibility that impaired STM may not always lead to sentence comprehension deficits, which would suggest that the association between these two cognitive processes may be due in part to the involvement in overlapping neuroanatomical regions.

Less problematic to our hypothesis, two participants also showed the opposite patterns: impaired performance on the SPM task (< 85% overall accuracy), but STM spans within the normal range (average forward span of > 3.5 items). Participant 3, for example, had an overall SPM accuracy of 71.25%, but a STM span of 4, whereas Participant 4 had an overall SPM accuracy of 83.75%, also with a STM span of 4. Of note, neither of these participants had damage to STM ROIs, raising the possibility that their SPM deficits result from other factors, such as specific deficits to syntactic processing. Consistent with this possibility, both participants performed most poorly on cleft object reversibles (40% and 50% accuracy, respectively), suggesting difficulty assigning the appropriate semantic-syntactic structure in the presence of noncanonical word order. Thus, not surprisingly, STM/WM deficits do not seem to be the only source of sentence comprehension impairments (Caplan & Waters, 2007a; Caramazza, Berndt, Basili, & Koller, 1981).

Lastly, we would also like to point out Participant 5's performance. Consistent with our hypothesis, this participant showed reductions in both STM (span = 2; WM span = 0) and SPM (overall accuracy = 83.75%). Looking only at her diffusion scan, this participant had no damage to any of the STM ROIs identified above. However, her perfusion scan indicated hypoperfusion to *all* of the STM ROIs, indicating a large diffusion-perfusion mismatch. As discussed elsewhere, this mismatch highlights the importance of not just lesion location, but also cortical hypoperfusion as indicated in perfusion imaging (e.g., Hillis, et al., 2001a, 2001b), as both types of ischemia can lead to behavioral deficits.

Discussion

In the present study, we examined the hypotheses that: (1) acute damage the STM/WM network in the left hemisphere causes impairment in STM and comprehension of syntactically complex sentences, and (2) severity of limitation in short-term memory resources can explain severity of impairment in comprehension of complex sentences, in line with memory capacity accounts of sentence comprehension. These accounts suggest that comprehension relies at least in part on limited capacity verbal STM resources for maintaining intermittent parsing stages until a final interpretation is reached (e.g., R. Martin & Romani, 1994; R. Martin et al., 1994; Papagno et al., 2007; Vallar & Baddeley, 1984; cf. Caplan & Waters, 1999). While this question has been examined rather extensively in individual differences in healthy controls and individuals with chronic brain damage, very little work has focused on participants in the acute phase after stroke. The present study resulted in multiple findings of interest, discussed in turn below.

Individual differences in STM are associated with sentence comprehension abilities

In the acute stroke participants tested herein, we found STM to be a significant predictor of sentence comprehension on various sentence types, supporting the notion that reductions in STM resources contribute to sentence comprehension when processing demands are great

(e.g., reversibles, cleft objects). More specifically, individual differences in STM predicted performance on multiple sentence types, including sentences with non-canonical word orders (e.g., object clefts) and greater syntactic-semantic integration demands (passive and cleft object reversibles). Importantly, this relationship was demonstrated while also controlling for other factors that might contribute to performance, including lesion size and participant age. Furthermore, given the data described herein were collected within approximately 48 hours of the participants' ischemic event, these results cannot be attributed to post-stroke recovery processes, such as heuristic development or greater practice with some sentence types over others.

The finding of an association between STM and sentence comprehension is in line with a number of studies from participants with brain damage, including both case studies (e.g., R. Martin et al., 1994; Papagno et al., 2007) and group studies (e.g., Caplan et al., 2013). A recent study of 61 participants with chronic aphasia by Caplan and colleagues (2013), for example, found that both STM and WM were related to a number of sentence comprehension abilities. As a result, Caplan et al. suggested that STM may play a supportive role in sentential parsing and interpretation, though they also note that one cannot rule out the possibility that STM resources are used for post-interpretive processes (i.e., maintaining the content of a parsed sentence in order to perform a task; see also Caplan & Waters, 1999). Although we have hypothesized that STM resources contribute to the maintenance of sentential content (order of grammatical constituents, semantic information) until it can be integrated into a syntactic frame, it should be noted that we used an offline measure of sentence comprehension in which participants applied the meaning of the parsed sentence to a picture matching task. As a result, we also cannot rule out the possibility that our results reflect a post-interpretive role for STM resources in this context.

Regarding the above-discussed findings, one limitation concerns the extent to which deficits to specific levels of linguistic representations or other language impairments contribute to the deficits in verbal STM and sentence comprehension described herein. For example, the individual items held in verbal STM are likely not independent of phonological, lexical, and semantic features of those items (e.g., Caplan et al., 2012; N. Martin & Saffran, 1997; R. Martin & Romani, 1994), and deficits to any of these levels of representations could contribute to the STM deficits found herein. Similarly, sentence comprehension is certainly dependent upon intact grammatical and syntactic processing. In-depth neuropsychological case study approaches are traditionally employed to examine and exclude the possibility that other linguistic/language impairments contribute to a behavior of interest, as has been done by a number of previous case studies examining the role for STM in sentence comprehension in participants with brain damage (e.g., R. Martin & Romani, 1994; R. Martin et al., 1994; Papagno et al., 2007). However, the present study was not designed in this way, at least in part due to the time constraints of testing participants while still in the acute phase (i.e., within 48 hours of their stroke). To help rule out the possibility that the results found herein were due to deficits to linguistic representations, we ran a follow-up analyses that included a covariate of WAB subtests hypothesized to provide an approximate measure of lexical-semantic access. Even with this additional covariate included, STM remained a significant predictor of sentence processing abilities, for only the more difficult sentences types, including reversibles and cleft objects. Although perhaps not an ideal

estimate of linguistic processing, it at the very least provides preliminary support for the notion that the association between STM and sentence comprehension found herein is due to a deficit in the maintenance of verbal representations, rather than deficits to phonological, lexical, or semantic processing per se. However, future work examining this question in participants with acute stroke should include more in-depth neuropsychological assessments of multiple levels of linguistic representations, as well as measures of grammatical/syntactic processing (e.g., grammaticality judgments), to better account for and control the contribution of deficits to these factors.

Thus far, we have taken a rather theoretically neutral stance concerning the type of verbal representations that are maintained in STM, primarily because the present study was not designed to differentiate between these accounts. That is, whereas some have emphasized a role for phonological STM in sentence comprehension (see Cecchetto & Papagno, 2011, for a review), others have emphasized the maintenance of semantic representations (e.g., R. Martin & He, 2004; R. Martin & Romani, 1994; R. Martin et al., 1994). As mentioned in the introduction, we used STM more generally to refer to verbal STM, under the assumption that STM measures likely reflect contributions from multiple levels of linguistic representations (see also N. Martin & Saffran, 1997; R. Martin & Romani, 1994). The findings of Caplan and colleagues (2013), however, may speak to this issue. Although they found that some aspects of STM were related to sentence comprehension, they found little evidence to support the notion that these STM mechanisms were purely phonological. Specifically, whereas there was an effect of simple forward (i.e., STM) span on sentence comprehension, there were no effects for span measures measured by either phonological similarity (hypothesized to reflect STM for phonological representations) or word length (hypothesized to reflect the use of rehearsal) on sentence comprehension. As a result, Caplan and colleagues suggested that purely phonological representations do not support syntactically based comprehension. Of note, however, others have argued primarily on the basis of case studies that phonological STM does make at least some contribution to sentence comprehension (for a review, see Cecchetto & Papagno, 2011).

Although a number of studies have found associations between STM and sentence comprehension in participants with chronic brain damage, it has been suggested that this association is a weak one (see, e.g., Caplan & Waters, 1999). In contrast to this conclusion, we found relatively strong associations between STM and sentence comprehension. One possible explanation for this discrepancy concerns the time frame in which behavioral testing occurs in the acute vs. chronic phase. Participants in the acute stage, as tested herein, have had very little time to recover from ischemia and the resulting cognitive impairments, such that their behavioral performance may be less affected by compensatory strategies. Participants in the chronic phase, on the other hand, have likely undergone some degree of recovery. These individuals likely differ not only in the number, intensity, and types of treatment received, but also in the extent to which they have developed strategies for overcoming specific deficits. As a result, testing participants in the acute phase might provide a stronger association between impaired cognitive processes, because the results may be less influenced by compensatory strategies and reorganization of the cognitive processes underlying sentence comprehension.

Lastly, looking at performance at the individual participant level, at least one participant (Participant 2) provided some evidence that preserved STM does not seem to be necessary for comprehension of syntactically complex sentences (at least passive reversible sentences) (see also Caplan & Waters, 1990; R. Martin, 1987). Such a finding raises the possibility that the association between deficits in STM and sentence comprehension is correlational rather than causal, driven by the fact that they rely on a subset of the same neuroanatomical regions. For example, Participant 2 had damage to BA 6 (premotor cortex) and BA 44, regions thought to be important for inner speech (or articulatory rehearsal; Marvel & Desmond, 2012; Paulesu et al., 1993) and was classified as having Transcortical Motor aphasia according to the WAB. Despite its impact on Participant 2's STM performance, this participant's frontal damage did not affect his SPM performance for passive reversible sentences (although he was impaired on cleft object and to a lesser extent, cleft subject sentences), perhaps because verbatim rehearsal plays less of a role in these sentence types than other resources, such as the semantic-syntactic integration. Furthermore, we also found the reverse dissociation – that impaired performance on the SPM task was not always driven by reduced STM, suggesting unsurprisingly that there are multiple factors that could lead to impaired sentence comprehension, with reductions to memory resources being just one of them.

WM explains little variance beyond that contributed by STM

As discussed, research examining the role of limited-capacity memory systems in sentence comprehension has varied. Studies of participants with chronic brain damage has tended to emphasize the maintenance of verbal representations (i.e., STM). In contrast, work with non-brain damaged participants has placed a larger emphasis on working memory, furthermore suggesting that WM capacity limitations can be extended to also explain the sentence comprehension deficits in aphasia (Miyake et al., 1994; but see R. Martin, 1995). Accordingly, we also examined the extent to which individual differences in WM could predict variability in sentence comprehension, above and beyond that which was already explained by STM. In short, we found only weak evidence for the contribution of WM (i.e., the “manipulation” component of WM) in sentence processing.

One reason why STM may show a stronger relationship with sentence comprehension in brain damaged participants is because this measure (relative to WM) has more variability. Given that WM tasks rely both on item maintenance and manipulation, difficulties with the former will subsequently affect the latter. Accordingly, STM may better reflect capacity limitations, and reduce contributions from floor effects. In the present study, for example, five participants had WM spans of ‘0’ (despite having STM spans > 0), whereas the lowest STM span was 1.5 (in a participant with a WM span of 0). As a result, WM may not provide a good estimate of corresponding STM in brain damaged populations; in non-brain damaged populations, in contrast, WM may be a better reflection of *both* maintenance and manipulation, given the former is functioning normally in these groups of participants. Alternatively, Cecchetto and Papagno (2011) have suggested that STM and WM differ in the extent to which they involve automatized vs. conscious abilities, respectively. They hypothesize that STM involves “largely automatized lower level abilities that might be used in language comprehension” (p. 449); WM, in contrast, also requires that one coordinate

multiple complex abilities. Given the automatized nature of language comprehension, then, STM may be a more appropriate measure of memory span.

Damage to the network of regions supporting STM/WM is associated with impaired sentence comprehension

Another finding of interest from the present study was that damage to the STM/WM network was associated with impairment on most reversible (but not irreversible) sentence types. This pattern of results is similar to the behavioral findings insofar as damage to regions supporting STM/WM was associated with impairment to the comprehension of more complex sentence types, i.e., those that cannot be understood on the basis of word order or semantics alone. Reversible sentence types instead depend on the maintenance of sentential representations until they can be integrated into a sentential context. Furthermore, the lack of association between damage to the STM/WM network and irreversible sentence types is also consistent with this interpretation: when sentence comprehension makes fewer demands on verbal STM, damage to the STM/WM network does not affect comprehension performance. Of note, all of the above findings were from a group of acute stroke participants, tested before they have had a chance to recover or develop heuristic strategies for overcoming specific deficits.

There were two minor differences between the behavioral and lesion-association findings. First, in the behavioral analyses, STM was significantly associated with performance on cleft object sentences as a whole (averaged over reversible and irreversible sentence types), whereas in the lesion analyses, damage to the STM/WM network was not associated with this sentence category once corrected for multiple comparisons ($p = .04$). Second, in the behavioral analyses, STM was not associated with performance on active reversibles once corrected for multiple comparisons ($p = .03$), whereas damage to the STM/WM network was associated with impairment to this subset of sentences. However, we do not find these differences to be problematic, given they support the same general patterns of findings discussed above.

Limitations of this study include the fact that we assessed STM and WM only with span tasks, which may not be the most valid or sensitive tasks of these functions. However, they are reliable, and easy to administer in acute stroke. Additionally, we had only a single offline measure of sentence comprehension. Furthermore, as discussed above, extensive background neuropsychological assessments were not available; thus, we have limited ability to describe the extent to which the participants included herein also had impairments in phonological/lexical/semantic access and syntactic processing. Thus, future work could systematically examine and rule out the contribution of these sorts of neuropsychological factors to the association between STM and sentence comprehension. We also were not able to acquire PWI in all participants, in part because of impaired renal function or difficulty with IV access in some participants, preventing the use of Gadolinium contrast. Therefore, some participants may have had dysfunction in some of the STM network not visible on available imaging methods.

In summary, the present study provides support for the association between STM (storage capacity) and sentence comprehension in participants with acute stroke. Such an association

is consistent with previous neuropsychological studies (Leff et al., 2009; R. Martin & Romani, 1994; R. Martin et al., 1994; Papagno et al., 2007; Vallar & Baddeley, 1984) suggesting that reductions to storage capacity oftentimes leads to impaired comprehension of syntactically complex sentences, although this deficit is certainly not the only source of impaired comprehension.

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Appendix

References

Army Individual Test Battery. Manual of Directions and Scoring. War Department, Adjutant General's Office; Washington, DC: 1944.

- Baddeley AD. Working memory: Theories, models, and controversies. *Annual Review of Psychology*. 2012; 63:1–29. doi: 10.1146/annurev-psych-120710-100422.
- Baddeley, AD.; Hitch, GJ. Working memory.. In: Bower, GA., editor. *The Psychology of Learning and Motivation: Advances in Research and Theory*. Academic Press; New York: 1974. p. 47-89.
- Baldo JV, Katseff S, Dronkers NF. Brain regions underlying repetition and auditory-verbal short-term memory deficits in aphasia: Evidence from voxel-based lesion symptom mapping. *Aphasiology*. 2012; 26:338–354. doi: 10.1080/02687038.2011.602391. [PubMed: 24976669]
- Butterworth B, Campbell R, Howard D. The uses of short-term memory: A case study. *The Quarterly Journal of Experimental Psychology*. 1986; 38A:705–737. doi: 10.1080/14640748608401622. [PubMed: 3809577]
- Caplan D, Michaud J, Hufford R. Short-term memory, working memory, and syntactic comprehension in aphasia. *Cognitive Neuropsychology*. 2013; 30:77–109. doi:10.1080/02643294.2013.803958. [PubMed: 23865692]
- Caplan, D.; Waters, GS. Short-term memory and language comprehension: A critical review of the neuropsychological literature.. In: Vallar, G.; Shallice, T., editors. *Neuropsychological impairments of short-term memory (337-389)*. Cambridge University Press; New York, NY: 1990. doi: 10.1017/CBO9780511665547.019
- Caplan D, Waters GS. Verbal working memory and sentence comprehension. *Behavioral and Brain Sciences*. 1999; 22:77–94. doi: 10.1017/S0140525X99001788. [PubMed: 11301522]
- Caplan D, Waters G, Dede G, Michaud J, Reddy A. A study of syntactic processing in aphasia I: Behavioral (psycholinguistic) aspects. *Brain and Language*. 2007a; 101:103–50. doi:10.1016/j.bandl.2006.06.225. [PubMed: 16999989]
- Caplan D, Waters G, Howard D. Slave systems in verbal short-term memory. *Aphasiology*. 2012; 26:37–41. doi:10.1080/02687038.2011.642795.
- Caplan D, Waters G, Kennedy D, Alpert N, Makris N, Dede G, Michaud J, et al. A study of syntactic processing in aphasia II: Neurological aspects. *Brain and Language*. 2007b; 101:151–77. doi: 10.1016/j.bandl.2006.06.226. [PubMed: 16997366]
- Caramazza A, Berndt RS, Basili AG, Koller JJ. Syntactic processing deficits in aphasia. *Cortex*. 1981; 17:333–347. doi: 10.1016/S0010-9452(81)80021-4. [PubMed: 7333108]
- Cecchetto, C.; Papagno, C. Bridging the gap between brain and syntax: A case for a role of the phonological loop.. In: Boeckx, C.; Di Sciullo, AM., editors. *The Bilingual Enterprise: New Perspectives on the Evolution and Nature of Human Language*. Oxford University Press; Oxford: 2011. p. 440-460.
- Damasio, H.; Damasio, A. *Lesion analysis in neuropsychology*. Oxford University Press; New York, NY: 1989.
- Daneman M, Merikle PM. Working memory and language comprehension: A meta-analysis. *Psychonomic Bulletin & Review*. 1996; 3:422–433. doi: 10.3758/BF03214546. [PubMed: 24213976]
- D'Esposito M, Postle BR. The dependence of span and delayed-response performance on prefrontal cortex. *Neuropsychologia*. 1999; 37:1303–1315. doi: 10.1016/S0028-3932(99)00021-4. [PubMed: 10530730]
- D'Esposito M, Postle BR, Ballard D, Lease J. Maintenance versus manipulation of information held in working memory: An event related fMRI study. *Brain and Cognition*. 1999; 41:66–86. doi: 10.1006/brcg.1999.1096. [PubMed: 10536086]
- Engle RW, Tuholski SW, Laughlin JE, Conway ARA. Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General*. 1999; 128:309–331. doi: 10.1037/0096-3445.128.3.309. [PubMed: 10513398]
- Friedrich F, Martin R, Kemper S. Consequences of a phonological coding deficit on sentence processing. *Cognitive Neuropsychology*. 1985; 2:385–412. doi: 10.1080/02643298508252667.
- Goodglass, H.; Kaplan, E. *The Assessment of Aphasia and Related Disorders*. Lea & Febiger; Philadelphia: 1972.
- Gordon PC, Hendrick R, Levine WH. Memory-load interference in syntactic processing. *Psychological Science*. 2002; 13:425–430. doi: 10.1111/1467-9280.00475. [PubMed: 12219808]

- Henson RNA, Burgess N, Frith CD. Recoding, storage, rehearsal and grouping in verbal short-term memory: An fMRI study. *Neuropsychologia*. 2000; 38:426–440. doi: 10.1016/S0028-3932(99)00098-6. [PubMed: 10683393]
- Hickok G, Poeppel D. Dorsal and ventral streams: A framework for understanding aspects of the functional anatomy of language. *Cognition*. 2004; 92:67–99. doi: 10.1016/j.cognition.2003.10.011. [PubMed: 15037127]
- Hillis AE, Barker PB, DPhil PBB, Beauchamp NJ, Winters BD, Mirski M, Wityk RJ. Restoring blood pressure reperfused Wernicke's area and improved language. *Neurology*. 2001a; 56:670–672. doi: 10.1212/WNL.56.5.670. [PubMed: 11245724]
- Hillis AE, Wityk RJ, Tuffiash E, Beauchamp NJ, Jacobs MA, DPhil PBB, Selnes OA. Hypoperfusion of Wernicke's area predicts severity of semantic deficit in acute stroke. *Annals of Neurology*. 2001b; 50:561–566. doi: 10.1002/ana.1265. [PubMed: 11706960]
- Just MA, Carpenter PA. A capacity theory of comprehension: Individual differences in working memory. *Psychological Review*. 1992; 99:122–149. doi: 10.1037/0033-295X.99.1.122. [PubMed: 1546114]
- Kertesz, A. Western Aphasia Battery–Revised (WAB-R). Pro-Ed; Austin, TX: 2006.
- King J, Just MA. Individual differences in syntactic processing: The role of working memory. *Journal of Memory and Language*. 1991; 30:580–602. doi: 10.1016/0749-596X(91)90027-H.
- Leff AP, Schofield TM, Crinion JT, Seghier ML, Grogan A, Green DW, Price CJ. The left superior temporal gyrus is a shared substrate for auditory short-term memory and speech comprehension: evidence from 210 patients with stroke. *Brain*. 2009; 132:3401–10. doi:10.1093/brain/awp273. [PubMed: 19892765]
- Martin N, Ayala J. Measurements of auditory-verbal STM span in aphasia: Effects of item, task, and lexical impairment. *Brain and Language*. 2004; 89:464–483. doi: 10.1016/j.bandl.2003.12.004. [PubMed: 15120538]
- Martin N, Saffran EM. Language and auditory-verbal short-term memory impairments: Evidence from common underlying processes. *Cognitive Neuropsychology*. 1997; 14:641–682. doi: 10.1080/026432997381402.
- Martin RC. Articulatory and phonological deficits in short-term memory and their relation to syntactic processing. *Brain and Language*. 1987; 32:159–192. doi: 10.1016/0093-934X(87)90122-2. [PubMed: 3651806]
- Martin RC. Working memory doesn't work: A critique of Miyake et al.'s capacity theory of aphasic comprehension deficits. *Cognitive Neuropsychology*. 1995; 12:623–636. doi: 10.1080/02643299508252010.
- Martin RC, He T. Semantic short-term memory and its role in sentence processing: A replication. *Brain and Language*. 2004; 89:76–82. doi: 10.1016/S0093-934X(03)00300-6. [PubMed: 15010239]
- Martin R, Romani C. Verbal working memory and sentence comprehension: A multiple-components view. *Neuropsychology*. 1994; 8(4):506–523. doi:10.1037/0894-4105.8.4.506.
- Martin R, Shelton J, Yaffee L. Language processing and working memory: Neuropsychological evidence for separate phonological and semantic capacities. *Journal of Memory and Language*. 1994; 33:83–111. doi:10.1006/jmla.1994.1005.
- Martin RC, Wu D, Freedman M, Jackson EF, Lesch M. An event-related fMRI investigation of phonological versus semantic short-term memory. *Journal of Neurolinguistics*. 2003; 16:341–360. doi: 10.1016/S0911-6044(03)00025-3.
- Marvel CL, Desmond JE. From storage to manipulation: How the neural correlates of verbal working memory reflect varying demands of inner speech. *Brain and Language*. 2012; 120:42–51. doi: <http://dx.doi.org/10.1016/j.bandl.2011.08.005>. [PubMed: 21889195]
- Miyake A, Carpenter PA, Just MA. A capacity approach to syntactic comprehension disorders: Making normal adults perform like aphasic patients. *Cognitive Neuropsychology*. 1994; 11:671–717. doi: 10.1080/02643299408251989.
- Papagno C, Cecchetto C, Reati F, Bello L. Processing of syntactically complex sentences relies on verbal short-term memory: Evidence from a short-term memory patient. *Cognitive Neuropsychology*. 2007; 24:292–311. doi: 10.1080/02643290701211928. [PubMed: 18416493]

- Paulesu E, Frith CD, Frackowiak RSJ. The neural correlates of the verbal component of working memory. *Nature*. 1993; 362:342–345. doi: 10.1038/362342a0. [PubMed: 8455719]
- Race D, Ochfeld E, Hillis AE. Lesion analysis of cortical regions associated with the comprehension of nonreversible and reversible yes/no questions. *Neuropsychologia*. 2012; 50:1946–1953. doi: 10.1016/j.neuropsychologia.2012.04.019. [PubMed: 22564483]
- Romero L, Walsh V, Papagno C. The neural correlates of phonological short-term memory: A repetitive transcranial magnetic stimulation study. *Journal of Cognitive Neuroscience*. 2006; 18:1147–1155. doi: 10.1162/jocn.2006.18.7.1147. [PubMed: 16839288]
- Sobesky J, Zaro-Weber O, Lehnhardt FG, Hesselmann V, Thiel A, Dohmen C, Heiss WD. Which time-to-peak threshold best identifies penumbral flow? A comparison of perfusion-weighted magnetic resonance imaging and positron emission tomography in acute ischemic stroke. *Stroke*. 2004; 35:2843–2847. doi: 10.1161/01.STR.0000147043.29399.f6. [PubMed: 15514190]
- Thothathiri M, Kimberg DY, Schwartz MF. The neural basis of reversible sentence comprehension: evidence from voxel-based lesion symptom mapping in aphasia. *Journal of Cognitive Neuroscience*. 2012; 24:212–222. doi:10.1162/jocn_a_00118. [PubMed: 21861679]
- Thompson C, den Ouden D, Bonakdarpour B, Garibaldi K, Parrish T. Neural plasticity and treatment-induced recovery of sentence processing in agrammatism. *Neuropsychologia*. 2010; 48:3211–3227. doi: 10.1016/j.neuropsychologia.2010.06.036. [PubMed: 20603138]
- Vallar G, Baddeley AD. Phonological short-term store, phonological processing and sentence comprehension: A neuropsychological case study. *Cognitive Neuropsychology*. 1984; 1:121–141. doi: 10.1080/02643298408252018.
- Zaro-Weber O, Moeller-Hartmann W, Heiss WD, Sobesky J. Maps of time to maximum and time to peak for mismatch definition in clinical stroke studies validated with positron emission tomography. *Stroke*. 2010; 41:2817–2821. doi: 10.1161/STROKEAHA.110.594432. [PubMed: 21030699]

Table 1

Demographic and descriptive statistics for acute stroke and TIA participants

Variable	Acute Stroke Participants				TIA Participants				
	M	SD	Range	n	M	SD	Range	n	Effect of group
N				47				14	
N with both STM & SPM				36				11	
Age	59.8	14.9	(17-85)	47	57.7	10.1	(44-75)	14	$F(1,59) = 0.24, p = .63, \eta^2 = .004$
Education	13.6	3.8	(4-21)	47	14.8	3.6	(10-24)	13	$F(1,58) = 0.94, p = .34, \eta^2 = .02$
Lesion size (cc)	13.3	18.7	(0.13-100.3)	47	-			-	
WAB Aphasia Quotient	84.9	18.4	(24.3-100)	38	95.3	5.7	(78.6-99.4)	12	$F(1,48) = 3.64, p = .06, \eta^2 = .07$
WAB, Spontaneous Speech (/20)	16.1	4.9	(0-20)	39	18.8	2.3	(12-20)	12	$F(1,49) = 3.15, p = .08, \eta^2 = .06$
WAB, Aud. Verbal Comp. (/10)	9.1	1.3	(4.3-10)	44	9.9	0.23	(9.2-10)	13	$F(1,55) = 4.45, p = .03, \eta^2 = .08^*$
WAB, Repetition (/10)	8.9	1.6	(0-10)	45	9.6	0.49	(8.2-10)	13	$F(1,56) = 2.22, p = .14, \eta^2 = .04$
WAB, Naming & Word Finding (/10)	8.4	2.1	(0-10)	44	9.4	0.54	(8-10)	13	$F(1,55) = 3.42, p = .09, \eta^2 = .05$
STM (span)	4.9	1.9	(1-9)	40	6.1	1.5	(3.5-9)	13	$F(1,51) = 4.37, p = .04, \eta^2 = .08^*$
WM (span)	3.1	1.7	(0-6.5)		4.3	1.7	(2.5-8)		$F(1,51) = 5.03, p = .03, \eta^2 = .09^*$
M SPM (% correct)	90.5	11.1	(46.9-100)	43	95.1	4.8	(85-100)	12	$F(1,53) = 1.98, p = .17, \eta^2 = .04$
M Active (% correct)	94.9	9.2	(55-100)		97.5	4.0	(90-100)		$F(1,53) = 0.88, p = .35, \eta^2 = .02$
M Passive (% correct)	88.1	14.2		(25-100)	94.6	8.4	(75-100)		$F(1,53) = 2.24, p = .14, \eta^2 = .04$
M Cleft Subject (% correct)	91.4	12.2		(58.3-100)	95.4	5.0	(85-100)		$F(1,53) = 1.26, p = .27, \eta^2 = .02$
M Cleft Object (% correct)	87.5	14.2		(37.5-100)	95	6.0	(80-100)		$F(1,53) = 3.14, p = .08, \eta^2 = .06$
M Irreversible (% correct)	94.3	11.5	(35.4-100)		96.9	3.7	(90-100)		$F(1,53) = 0.57, p = .45, \eta^2 = .01$
M Reversible (% correct)	86.6	12.7		(58.3-100)	94.4	6.0	(80-100)		$F(1,53) = 4.12, p = .05, \eta^2 = .07^*$

Note. STM = short-term memory. SPM = sentence-picture matching. cc = cubic centimeter. WAB = Western Aphasia Battery.

*

$p < .05$.

Table 2

Variable	Participants without lesions to STM/WM ROIs				Participants with lesions to STM/WM ROIs			
	<i>M</i>	<i>SD</i>	Range	<i>n</i>	<i>M</i>	<i>SD</i>	Range	<i>n</i>
N				26				21
N with both STM & SPM				20				16
Age	61.8	14.1	(20-81)	26	57.3	15.9	(17-85)	21
Education	13.4	4	(4-21)	26	13.9	3.8	(5-19)	21
Lesion size (mm ³)	10.3	15.1	(0.13-57.0)	26	17.1	22.2	(0.20-100.3)	21
WAB Aphasia Quotient	93.9	6.6	(76.9-100)	21	73.8	22.2	(24.3-98.2)	21
WAB Spontaneous Speech (/20)	18.6	1.7	(15-20)	22	12.9	5.8	(0-20)	17
WAB Aud. Verbal Comp. (/10)	9.5	0.9	(6.5-10)	23	8.7	1.6	(4.3-10)	21
WAB Repetition (/10)	9.5	0.5	(8.4-10)	24	8.2	2.2	(0-10)	21
WAB Naming & Word Finding (/10)	9.2	1.0	(6-10)	23	7.5	2.6	(0-10)	21
STM (span)	5.6	1.8	(3-9)	21	4	1.7	(1-8)	19
WM (span)	3.6	1.5	(0-6.5)		2.5	1.8	(0-5)	
M SPM (% correct)	94.4	6.4	(71-100)	25	85.1	13.8	(47-100)	18
M Active (% correct)	98	4.1	(85-100)		90.6	12.4	(55-100)	
M Passive (% correct)	93	6.6		(80-100)	81.4	18.8	(25-100)	
M Cleft Subject (% correct)	94.2	9.1		(60-100)	87.4	14.9	(58-100)	
M Cleft Object (% correct)	92.2	10.5		(55-100)	81	16.3	(38-100)	
M Irreversible (% correct)	96.9	5.2		(78-100)	90.7	16.3	(35-100)	
M Reversible (% correct)	91.8	8.4		(65-100)	79.5	14.4	(58-100)	

Note. STM = short-term memory. SPM = sentence-picture matching. cc = cubic centimeter. WAB = Western Aphasia Battery.

* *p* .05.

Table 3

Multiple regression results for sentence comprehension regressed on STM

	B	SE B	β	p	Model R²
a) Passive					
STM	2.13	0.90	0.27	0.02	0.74
b) Cleft object					
STM	2.39	0.77	0.31	* 0.004	0.79
c) Reversible					
STM	3.02	0.90	0.44	* 0.002	0.64
d) Active reversible					
STM	1.83	0.77	0.37	0.03	0.45
e) Passive reversible					
STM	5.30	1.69	* 0.52	0.004	0.41
f) Cleft subject reversible					
STM	0.27	1.04	0.04	0.80	0.48
g) Cleft object reversible					
STM	5.11	1.53	* 0.46	0.002	0.59

* $p < .007$, corrected for multiple comparisons

Table 4

Multiple regression results for sentence comprehension regressed on STM and WM residual

	B	SE B	β	p	Model R²
a) Passive					
STM	2.17	0.93	0.28	0.03	0.74
WM residual	0.38	1.59	0.03	0.82	
b) Cleft object					
STM	2.59	0.75	0.33 [*]	0.002	0.81
WM residual	2.34	1.27	0.16	0.08	
c) Reversible					
STM	3.27	0.86	0.47 [*]	0.001	0.68
WM residual	2.96	1.46	0.23	0.05	
d) Active reversible					
STM	1.9	0.78	0.38	0.02	0.46
WM residual	1.12	1.48	0.12	0.46	
e) Passive reversible					
STM	5.53	1.59	0.54 [*]	0.002	0.49
WM residual	5.74	2.58	0.31	0.03	
f) Cleft subject reversible					
STM	0.31	1.07	0.05	0.77	0.48
WM residual	0.39	1.84	0.03	0.84	
g) Cleft object reversible					
STM	5.47	1.47	0.49 [*]	0.001	0.63
WM residual	4.96	2.52	0.24	0.06	

* $p < .007$, corrected for multiple comparisons