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Effects of working memory load on processing of sounds and meanings of words in aphasia

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Abstract

Background—Language performance in aphasia can vary depending on several variables such as stimulus characteristics and task demands. This study focuses on the degree of verbal working memory (WM) load inherent in the language task and how this variable affects language performance by individuals with aphasia.

Aims—The first aim was to identify the effects of increased verbal WM load on the performance of judgments of semantic similarity (synonymy) and phonological similarity (rhyming). The second aim was to determine if any of the following abilities could modulate the verbal WM load effect: semantic or phonological access, semantic or phonological short-term memory (STM) and any of the following executive processing abilities: inhibition, verbal WM updating, and set shifting.

Method and Procedures—Thirty-one individuals with aphasia and 11 controls participated in this study. They were administered a synonymy judgment task and a rhyming judgment task under high and low verbal WM load conditions that were compared to each other. In a second set of analyses, multiple regression was used to identify which factors (as noted above) modulated the verbal WM load effect.

Outcome and Results—For participants with aphasia, increased verbal WM load significantly reduced accuracy of performance on synonymy and rhyming judgments. Better performance in the low verbal WM load conditions was evident even after correcting for chance. The synonymy task included concrete and abstract word triplets. When these were examined separately, the verbal WM load effect was significant for the abstract words, but not the concrete words. The same pattern was observed in the performance of the control participants. Additionally, the second set of analyses revealed that semantic STM and one executive function, inhibition ability, emerged as the strongest predictors of the verbal WM load effect in these judgment tasks for individuals with aphasia.

Conclusions—The results of this study have important implications for diagnosis and treatment of aphasia. As the roles of verbal STM capacity, executive functions and verbal WM load in language processing are better understood, measurements of these variables can be incorporated into our diagnostic protocols. Moreover, if cognitive abilities such as STM and executive functions support language processing and their impairment adversely affects language function, treating them directly in the context of language tasks should translate into improved language function.

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Introduction

In this study, we investigated the effects of increased verbal working memory (WM) load on accuracy of judgments of semantic and phonological similarity made by individuals with aphasia. It is widely accepted that in many cases of aphasia the impairment appears to affect *access* to language representations and not loss of language knowledge (Schuell, Jenkins, & Jimenez-Pabon, 1964; McNeil, 1982; McNeil & Pratt, 2001, Murray, 2000).¹ Evidence for this comes from variability in language performance across language tasks. The ability to successfully process words may be intact in one task (e.g., repetition) but not others (e.g., naming). A number of factors affect this variability. First, the speed and accuracy of word processing in aphasia is influenced by characteristics of a word, such as frequency (e.g., Goodglass, Hyde & Blumstein, 1969; Kittredge, Dell, Verkuilen & Schwartz, 2007, imageability (Hanley & Kay, 1997; Martin & Saffran, 1997), length (Nickels, 1995; Nickels & Howard, 1994; 1995) and age of acquisition (Ellis & Morrison, 1998; Kremin, Lorenz, de Wilde, Perrier, Arabia, Labonde, et al., 2003). A second factor that affects variability of retrieving words is procedural in nature. Stimulation techniques such as semantic or phonemic cueing can facilitate retrieval of words (Linebaugh & Lehrner, 1977; Wambaugh, Linebaugh, Doyle, Martinez, Kalinyak-Fliszar, 2001) and they are often used as part of treatment protocols to elicit a word that cannot be produced independently. Priming is another such procedure that affects the probability of accurate word processing. Presentation of a stimulus in one task (e.g., repetition) makes a target word more available in the same task or another task (e.g., picture naming). Priming is often facilitative, as it raises the activation of the target word in the lexicon, making it more accessible. However, under some circumstances priming can be detrimental. For example, in a massed priming paradigm, a prime stimulus that is related to the target is repeated several times, and although its activation primes the target word, its own activation is being reinforced as well, making it a stronger competitor with the target word (Martin, Fink, Laine & Ayala, 2004). A third factor that has been shown to affect ability to access or retrieve words is the verbal WM load associated with a particular verbal task. Martin, Saffran and Dell (1996) and Martin, Kohen and Kalinyak-Fliszar (2010) have shown that accurate performance on a particular language task (e.g., repeating a word or judging the similarity of two verbal stimuli) can be reduced by imposing a delay between the verbal stimuli and a response. Variability in language performance based on stimuli characteristics and procedural variations provides theoretically important evidence that aphasia is an access disorder rather than a knowledge disorder. The clinical implications of this variability are equally important as these stimulus variables must be balanced or manipulated carefully in developing treatment protocols for word processing impairments.

In the present study, we focus on the last factor mentioned above, namely the influence of task-related verbal WM load on the ability to process semantic and/or phonological representations of words by individuals with aphasia and normal controls. In an earlier study (Kohen, Martin, Kalinyak-Fliszar, Bunta, & Dimarco, 2007), we demonstrated an adverse effect of verbal WM load on performance of two semantic judgment tasks by individuals with aphasia. In each task, the number of items that needed to be held in verbal WM was increased without changing the number of items that had to be judged as semantically related (synonymous in one task and categorically related in another). Performance on each task declined significantly as the verbal WM load increased. This study is a follow up and extension of that study. We report data from two similarity judgments tasks, synonymy and rhyming, and examine the role of three factors that may modulate the effect of verbal WM load on performance on these language tasks: ability to access semantic and phonological

¹It should be noted that individuals with severe aphasia are often excluded from studies of the nature of aphasia. Thus, it is yet to be verified whether severe aphasia also is primarily an access disorder.

representations, verbal (semantic and phonological) short-term memory (STM) capacity, and executive function ability. Consideration of these factors in the assessment of aphasia allows for a finer description of linguistic and cognitive deficits that influence a person's language function. Moreover, manipulations of verbal WM load can be used as part of a treatment protocol to improve language function in the contexts that involve greater verbal WM capacity (e.g. Helm-Estabrooks, 2002; Nicholas, Sinotte & Helm-Estabrooks, 2011; Murray, 2004; Morrow & Fridriksson, 2006)

It is important to make a distinction between the terms verbal STM and verbal WM. The two concepts overlap in that they both refer to temporary storage of language representations. However, verbal WM also entails manipulation and/or organization of information that is being temporarily stored. This function engages executive processes. Verbal STM can be viewed as a function that supports verbal WM, although the two are not entirely separable. For example, verbal span tasks are interpreted as measures of verbal STM capacity, but even immediate recall of a sequence of digits or words involves some minimal organization of that sequence, and thus a minimal amount of WM. The synonymy and rhyming judgment tasks used as dependent variables in the experiments reported here are examples of a verbal WM tasks because they involve accessing semantic and phonological representations of words, short-term maintenance of those activated representations and comparing them for similarity. Accordingly, as noted above, this study will examine how well these variables predict performance of these working memory tasks.

There is a considerable history of research on verbal STM, executive functions and language processing in aphasia that precedes this study and others exploring clinical implications of the relationship among these variables. Below, we provide a brief review of this theoretical and empirical background.

Studies of the roles of verbal STM and executive functions in language processing

Verbal STM and language processing—The relationship between verbal STM and language processing has long been of great interest to cognitive scientists for the simple reason that language processing takes place over time, and therefore must involve some means of maintaining activation of word representations over time. A number of models of verbal STM proposed in the latter part of the 20th century (e.g., Atkinson & Shiffrin, 1968; Craik & Lockhart, 1972) served as a foundation for investigations of verbal STM in relation to normal language processing. Another model developed during this period, Baddeley's WM model (Baddeley & Hitch, 1974), was influential as a framework for studies of verbal STM in normal and language impaired populations. In this model, a phonological short-term store maintains temporary activations of long-term phonological knowledge. These representations are periodically refreshed by a rehearsal process that accesses long-term semantic and phonological representations. This model provided a suitable framework for early views of language and verbal STM as separable, independent systems (e.g., Warrington & Shallice, 1969; Shallice & Warrington, 1970; Shallice, 1988). An alternative view soon emerged, however, motivated by evidence of language influences on verbal span of normal speakers (Brener, 1940; Hulme, Maughan, & Brown, 1991; Conrad & Hull, 1964; Watkins & Watkins, 1977; Hulme, Roodenrys, Schweicker, Brown, Martin, & Stuart, 1997; Shulman, 1971; Crowder, 1979; Brooks & Watkins, 1990; Poirier & Saint Aubin, 1995) and people with aphasia (Saffran & Marin, 1975; Saffran, 1990; Saffran & Martin, 1990; Berndt & Mitchum, 1990; R. Martin, Shelton, & Yaffee, 1994). The model is based on the premise that language and verbal STM systems are linked by a shared fundamental process, activation and maintenance of semantic and phonological representations of words. Language processing happens over time, and this is true even in processing a single word. This requires some mechanism to maintain activation of that word's representations until it

is comprehended, repeated or retrieved in production. It is this brief period of activation maintenance that supports performance on single word tasks and multiple word tasks such as verbal span (see Martin, 2008, for review). Another important assumption of this model is that all levels of word representation (phonological, lexical, and semantic) are held in verbal STM (R. Martin et al., 1994), not just phonological representations. This multi-store framework has been quite successful in accounting for numerous findings of associations between language and verbal STM impairments in aphasia (e.g., R. Martin, 1993; R. Martin & Lesch, 1996; Martin et al., 1996; Martin & Saffran, 1997; Martin & Ayala, 2004).

As part of their account of the verbal STM deficit in aphasia, Martin and colleagues proposed an important extension of the hypothesis that a single process, activation maintenance of semantic, lexical and phonological representations of words, supported performance on single word and multi-word tasks (Martin et al., 1996; Martin & Ayala, 2004; Martin & Gupta, 2004; Martin, 2008). Martin et al. (1996) observed quantitative and qualitative changes in both verbal STM span and word repetition abilities of a single case, NC, over the course of his recovery from aphasia. They accounted for these associated patterns of improvement as resulting from recovery of a single impairment to the ability to maintain activation of word representations: too-fast decay of that activation. In subsequent studies, Martin & Ayala (2004) demonstrated significant correlations between severity of language impairment (both phonological and lexical-semantic measures) and the size of digit and word span (repetition and pointing response conditions) in a larger group of individuals with aphasia (n=46). From this, they proposed the severity continuum hypothesis that a severe impairment of the ability to maintain activation of representations leads to a deficit pattern of aphasia *and* verbal STM impairment, while a milder impairment of this ability leads to a deficit pattern limited to verbal STM impairment.

Executive functions, language processing and verbal WM—As discussed above, verbal WM has two components. It is supported by verbal STM capacity, an ability that is typically measured in verbal span tasks such as digit or word span. The second component is the 'working' aspect and involves holding information in a short-term store *and* manipulating that information to complete some language task. Executive processes have been implicated in the latter component (Baddeley, 1996; Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000)). These refer to higher-level cognitive abilities such as planning, sequencing, inhibiting irrelevant stimuli, coordination of simultaneous ability and cognitive flexibility (Crawford, 1998). In the domain of verbal WM, executive control processes enable purposeful manipulation of verbal information held in a temporary store and suppression of irrelevant information. Executive abilities play a fundamental role in everyday communication where there is a need to attend to a communication partner, sequence information to be communicated, monitor ongoing communication and shift strategies in accordance with ongoing conversation (Ramsberger 1994). As executive abilities may be compromised in neurological impairments, there is a clear need for research on the role of executive functions in language function and for development of clinical tools to evaluate and treat executive impairments.

Miyake et al. (2000) noted three basic executive functions that are also important to the regulation of language processing: mental shifting, inhibition and WM updating and monitoring. There is evidence (Lehto, 1996) and general agreement (Baddeley, 1996; 2007) that these functions are separable from each other and contribute in different (perhaps interactive) ways to cognitive function. *Mental shifting*, also referred to as attention switching, denotes switching from one task to another. *Inhibition* refers to suppression of irrelevant stimuli in order to focus on currently relevant information. *Working memory updating* refers to monitoring and coding of information in WM that involves refreshing WM contents in accordance with the task at hand.

There has been considerable research interest in executive processing impairments and their role in language and communication abilities following traumatic brain injury (e.g., Coehlo, Liles & Duffy, 1995) and more recently in aphasia (Murray & Ramage, 2000; Purdy, 2002; Frankel, Penn & Ormond-Brown, 2007). One line of investigation uses dual task paradigms to examine the abilities of individuals with aphasia to allocate attentional resources effectively. These studies have shown adverse effects of divided attention on a number of language abilities, including lexical decision and semantic judgments (Arvedson & McNeil, 1986), phoneme monitoring and semantic judgments (Tseng, McNeil & Milenkovic, 1993), word retrieval (Murray, Holland & Beeson, 1998; Murray, 2000), auditory processing tasks (Murray, Holland & Beeson, 1997a), and grammaticality judgments (Murray et al., 1997b). Another line of inquiry regarding executive processing abilities in aphasia has been related explicitly to their role in semantic STM deficits in aphasia (e.g., R. Martin, 2007; Barde, Schwartz, Chrysikou & Thompson-Schill, 2010; Hoffman, Jefferies, Ehsan, Hopper, & Lambon Ralph, 2009). At issue is whether semantic STM impairments reflect a reduced storage capacity or a difficulty in inhibiting irrelevant information. We do not address this question directly in the studies reported here, but do provide evidence that both abilities play a role in verbal WM tasks.

The present study: verbal WM load and judgments of semantic and phonological similarity of words

In this study, we investigated the effects of increasing verbal WM load on performance of two tasks that involve making judgments about relationships among words. The first was a synonymy judgment task that involves comparing the closeness of meanings of two or more words. The second was a rhyming judgment task that probes sensitivity to the sounds of words. These tasks represent basic approaches to assessment of semantic and phonological abilities in aphasia, but each can be presented in ways that vary the verbal WM load of the task. This makes them ideal to investigate the effects of increasing verbal WM load on semantic and phonological processing of words. Given that everyday language function takes place in contexts in which verbal WM load might vary, it is important to understand this variable's effect on language performance and to develop clinical tools to assess this variable.

First we addressed whether performance on synonymy and rhyming judgment tasks was adversely affected by increasing the verbal WM load inherent in the task. The judgment tasks were presented under two conditions that systematically varied the number of word pairs to be compared (2 vs. 3). We predicted a significant decline in performance for participants with aphasia in the 3-pair task compared to the 2-pair task, even when chance was taken into account. For control participants, we anticipated that performance would be closer to ceiling but would show some decline in the higher verbal WM load condition. This first question is addressed in Analysis 1.

In Analyses 2 and 3, we examined these data further to determine the extent to which verbal processing, verbal STM capacity and executive abilities can account for any verbal WM load effect observed in the first analyses. For each judgment task, we considered three potential impairments that might modulate the verbal WM load effects on the synonymy and rhyming judgments: (1) *access* - impaired activation of semantic or phonological representations, (2) *verbal STM* - impaired ability to maintain activation of semantic or phonological representations and (3) *control* - impairment of executive functions that enable systematic comparisons and selection among response alternatives being held in verbal WM.

Although these analyses were somewhat exploratory, we did anticipate some outcomes based on previous studies (e.g., Hamilton & R. Martin, 2007). We did not anticipate that semantic or phonological access would be a strong predictor of performance on verbal WM

tasks. Although it is conceivable more imprecisely activated word representations may be less stable in STM and contribute to a verbal WM load effect, dissociations between access to and maintenance of semantic and phonological representations have been reported (e.g., R. Martin & Lesch, 1996). Therefore, we did not expect that the contributions of this variable would be paramount.

We expected that verbal STM capacity would predict performance on verbal WM tasks and more specifically, that semantic STM capacity would modulate performance of synonymy judgments and phonological STM capacity would modulate performance of rhyming judgments. In both cases, lower spans on our measures of these abilities should be associated with enhanced sensitivity to verbal WM load effects in the semantic and rhyming judgments.

We also anticipated that executive control processes would influence performance of verbal WM tasks. We examined the role of three executive control processes that have been deemed relevant to language, STM and WM (Miyake et al., 2000), namely inhibition, WM updating and set shifting. We anticipated that inhibition would account for some of the verbal WM load effect, as this executive ability has been implicated in semantic STM (R. Martin, 2007; Hamilton & Martin, 2005; 2007; Hoffman et al., 2009). Decreased updating ability should also increase sensitivity to verbal WM load effects if the task in question calls for manipulation of the verbal WM contents. Thus, we anticipated some role of WM updating ability in any verbal WM load effects we might observe. We did not anticipate that set shifting would be related to performance on these judgment tasks because they do not involve shifting from one 'set' of judgments to another (i.e., synonymy and rhyming are separate tasks). One note about the executive processes that were explored in these analyses is that they were examined in the context of nonverbal tasks. We chose to do this to avoid any confound of language processing that would be part of executive tasks that do involve verbal processing. That said, however, it is important for future research endeavors to examine how executive processes operate directly in the context of language tasks (e.g., Wright, Downey, Gravier, Love, & Shapiro, 2007; Christensen & Wright, 2010). In a Analysis 4, we addressed a question about the relationship between severity of aphasia and the effects of verbal WM on language performance. If language processing and verbal STM share a common process that maintains activation of semantic and phonological representations of words, and verbal STM capacity supports verbal WM, performance levels on verbal span tasks and verbal WM memory should be associated with overall severity of language impairment. We used the Western Aphasia Battery WAB AQ score from the *Western Aphasia Battery- Revised* (WAB-R, Kertesz, 2006) as a measure of overall aphasia severity for this analysis.

Method

Participants

Thirty-one individuals with chronic aphasia representing a variety of aphasia types participated in this study. The average age was 56 years (range 34–79), average education was 14.29 years (range 10–19); and average months post-onset was 69 (range 6–300 months). Additionally, there were 11 control participants who were roughly matched in age and education to the participants with aphasia. The average age of this group was 46 years (range 31–60) which is significantly lower than that of the aphasic group ($t(19) = 2.91, p = .01$, two tailed). This difference is largely due to the lack of control participants over the age of 60. The proportion of participants in the mid-ranges between 40 and 60 are similar in the two groups (.58 for participants with aphasia and .64 for control participants). The average number of years of education was lower for the control participants (12.73 years, range 11–16). Although this difference was significant ($t(29) = 2.49, p = .02$), each group included a

wide range of educational experience. For the aphasic group, the distribution of aphasia types according to the *WAB-R* (Kertesz, 2006) was 7 Broca's, 17 anomic, 4 conduction, and 3 Wernicke's. Additionally, a wide range of aphasia severity was represented in this group. The average *WAB-R* aphasia quotient (*WAB AQ*) was 73.9 with a range of 33.8 to 95. Details of these background data are noted in Table 1.

All participants in our research, including those in this study, must pass an audiometric pure-tone, air conduction screening at 25 dB HL at 1K, 2K and 4K Hz for at least one ear. Vision is not formally tested, but all participants in this study reported no visual problems and good vision either with glasses or without.

Main experimental tasks and experimental design – Analyses 1 and 2

The two judgment tasks described below were presented on the computer using E-Prime 2 software (2010, Psychology Software Tools, Inc.). Each test item was visible on the screen until the participant made their decision. They indicated their response by pointing to (and/or verbalizing) the words or pictures they judged as similar. The examiner then advanced the program to the next trial.

Synonymy Triplet Judgments—This task assesses the ability to identify two words with similar meanings and it is thus sensitive to the ability to access semantics from written and spoken words. There are 40 word triplets, 20 concrete and 20 abstract (each with 10 nouns and 10 verbs). Items were designated as concrete or abstract according to the Kroll and Merves (1986) normative ratings. The synonymy judgment task was administered in two formats (A and B) that included the same 40 triplets, but with different instructions about making the judgment of similarity. In format A (3-pair condition), the examiner read aloud three written words that were presented in a diagonal array. No information about the meanings of the words was provided. The task was to select the two of the three words closest in meaning (e.g., *fiddle*, *violin*, and *clarinet*). Format B (2-pair condition) used the same items, also presented in a diagonal array, but with the middle word designated as the target (e.g., *violin*) and the other two words (e.g., *fiddle*, *clarinet*) designated as possible synonyms of the target word. The instructions in this format were to choose one of the two remaining words in the diagonal array which was most similar in meaning to the target word in the middle of the diagonal. The 40 items in each format were divided into two subsets (A_1 , A_2 , B_1 , B_2) and these subsets of 20 items were administered in an A_1 , B_2 , B_1 , A_2 design. The order of items within each set was randomized and the order of presentation of formats A and B was counterbalanced across participants. Proportions of nouns and verbs as well as concrete and abstract words were balanced across the four sets. Figures 1a and b show the two formats of this test.

Rhyming Triplet Judgments—This task was designed in the same way as the Synonymy Triplet Judgment task except the focus was on rhyming relations among words. Stimuli are 1-syllable, pictureable nouns with consonant-vowel structures: CVC, CCVC, CCVCC, CVCC. Two formats, A and B, varied the task instructions which in turn varied the WM load inherent in the task. There were 30 triplets altogether and these were each presented in the two formats. In format A (3-pair condition) three pictures were presented diagonally on the page from top-left to bottom right. Their names were presented auditorily, (up to 5 repetitions) in the same sequence as the picture display. Two of the picture names rhymed and the non-rhyming foil overlapped phonologically with one or two of the rhyming words in one of three ways: same initial phoneme (e.g., *fan*, *pan*, *pail*), same stressed vowel (e.g., *bag*, *rag*, *cat*), or same final phoneme (*corn*, *fern*, *horn*). This format requires holding three word pairs (e.g., *bag-rag*, *bag-cat*, *catrag*) in STM. In format B (2-pair condition), the same three pictures were presented diagonally on the page as before, and the center picture

was highlighted. The spoken name of the center picture was presented first (e.g., *pan*) followed by the names of the other two pictures. (e.g., *fan*, *pail*). The task was to determine which of these two words (*fan* or *pail*) rhymed with the target word (*pan*). In this task only two word pairs need to be held in verbal WM (*pan-fan*, *pan-pail*). Figures 2a and b show examples of the stimuli and presentation of each format.

The two formats of the synonymy and rhyming judgment tasks described above differed in verbal WM load in that each required a different number of word pairs to be held in verbal WM. In format A, the 3-pair condition, a decision would require consideration of the meanings of fiddle-clarinet, violin-clarinet and fiddle-violin. In format B, the 2-pair condition, a decision would require consideration of two word pairs. If violin is designated the target, the two pairs to be considered would be violin-fiddle and violin-clarinet. The same difference in verbal WM load holds for the two conditions of the rhyming judgment task.

Dependent measures—For each of these tasks, we calculated proportion correct in each verbal WM load condition and compared these by t-test to determine if performance on the lower verbal WM load condition (2-pair) was more accurate than accuracy on the high verbal WM load (3-pair) condition. We calculated results for the 31 participants with aphasia and 11 control participants. To compare the magnitude of the verbal WM load effect for each of these two groups, we used a two sample t-test (assuming unequal variances) to compare the 'difference scores' (proportion correct for 2-pair minus proportion correct for 3-pair) of each group. That difference score constitutes a measure of the detrimental effect of verbal WM load on performance of these judgment tasks. It also will be the dependent variable in the multiple regression analyses that will examine potential contributors to the verbal WM load effect: language processing, STM and executive functions. For all of these analyses, we used the difference score calculated from the raw data and also from data adjusted for chance. This calculation is described below.

Chance probability adjustment of scores—In addition to the difference in verbal WM load, the two conditions vary in the probabilities that the correct response could be made by chance (.50 in the 2-pair condition and .33 in the 3-pair condition). Thus, if performance is better in the lighter verbal WM load condition (the 2-pair condition), this result could be attributed to chance. To eliminate any element of chance probabilities accounting for differences in performance in the two conditions, we adjusted the scores with a formula score designed to account for guessing in multiple choice tests (Frary, 2005):

$$FS = R - W/(C-1)$$

Where *FS* = "corrected" or formula score

R = number of items answered correctly

W = number of items answered incorrectly

C = number of choices per item (same for all items)

Both the original and adjusted scores (mean proportion correct) were analyzed.

Independent measures to be used in multiple regression analyses – Analysis

2—The language and verbal STM measures described below were presented on the computer using E-Prime 2 software (2010, Psychology Software Tools, Inc.). The executive function measures described below were administered on the computer using Presentation software (Neurobehavioral Systems, 2011). The language and verbal STM tests are part of the Temple Assessment of Language and Short-term Memory in Aphasia (TALSA; Martin, Kohen & Kalinyak-Fliszar, 2010). The test is unpublished, but we are currently collecting

normative data from participants with aphasia and control participants and establishing its psychometric properties (Martin, Kohen, Kalinyak-Fliszar & Hula, in preparation). Table 2 shows data (means, standard deviations and range of performance) from the 31 individuals with aphasia who participated in this study and the same data from 10 control participants collected thus far in the normative study. Controls achieved ceiling or near ceiling performance on the Lexical Comprehension and Phoneme Discrimination tasks. The participants with aphasia, on average, also did well on these tasks, but there is a wider range of performance. For the Category Probe and Pointing Digit span tasks, both groups showed a range of performance, but the spans were, on average, higher in the control group and the range of span was greater in the group with aphasia. Each of these tests is described below.

Semantic and Phonological Access Measures—We used two measures of verbal processing to determine if the ability to access semantic or phonological words could predict the verbal WM load effect in the synonymy and rhyming judgment tasks.

(1) Semantic access: For a measure of access to semantics from words it is critical that the test involves minimal engagement of verbal STM. We used the lexical comprehension subtest of the *TALSA*, which uses a standard spoken word-to-picture matching paradigm in which a stimulus (spoken word, e.g., apple) is matched to one of four pictures of objects from the same semantic category. Target words and distracter items are concrete nouns. The outcome measure is proportion correct out of 20 items. This semantic access measure may show some association with performance of the synonymy judgment tasks if access to semantic representations of words is not stable. This would be especially true in severe semantic access deficits (e.g., in the case of transcortical sensory aphasia). Apart from those cases, however, mild to moderate impairments of access to semantics from spoken words might not be sufficient to affect verbal WM. Additionally, the presence of the written word in the synonymy judgment tasks and multiple presentations of the spoken word in each task (as needed), might compensate for any impairment of semantic access. Although these procedures facilitate access to semantics from the spoken word, they do not guarantee it. Nonetheless, at least in the present setup, we do not expect this variable to be a strong predictor of the verbal WM load effect.

(2) Phonological access: The test used to measure access to phonology was the Phonological Discrimination Test from the *TALSA* Battery (Martin, et al., 2010). This test uses a minimal pair identity judgment paradigm and includes 20 word (concrete, 1–3 syllables) and 20 nonword pairs. Nonwords were derived from the word stimuli by changing 1 or 2 phonemes at initial, medial or final positions. Participants hear two words or two nonwords and determine whether they are the same or not. Only data from the nonword condition was used as a predictor variable in order to minimize any lexical involvement in the discrimination of phoneme differences. This variable should not be predictive of performance of any of the similarity judgment tasks, as this ability can be intact even when phonological STM is reduced. As in the case of the test of semantic access, it is likely that severe cases of phonological input processing might affect performance and contribute to the verbal WM load effect, but the more common mild-to-moderate impairments that are present in most cases of aphasia should not compromise performance of the synonymy or rhyming judgments and also should not influence the verbal WM load effect.

Semantic and Phonological STM Measures

Semantic STM span—To assess semantic STM span, we used the Category Probe Span test from the *TALSA* Battery (Martin et al., 2010). The participant hears a sequence of words followed by a spoken probe word. Half of the probes contain a word that is semantically related to a word in the list (member of the same semantic category, e.g.,

probe: *peach*; word in list: *apple*) and the other half contain words that are unrelated to any word in the list (e.g., *peach*; no names of `fruit' in list). The task is to judge whether or not the probe is categorically related to a word in the list. This task was developed by R. Martin & colleagues and has been used to assess semantic STM capacity of individuals with aphasia (R. Martin et al., 1994; R. Martin & He, 2004) and without aphasia (Martin, Bunta, Gruberg, Postman-Caucheteux & Hegedus, 2008). Like any task that uses words, activation of phonological representations of words is unavoidable. However, the task of recognizing that a probe word is in the same semantic category as a word in a string of words makes this span measure sensitive to the ability to maintain activation of semantic representations in verbal STM.

The version of this task developed for the *TALSA* battery includes list lengths up to 8 items. Probe matches were sampled 5 times from all positions in the list. Thus, the number of lists for each length condition ranged from 10 for the 1-item lists (five with category matches and five with no match) to 80 for the 8-item lists. All testing began with the single item list length and proceeded until the participant fell below 75% accuracy at a particular list length. Span was defined as the list length completed at 75% correct plus a portion of the next list length determined through linear interpolation. As an example, consider the following performance:

Proportion correct, List length 3 (L) = .85

Proportion correct, List length 4 (H) = .60

In order to capture a participant's "true" span, an estimation of the list length that is between List length 3 and List length 4 that would equal .75 correct is calculated. The formula for span is:

$$L + (\text{proportion correct at } L - .75) / (\text{proportion correct at } L - \text{proportion correct at } H)$$

In the above case, the calculation is: $3 + (.85 - .75) / (.85 - .60) = 3.40$

This formula accounts not only for proportion correct at the list length that falls below .75 (list length 4), but also the proportion correct at the list length that is shorter (list length 3).

Phonological STM span—For this measure, we wanted a span task that minimized lexical-semantic content and maximized phonological STM, but, like the Category Probe Span, did not require a verbal response. We therefore used another span task from the *TALSA* battery, the pointing version of our standard digit span task. This test consists of 10 lists of digits in each of 6 list-length conditions (1 digit, 2 digits, 3 digits etc). Sequences of numbers for each list are generated from a finite set of nine digits (1–9). The participant hears a sequence of numbers and should reproduce that sequence in serial order by pointing to the sequence on a visual array (randomly changed on each trial) of the nine digits.

Executive Function Measures—Three executive function abilities were examined: inhibition, WM updating, and set shifting. The set shifting task has two parts, a letter condition and a number condition. These were combined for this analysis. Thus, three measures of executive processing were considered initially in the multiple regression analyses. The tests to measure these executive functions are part of a cognitive test battery adapted for bilingualism research (Soveri, Rodriguez-Fornells & Laine, submitted). They are based on Miyake et al.'s (2000) proposal that three executive abilities, inhibition, set shifting and WM updating, are fundamental to language processing. These are designed to minimize the involvement of language processes: (1) the Simon Task (inhibition; Simon & Wolfe, 1963; Simon & Ruddell, 1967), the Number-Letter Set Shifting Task (set shifting; adapted from Rogers and Monsell, 1995) and a visuospatial version of the n-back Working Memory Updating Task (adapted from Carlsson, Martinkauppi, Rama, Salli, Kovenoja, & Ahonen,

1998). Only 21 of the participants with aphasia in this study completed these tasks. Nine of ten were unavailable for testing and one person was not able to complete all three tasks. Both accuracy and reaction times were obtained, but only reaction time data are reported here because accuracy of performance on the Simon Task was near ceiling. Prior to the analyses, reaction times for correct responses were checked for extreme outliers (more than three standard deviations above or below the individual mean) but none of them needed to be discarded. Table 3 details the means, standard deviations and ranges of reaction times on these measures for the 21 participants. The three tests are described briefly below.

Inhibition: The Simon Task—A blue or a red square appears on either the left or the right side of the screen. The task is to decide the color of the square irrespective of the side of the screen where it appears. This is indicated by left or right button presses corresponding to the colors blue and red respectively. In congruent trials the square is on the same side as the response button and in incongruent trials, it is on the opposite side of the response button. There are 100 trials (50 congruent, 50 incongruent). Presentation order of the trials is randomized for each participant. There are four blocks of trials with a five second break between blocks. Each trial begins with a fixation cross appearing in the center of the screen. This vanishes after 800 milliseconds (ms.), and a blue or a red square appears on the left or right side of the screen for 5000 ms. or until a response is given, after which there is a blank interval of 1000 ms.

The measure that was included in the regression analyses described below was the difference in reaction times (for correct trials only) on the congruent and incongruent trials.

WM updating: The Spatial N-back task—A white square is presented in one of eight locations on the screen. The task is either to remember the location of the previous square (1-back) or the one before the previous square (2-back), depending on the instructions given. Figure 3 shows an example of the screen display in the n-back task.

There are 160 trials, 80 1-back and 80 2-back trials. These are divided into two blocks of 80 trials with a 15 second break between. Each block has four conditions of 20 trials: 2 sequences of the 1-back and 2 sequences of the 2-back condition. The order of the conditions is 1-back, 2-back, and 2-back, 1-back within the first block and 2-back, 1-back, 1-back, 2-back within the second block. The participant presses the right buttons if the square appears in the same location as the previous square and the left button if the location is different. Throughout the task, a fixation cross remains in the middle of the screen, and squares are presented at one of eight possible locations. The squares remains on the screen for 150 ms., and are presented at 5000 ms. intervals.

The measure that was included in the regression analyses described below was the difference in reaction times (for correct trials only) on the 1-back and 2-back trials.

Set-Shifting the Number-letter task—A number-letter combination appears in one of two squares in the center of the screen. If the number-letter pair appears in the top square, the task is to determine whether the number is even or odd, and if it appears in the bottom square, the task is to determine whether the letter is a vowel or a consonant. Thus, the squares serve as cues for which task to perform. An example of the visual display in the Number-Letter Set Shifting Task is shown in Figure 4.

There are non-switch trials, in which the number-letter combination is in the same square on successive trials and switch trials, in which the location of the stimulus alternates. The task switching is unpredictable for the subject, because the number-letter combination appears in the two squares randomly. There are three blocks with breaks between. Block 1 has 32 non-

switch trials with equal numbers of even and odd numbers and all stimuli appearing in the upper square. The task is to determine if the number in the number-letter combination is even or odd. Block 2 has 32 non-switch trials with the same number of vowels and consonants and all stimuli appearing in the lower box. The task is to decide if the letter in the number-letter combination is a vowel or a consonant. Block 3 has 32 switch trials and 48 non-switch trials. The switch trials include equal number of trials in which the task is to switch from numbers to letters and vice versa. The 48 non-switch trials include 24 trials that require deciding if the number is even or odd and 24 that require deciding if the letter is a vowel or a consonant. Each trial begins with a fixation cross appearing in the center of the screen. This vanishes after 1000 ms. and two small boxes appear in the center of the screen, with a number-letter combination in one of the boxes. The stimuli remain on the screen for 3000 ms. or until a response is given.

The measure that was included in the regression analyses described in Analysis 2 was the difference in reaction times (for correct trials only) on the switch and non-switch trials in Block 3 which is a measure of the switching cost.

Results

Analysis 1: Does increased verbal WM load reduce accuracy of performance of synonymy and rhyming judgment tasks?

If word processing impairments are related to an inability to maintain activation of word representations, performance of language tasks should be sensitive to increases in the WM load inherent in that task. To recapitulate our predictions, for the participants with aphasia, performance should be better in the low verbal WM load condition (two pairs) than the high verbal WM load condition (three pairs). For the control participants, performance should be closer to ceiling and although performance should decline in the high verbal WM load condition, this change should not be significant.

Results of Analysis 1—Table 4 shows the results of the t-tests comparisons of proportion correct on each format. The original and chance corrected data are shown for the participants with aphasia and the control participants. For the original data from participants with aphasia's in all three tasks, proportions correct were significantly greater for the low verbal WM load condition (2-pair) compared to the high verbal WM load condition (3-pair). When data were corrected for chance probabilities of correct responses, the differences in the two conditions were significant for the abstract items in the Synonymy Triplets and Rhyming Triplets. For the concrete items in the Synonymy Triplets, a one-tailed comparison revealed a trend for better performance in the low verbal WM load condition ($p = .08$). For the control participants, verbal WM load significantly affected performance of the Rhyming Triplet Judgments (original and chance-corrected data) and there was a trend of an effect ($p = .07$, one-tailed t-test) for the concrete items in the Synonymy Triplets.

Magnitude of the verbal WM load effect—The effect of verbal WM load on performance of similarity judgments is seemingly of greater magnitude for the participants with aphasia than for the control participants. This was partially confirmed in a comparison of the difference scores for the 2-pair and 3-pair conditions of these two groups. For the concrete items in the Synonymy Triplets Judgment task, the magnitude of difference scores was greater for the participants with aphasia than for the controls in the original data only ($t(27) = 1.72$, $p = .05$, one-tailed test). For the data corrected for chance, there was a trend in this direction ($t(30) = 1.44$, $p = .08$, one-tailed test). For the abstract items in the Synonymy Triplets Judgment task, the magnitude of difference scores was greater for the participants with aphasia than for the controls in the case of the original data ($t(38) = 3.74$, $p = .0003$,

one-tailed test) and the corrected data ($t(33) = 3.67, p = .0004$, one-tailed test). For the rhyming judgment task, the magnitude of difference scores was greater for the participants with aphasia than for the controls in the original data ($t(27) = 2.83, p = .004$, one-tailed test), but only a trend was observed when data were corrected for chance ($t(29) = 1.54, p = .07$, one-tailed test). The pattern is the same for 2-tailed tests (also shown in Table 4) for the participants with aphasia, but for the controls, no comparisons reached significance.

In the next analysis, we examine the role of linguistic and cognitive factors on the strength of the verbal WM load effects on these judgment tasks.

Analysis 2. Are verbal access, verbal STM and/or executive function abilities related to the verbal WM load effect on performance of the Synonymy and Rhyming Triplet Judgment tasks?

As verbal WM in the Synonymy and Rhyming Triplet Judgment tasks is supported by verbal processing, verbal STM and executive functions, it is conceivable that any or all of these measures could predict the verbal WM load effect in these tasks. We conducted a series of multiple regression analyses to determine the relative contributions of access to semantic and phonological representations, semantic STM and phonological STM and executive control of activated representations to the verbal WM load effect in the performance of the Synonymy and Rhyming Triplet Judgment tasks. As discussed in the Introduction, we anticipated that verbal STM capacity (semantic and/or phonological) and at least two executive functions (inhibition and WM updating) would be related to the verbal WM load effects observed in Analysis 1.

Results of Analysis 2

(1) Semantic and phonological access and verbal STM variables: We first used a stepwise multiple regression with backward elimination of predictors to examine the contributions of semantic and phonological access (measures: Lexical Comprehension, Phoneme Discrimination) and Semantic and Phonological STM (measures: Category Probe Span and Pointing Digit Span respectively) to the verbal WM load effect observed in the first analysis. We used the backward selection approach, as recommended by Field (2005) for the stepwise analysis. The stepwise backward elimination method is an exploratory technique that determines which variables might predict a particular outcome measure. Models with p values greater than .10 were eliminated in this process. The variables that are identified as significant predictors were entered into standard multiple regression analyses in Analysis 3. The difference between performance on 3-item and 2-item Synonymy and Rhyming Judgments was not attributable to differences in chance probability of a correct response in the two conditions (with the exception of concrete synonymy items, see Table 4). We therefore used the original data in these analyses and reported the analyses of data corrected for chance only when the outcomes differed from the analyses of the original data.

These analyses were conducted with all 31 participants. We completed the analyses with the original data and data corrected for chance. We did not carry out these analyses on the control participants because of their small number, and their performance of these measures was close to ceiling with little variance (see Table 2). We also do not have data from all of the control participants on the executive processing measures. The correlations between span measures and the dependent variable (difference score between high and low memory conditions) should be negative. For example, a reduced span on the Category Probe Span task would be associated with a greater verbal WM load effect. Table 5 summarizes the results of this stepwise multiple regression analysis.

When both concrete and abstract items of the Synonymy Judgment task were analyzed together, the only statistically significant model obtained was the one that included only Category Probe Span (the measure of semantic STM) as a predictor of the verbal WM load effect (as measured by the difference score between high and low verbal WM load conditions). After adjusting for chance, this model was marginally significant ($F(1, 29) = 3.847, p = .059; t = -1.961, p = .059$). When only concrete items were examined, a single statistically significant model emerged, having only the Category Probe Span as a predictor (Table 5). After adjusting for chance, the model was not significant. When the abstract items were analyzed separately, no significant models were obtained. When data corrected for chance were analyzed, a model emerged that included Category Probe Span as the sole predictor, but the contribution of this variable was not significant ($t = 1.706, p = .099$). For the Rhyming Judgment Task, the stepwise backward elimination regression resulted in one significant model which included Pointing Digit Span, our measure of Phonological STM as the only variable that predicted the verbal WM load effect (Table 5). Thus, overall, these results are consistent with the idea that semantic STM span is associated with sensitivity to the verbal WM load effect on judgments of semantic similarity (synonymy) while phonological STM span is sensitive to the verbal WM load effect on judgments of phonological similarity (rhyming). These two variables were entered into standard regression analysis in Analysis 3.

Additionally, the pattern of results provides some convergent validity confirming that these span measures are sensitive to what they are intended to measure (category probe - semantic STM and Pointing Digit Span - phonological STM). At the same time, the two measures are somewhat discriminate; they do not correlate significantly with each other, although there is a trend in that direction ($r(30) = .30, p = .10$).

(2) Executive function variables: The correlations between the executive function tasks and the verbal WM load effect were expected to be positive. That is, if someone shows a large executive cost (i.e., a large performance difference between conditions of high executive load vs. low executive load), they should also show a larger decrement in performance of the judgment tasks if verbal WM load is increased.

In the first of these multiple regression analyses, we used the stepwise backward selection approach to determine if any of the three executive function tasks -- the Simon Task, the Spatial N-back task and the Number-Letter Set Shifting task -- would emerge as a significant predictor of the verbal WM load effect. When both concrete and abstract items in the Synonymy Judgment task were analyzed, three statistically significant models emerged, but the final model outcome of the backward analysis included only the Simon Task as a predictor variable ($F(1, 19) = 10.81, p = .004$, shown in Table 6). The other two models included (1) Simon plus Number-Letter Set Shifting as predictors ($F(2, 18) = 5.50, p = .014$) and (2) Simon Task plus Number-Letter Set Shifting and Spatial N-back as Predictors ($F(3, 17) = 3.53, p = .039$). When looking at the contribution of the individual predictors, the t-statistics in each of these models were only significant for the contribution of the Simon Task. When the data corrected for chance were analyzed, only two statistically significant models emerged, one with the Simon Task as the only predictor and one with Set Shifting and Simon Tasks as predictors. As in the analyses of the original data, the Simon Task was the only significant contributing variable in each model.

When the analysis was conducted for concrete items only, one marginally significant model with the Simon Task as the sole predictor was obtained ($F(1, 19) = 4.151, p = .056$, shown in Table 6). When the data corrected for chance were analyzed, no significant models were obtained.

For the abstract item analysis, three statistically significant models were identified, but the final model outcome (shown in Table 6) included only the Simon Task as a predictor ($F(1, 19) = 13.198, p = .002$). The other two models included (1) Simon Task plus Spatial N-back as predictors ($F(2, 18) = 6.55, p = .007$) and (2) the Simon Task, Spatial N-back and Number-Letter Set Shifting as predictors ($F(3, 17) = 4.14, p = .022$). In each of these latter two models, *t*-statistics were only significant for the contribution of the Simon Task. When the data corrected for chance were analyzed, the same three models emerged and were significant, but again, the only variable that contributed significantly to the model was performance on the Simon Task.

For the Rhyming Judgment Task, the only model that predicted the verbal WM load effect was the one that included the Simon Task as the single predictor ($F(1, 19) = 4.733, p = .042$, shown in Table 6). When data corrected for chance were analyzed, this same model was obtained, but the significance of the Simon Task's contribution was now marginally significant ($F(1, 19) = 3.924, p = .062, t = 1.981, p = .062$). Thus, as a predictor variable, inhibition does seem to be aligned both with semantic and phonological levels of processing.

Analysis 3. Examining the contributions of verbal span tasks and Simon Task on verbal WM load effects

We next conducted a standard multiple regression analysis in which we entered into the model the three independent variables that emerged in the stepwise regression as potential predictors of the verbal WM load effect in these judgment tasks: Category Probe Span, Pointing Digit Span and the Simon Task. These tasks measure respectively, semantic STM, phonological STM, and inhibition. We were especially interested in the relative contributions of verbal STM and the executive function, inhibition. Thus far, the analyses suggest that both contribute to the verbal WM load effects in these judgment tasks, but would one variable emerge as more dominant? The results of this regression analysis are shown in Table 7. Semantic STM and the Simon Task emerged as predictors of the verbal WM load effect in the Synonymy Judgment Task. None of these variables significantly predicted this effect in the Rhyming Judgment Task. When the data corrected for chance were analyzed, the pattern of results was the same.

In a final regression analysis, we entered just the measures of semantic STM (Category Probe Span) and inhibition (Simon Task) into the model. We anticipated that both would be strong predictors of the verbal WM load effect on the judgment tasks. Table 8 shows these results. These two variables accounted for much of the verbal WM load effect on the Synonymy Judgment Task. Only the Simon Task predicted performance on the Rhyming Judgment Task. When the data corrected for chance were analyzed, the pattern of results was the same. The Simon Task was a significant predictor of the verbal WM load effect in the Synonymy and Rhyming Judgment Tasks and the Category Probe Span was a significant predictor of the verbal WM load effects in the Synonymy Judgment Task. It is important to note that these two variables are not correlated strongly with each other ($r(1) = .16$), suggesting that their contributions to the model predicting a verbal WM load effect on the Synonymy and Rhyming Judgment tasks are independent. In actual values, inhibition is the more robust predictor of the verbal WM load, but semantic STM also contributes strongly to this effect.

Analysis 4. Severity of aphasia and the verbal WM load effect

As noted in the Introduction, the verbal STM deficit in aphasia has been shown to fall along a severity continuum, with more severe deficits leading to a profile of word processing impairment and reduction in verbal span and a milder deficit leading to no apparent word processing deficits, but reduced verbal STM span (Martin et al., 1996; Martin & Ayala,

2006; Martin & Gupta, 2004; Martin, 2008). As our measures of semantic and phonologic STM have been shown to predict performance on, respectively, the Synonymy and Rhyming Judgment Tasks, we should see a continuum relationship between aphasia severity and performance on the two judgment tasks (lower performance associated with greater severity) as well as between. We should also see a continuum relationship between measures of semantic and phonological span and aphasia severity. The WAB AQ score reported in Table 1 is taken as an estimate of overall aphasia severity. We correlated the WAB AQ scores for this group of 31 participants with aphasia with scores on the Synonymy and Rhyming Judgment tasks: 3-pair concrete synonymy ranging, $r(30) = .49$, $p = .005$; 3-pair abstract synonymy, $r(30) = .49$, $p = .005$; 3-pair rhyming, $r(30) = .71$, $p = .000$.

To determine if there is a relationship between aphasia severity and semantic and phonological STM, we used a multiple regression analysis with the WAB AQ score as the dependent variable and the Category Probe spans and Pointing Digit spans as predictor variables. The resulting model was highly significant ($R = .816$, $R^2 = .666$, $F(30) = 27.92$, $p = .000$). Only the, measure of phonological STM, Pointing Digit span, predicted aphasia severity ($t = 6.783$, $p = .000$).

Additionally, we might expect the executive processing task that predicted performance on the judgment tasks would also relate to aphasia severity. We correlated the reaction times on the the Simon Task with the WAB AQ scores. This resulted in a marginally significant association with aphasia severity for the 21 participants in this study ($r(20) = .42$, $p = .06$).

General Discussion

In this study, we have shown that increasing the number of items that need to be held in verbal WM during judgments of synonymy or rhyming relations reduces the rate of correct judgments. Additionally, for participants with aphasia, multiple regression analyses indicated that two abilities, semantic STM and an executive function, inhibition, significantly predicted the verbal WM load effect on Synonymy Judgment Test and inhibition ability predicted the verbal WM load effect on the Rhyming Judgment Task. These results are consistent with the view that aphasia involves processing deficits and is not solely due to degradation of linguistic knowledge. It is our view that aphasia can be characterized largely as a disorder of activating representations of words (access), maintaining that activation in verbal STM, and controlling that activation (executive functions). The observation of better performance of semantic and phonological judgment tasks when there are fewer items to consider in making that judgment is a clear indication that the language knowledge is present, but more difficult to access and maintain in the context of increased verbal WM load. This study and others (e.g., Tseng et al, 1993; Murray et al., 1997a and b; Murray et al., 1998) provide evidence of variability in accuracy on a language task that is precipitated by a change in task conditions, which in turn supports the idea that processing impairment is a significant component of aphasia.

These data and previous demonstrations of the influences of verbal STM capacity and executive processes on language function expand the definition of aphasia beyond its linguistic characteristics to include 'processing' characteristics that enable language representations to be accessed and retrieved over the time course of completing any language task (see McNeil & Pratt, 2001 for discussion). The degree to which verbal STM ('activation maintenance') and executive functions would be engaged in language processing would depend on the verbal WM load inherent in the task and context in which it is occurring. For example, simple word-to-picture matching tasks might only require accessing representations long enough to match a word to a visual image. If other pictures are present and these are from a similar semantic category, more verbal STM capacity may be needed to

consider the other images, and inhibitory processes may be invoked to suppress non-target words that are semantically similar to the target word. Thus, although one might think that involvement of verbal STM and executive processes in language processing is more associated with tasks involving multiple word processing (e.g., sentence-level and discourse processing), they are likely involved to some degree in most language tasks.

We identified one executive function, inhibition, as a predictor of the verbal WM load effect observed in this study. This is consistent with other studies examining executive functions in relation to language impairment in aphasia (e.g., Purdy, 2002, Hamilton & Martin, 2005, 2007; Hoffman et al., 2009). We did not observe a relation between the verbal WM load effect in these judgment tasks and the other two executive functions we examined, WM updating (as measured by the Spatial N-back task) and set shifting (as measured by the letter-number task). We expected that the latter task may not apply to our triplet judgment tasks because they do not involve task switching. WM updating, however, would seem a likely candidate for being involved in these judgment tasks, as one must keep track of words meanings or sound patterns that have been compared already while considering other pairs of meanings or sound patterns. One account for not observing an influence of this variable might be that WM updating is more domain-specific, but inhibition is a more domain general executive function. This account is consistent with Baddeley's WM model (Baddeley & Hitch, 1974) that separates the phonological and visual short-term stores (phonological loop and visual spatial sketchpad). To determine the domain specificity of these variables, one would need verbal versions of both of these tasks to compare to the nonverbal versions that we used here (e.g., Wright, Downey, Gravier, Love & Shapiro, 2007; Christensen & Wright, 2010).

Clinical implications of this study

Martin and colleagues (Martin et al., 1996; Martin & Ayala, 2006; Martin & Gupta, 2004; Martin, 2008) demonstrated that verbal STM deficit in aphasia can be tracked along a continuum of language impairment severity. Milder language impairment is associated with a reduced verbal span, but no difficulty in processing single words (in lexical decision and picture naming tasks). More severe language impairment is associated with reduced verbal span as well as single word processing difficulties. In a final analysis, we showed that performance on the Synonymy and Rhyming Judgment tasks and on the Simon task correlated positively with a measure of aphasia severity, the WAB AQ. When we examined the possibility of a direct relationship between semantic and phonological STM and aphasia severity, only the measure of phonological STM (Pointing Digit Span) was associated with aphasia severity. This result is consistent with a continuum relationship between language ability and two variables that influence working memory capacity, verbal STM and the executive process, inhibition. Hoffman et al. (2009) have proposed a similar severity continuum for executive processing impairments observed in aphasia. The continuum model is suited to STM and executive control systems that support language function. For example, mild or severe impairment of STM (verbal or nonverbal) has a concrete referent in size of span. In contrast, it appears unreasonable to try to quantify mild or severe linguistic impairments in a single measure as they represent multifaceted phenomena.

Although aphasia always will be characterized in terms of its linguistic characteristics, as it should be, an accompanying profile of nonlinguistic support processes should have several positive clinical implications. First, when impairment falls on a severity continuum, that continuum includes severe, moderate and mild impairments. A particularly disenfranchised group of people with aphasia are those whose language impairments are mild and not evident on most standardized batteries of language assessment. There are few aphasia test batteries that provide assessments of verbal STM or executive function in the context of language tasks (but see Kalbe, Reinhold, Brand, Markowitsch, & Kessler, 2005; Marshall &

Wright, 2006; Martin et al., 2010). Often a person's verbal span is equated with their digit span, which does not take into account the effect of language variables on the size of span. Someone with mild aphasia may score at ceiling on many measures of word processing (e.g., word-to-picture matching, phoneme discrimination). And yet, when participating in conversations, they may still experience difficulty in 'keeping up' with the language content from other speakers, or they may have difficulty formulating responses in time to offer their contributions to a conversation. Individuals with this milder level of aphasia, however, will show impairment on word span tasks, and these difficulties have been shown to systematically affect retention of semantic or phonological aspects of words in STM (R. Martin et al., 1994). Thus, verbal span tasks that vary semantic and phonological content can provide important diagnostic information in cases of mild aphasia.

Other clinical implications of this study relate to task design, diagnosis, and treatment of language impairments. The data from this study indicate that how a task is presented (in this case how much verbal WM load is included in the language task) can affect performance on that task and give a false impression of the degree of semantic or phonological impairment in that individual. At the same time, if a low verbal WM load version of these tests (or any language task) were used to assess language ability, there could be a missed opportunity to observe the stability of a person's language ability under conditions of greater verbal WM load. This is especially important with respect to functional language abilities in everyday speaking situations in which variables such as verbal WM load are at play. Thus, in an ideal clinical context that allows testing of language abilities under varying verbal WM load conditions, it would be possible to identify those individuals who will be particularly sensitive to this variable. This suggests another clinical implication of including verbal STM and executive function abilities as part of the profile of aphasia. If these aspects of language function are impaired, they can be addressed in treatment in conjunction with linguistic aspects of the aphasia. We have shown here how semantic or rhyming judgment tasks can be varied in format to increase or decrease verbal WM load. Most language tasks can be similarly varied systematically and used to improve someone's ability to withstand variations in verbal WM load as it affects language function.

Further investigations of language in relation to STM and executive processes are needed to fully understand the role of nonlinguistic cognitive processes in aphasia. Nonetheless, there have been some promising recent efforts to develop diagnostic and treatment approaches that incorporate STM and executive processes in the context of language tasks with the goal of improving language (e.g., Helm-Estabrooks, Connor, & Albert 2000; McNeil, Matthews, Hula, Doyle & Fossett, 2006; Murray & Ramage, 2000; Martin, Kohen & Kalinyak-Fliszar, 2010). Also, in the last few years, the idea of a common process underlying STM and language processes has served as a foundation for treatment programs aiming to improve language function by treatment of the ability to maintain activation of verbal representations in STM (Majerus, Van der Kaa, Renard, Van der Linden, & Poncet, 2005; Stark, 2005; Koenig-Bruhin & Studer-Eichenberger, 2007; Kalinyak-Fliszar, Kohen, & Martin, in press; also see Murray, this volume for review).

Study Limitations

Although this study provides some important data in support of models of language and language impairment that incorporate roles of other STM and executive processes, there are two methodological considerations that should be addressed in future studies. First, the Synonymy and Rhyming Triplet Judgment tasks used in this study are part of a larger test battery for aphasia (TALSA battery). Because collection of normative data for the TALSA battery is not yet complete, the number of controls used in this study is small compared to the experimental group of participants with aphasia. Additionally, the experimental and control groups are not currently matched in age and education, although ranges of each

variable are substantial in each group. Second, the Synonymy and Rhyming Judgment tasks, Lexical Comprehension, Phoneme Discrimination, Pointing Digit Span and Category Probe Span also are part of this test battery. Until normative data collection is complete, the psychometric properties of the battery cannot be fully established. However, it should be noted that the Synonymy Judgment, Lexical Comprehension and Phoneme Discrimination tasks are derived from similar tests reported in a normative study (Martin, Schwartz & Kohen, 2005). The Pointing Digit Span task has been used in other studies with a separate and larger sample ($n=46$) than in the present study (Martin & Ayala, 2004). Finally, the Category Probe Span task is based on a similar task (but with different items) that has been shown to measure semantic STM in aphasia (R. Martin et al., 1994; R. Martin & He, 2004). The only new measure in this study is the Rhyming Triplets Judgment task.

Conclusions

The data reported in this study indicate that performance of semantic and phonological judgment tasks varies depending on the verbal WM load inherent in the language task. This relationship appears to be related to verbal STM and inhibition, an executive function impairment that may co-occur with aphasia and which play a role in verbal WM. Although these relationships need to be investigated in more language tasks, it is clear that nonlinguistic cognitive processes exert some measure of influence on language performance in aphasia. More systematic aphasia assessments that take into account both verbal STM and executive functioning in combination with linguistic variables will lead to a more in-depth understanding of the nature of the deficits in persons with aphasia. This, in turn, can guide therapeutic approaches to target linguistic and nonlinguistic deficits at both the impairment level and within functional communication contexts.

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Figure 1a.

Instructions: Which two words are most similar in meaning: fiddle, violin, clarinet?

Figure 1a.

Synonymy judgment task Condition 1: 3- pair comparisons to complete task.

Figure 1b.

Instructions: Which of these two words (pointing to words), clarinet or fiddle, are most similar in meaning to this word in the middle, 'violin'?

Figure 1b.

Synonymy judgment task Condition 2: 2- pair comparisons to complete task.

Instructions: Which two names of these objects rhyme: mouse, dice, house?

Figure 2a.

Rhyming judgment task Condition 1: 3- pair comparisons to complete task.

Instructions: Which of these two object names (pointing to pictures), dice or mouse, rhymes with the object in the middle, house?

Figure 2b.

Rhyming judgment task Condition 2: 2-pair comparisons to complete task.

Figure 3.
An example of a visual display in the Spatial N-back Task.

Figure 4.
An example of a visual display in the Number-Letter Set Shifting Task.

Table 1

Background Information on Participants with Aphasia.

Participant	Age at Testing	Time Post-onset (months)	Years of Education	Etiology	Classification of aphasia	WAB AQ	WM Load Study
1 TUCT7	45	132	10	L MCA in frontal parietal region	Broca's	62.4	
2 TUDD6	57	70	16	L temporal abcess ; L infarct inferior, latero-frontal lobes & small infarct L parietal	Broca's	57.4	×
3 TUEC15	54	107	17	L frontal parietal, L frontal parietal hypodensity / L subcortical CVA / Frontal parietal	Anomic	83.5	×
4 TUEC25	63	300	18	LCVA secondary to cerebral aneurysm; frontal and parietal involvement	Broca's	66.6	
5 TUEL5	46	144	12	L CVA thrombo-embolic	Anomic	94.3	×
6 TUFDD26	72	16	18	L CVA	Anomic	95	
7 TUFES1	53	12	12	L intracerebral hemorrhage around external capsule	Conduction	70.6	×
8 TUGI24	47	100	12	Left MCA infarct	Anomic	70	×
9 TUHI28	53	25	13	L caudate focal acute Old R corona radiata L subinsular MRI showed a L frontal infarct	Conduction	65.3	×
10 TUHN8	57	105	16	Left thalamic CVA	Anomic	91.3	×
11 TUIU19	65	12	17	CT on 3/1/07: chronic left parietal occipital infarct with probable newer left parietal embolic infarct in the left middle cerebral artery region	Anomic	82	×
12 TUKL12	61	30	14	Left thalamic CVA	Anomic	92.4	×
13 TUKL27	34	13	14	L CVA	Anomic	93.3	×
14 TUKX11	68	73	16	L CVA 2001	Wernicke's	47.3	
15 TUMI10	56	72	19	L posterior temporal and occipital CVA , L occipital AVM	Anomic	71.5	×
16 TUNH23	67	48	12	L CVA	Broca's	49.9	
17 TUQC30	47	16	14	9/2008 (L Basal Ganglia bleed); Diagnosed with moia-moia; surgery for bi-lateral stenosis of the arteries to the brain	Anomic	94.3	×
18 TUQH22	57	9	18	L Intra-cranial hemorrhage & craniectomy	Anomia	84.9	×
19 TUSC32	79	14	13	bilateral CVA- thalamic infarct	Anomia	95.4	×

Participant	Age at Testing	Time Post-onset (months)	Years of Education	Etiology	Classification of aphasia	WAB AQ	WM Load Study
20 TUSL21	55	107	14	Left AVM (parietal aneurysm)	Anomic	89	×
21 TUSX3	47	192	14	LMCA	Anomic	92.8	
22 TUTB16	39	46	12	LMCA infarct + water shed area of LMCA/PCA (L frontal parietal basal ganglia infarct)	Anomic	92.2	×
23 TUUN29	72	14	17	L CVA infarct	Broca's	33.8	
24 TUXD9	63	188	16	L CVA perisylvian	Broca's	47.2	
25 TUXXI7	63	43	10	LMCA, sylvian fissure	Wernicke's	66.8	
26 VA1-FL	61	93	12	Acute disseminated encephalomyelitis	Broca's	58.1	×
27 VA2-BI	60	48	12	CVA	Conduction	57	
28 VA3-KC	47	72	15	L CVA seizures	Wernicke's	60.9	×
29 VA4-TB	51	14	12	Non-hemorrhagic CVA; 7/31/06 MRI - old L temporal infarct, mild-moderate atrophy and insula cortex, L anterior thalamus & hypothalamus; 8/4/06 L posterior temporal parietal	Conduction	66.7	×
30 VA5-CM	47	6	14	L CVA	Anomic	89.3	×
31 VA6-UT	53	13	14	L CVA, MCA affecting L basal ganglia / corona radiata	Anomic	91	×

Abbreviations: L = Left, R = Right, CVA = Cerebral vascular accident, MCA = Middle cerebral artery, AVM = arteriovenous malformation, WM = working memory, WAB AQ = Western Aphasia Battery Aphasia Quotient.

Means, standard deviations and range of performance on the language and verbal span tasks used in multiple regression studies.

Table 2

		Language and Verbal Span Tasks			
		Lexical Comprehension (proportion correct)	Phoneme Discrimination (proportion correct)	Category Probe Span	Pointing Digit Span
Participants with aphasia in the present study (n=31)	Mean	0.97	0.93	3.65	3.37
	Standard Deviation	0.05	0.08	1.33	1.70
	Range	0.81 – 1.00	0.70 – 1.00	1.50 – 6.27	1 – 6.00
Control participants in normative study (n=10) [/]	Mean	1.00	0.99	5.92 (n=9)	6.58
	Standard Deviation		0.01	0.89	0.79
	Range	0.00	.98-1.00	4.69 – 7.00	5.80 – 7.00

[/]Data collection for these and other subtests of the Temple Assessment of Language and Short-term Memory in Aphasia is ongoing. For this reason, the 'Ns' vary slightly for some tests.

Reaction times (correct trials only) on the executive function tasks used in the multiple regression studies: Means, standard deviations and range of performance.

Table 3

		Executive Function Tasks					
		Simon Task		Spatial Working Memory Updating		Letter-Number Set Shifting	
Participants with aphasia in the present study (n=21)		Congruent	Incongruent	1 back	2 back	No Shift	Shift
	Mean	1074.10	1145.91	1647.57	1964.95	2097.18	2388.28
	Standard Deviation	310.39	348.57	517.69	507.33	763.85	809.95
	Range	532.25 – 1870.81	531.63 – 2011.31	978.73 – 2845.23	1035.87 – 2711.17	955.43 – 4057.54	1040.82 – 4339.91

Table 4

Summary of t-test analyses comparing performance on 2-pair vs. 3-pair versions of Synonymy and Rhyming Judgment Tasks.

Participants with Aphasia (n= 31)

<i>Original Data</i>	Mean Proportion Correct and Range			<i>p</i> -value	
	2-pair	Range	3-pair	Range	<i>t</i> -test 1-tailed 2-tailed
Synonymy (Concrete and Abstract items)	0.87	.53–1.00	0.75	.38–1.00	4.74 0.000 0.000
Concrete items only	0.88	.55 – 1.00	0.80	.35 – 1.00	3.18 0.002 0.003
Abstract items only	0.87	.50 – 1.00	0.71	.35 – 1.00	5.21 0.000 0.000
Rhyming	0.87	.53 – 1.00	0.75	.40 – 1.00	6.42 0.000 0.000
<i>Data Corrected for Chance</i>	2-pair	Range	3-pair	Range	<i>t</i> -test 1-tailed 2-tailed
Synonymy (Concrete and Abstract items)	0.75	.05 – 1.00	0.63	.06 – 1.00	2.93 0.000 0.010
Concrete items only	0.88	.10 – 1.00	0.70	.03 – 1.00	1.44 0.080 0.160
Abstract items only	0.73	.00 – 1.00	0.57	.03 – 1.00	3.60 0.001 0.001
Rhyming	0.75	.07 – 1.00	0.62	.10 – 1.00	3.89 0.000 0.001

Control Participants (n=11)

<i>Original Data</i>	Mean Proportion Correct and Range			<i>p</i> -value	
	2-pair	Range	3-pair	Range	<i>t</i> -test 1-tailed 2-tailed
Synonymy (Concrete and Abstract items)	0.97	.88 – 1.00	0.93	.85 – 1.00	3.52 0.002 0.010
Concrete items only	0.95	.85 – 1.00	0.93	.75 – 1.00	1.60 0.070 0.140
Abstract items only	0.98	.90 – 1.00	0.94	.75 – 1.00	1.94 0.041 0.082
Rhyming	0.997	.97 – 1.00	0.96	.80 – 1.00	1.92 0.042 0.083
<i>Data Corrected for Chance</i>	2-pair	Range	3-pair	Range	<i>t</i> -test 1-tailed 2-tailed
Synonymy (Concrete and Abstract items)	0.95	.81–1.00	0.90	.78 – 1.00	3.52 0.002 0.010
Concrete items only	0.93	.78 – 1.00	0.89	.63 – 1.00	1.60 0.069 0.139
Abstract items only	0.97	.85 – 1.00	0.90	.63 – 1.00	1.94 0.041 0.082
Rhyming	0.99	.95 – 1.00	0.96	.70 – 1.00	1.93 0.042 0.083

Table 5

Summary of Stepwise Regression Analyses: Verbal access (Lexical Comprehension, Phoneme Discrimination) and verbal span measures (Category Probe Span, Pointing Digit Span) regressed on the difference in proportions correct on the 2-pair and 3-pair conditions (WM load Effect), $n = 31$ participants with aphasia. (original data)

Dependent Variable	Predictor Variables	Multiple R, Adjusted R^2	F and p value of ANOVA	t Statistic
Synonymy (Concrete and Abstract items)	Category Probe Span	$R = .390$, $R^2 = .123$	$F(1, 29) = 5.204$ $p = .030$	$t = -2.281$
Concrete items only	Category Probe Span	$R = .372$, $R^2 = .109$	$F(1, 29) = 4.663$ $p = .039$	$t = -2.159$
Abstract items only	No significant models obtained			
Rhyming	Pointing Digit Span	$R = .374$ $R^2 = .110$	$F(1, 29) = 4.772$ $p = .038$	$t = -2.173$

Table 6

Summary of Stepwise Regression Analyses: Three executive measures (reaction times on Simon Task-inhibition, Spatial N-back Task - working memory updating, Number-Letter Set-shifting Task) regressed on the difference in proportions correct on the 2-pair and 3-pair conditions (WM load Effect) n= 21 participants with aphasia. (original data)

Dependent variable	Predictor variables	Multiple R, Adjusted R ²	F and p value of ANOVA	t Statistic
Synonymy (Concrete and Abstract items)	Simon Task	R = .602, R ² = .329	F (1,19) = 10.810 p = .004	t = 3.288
Concrete items only	Simon Task	R = .423 R ² = .136	F (1,19) = 4.151 p = .056	t = 2.037
Abstract items only	Simon Task	R = .640, R ² = .379	F (1,19) = 13.198 p = .002	t = 3.633
Rhyming	Simon Task	R = .448, R ² = .159	F (1,19) = 4.773 p = .042	t = 2.185

Table 7

Summary of Regression Analyses: Two span measures (Category Probe Span, Pointing Digit Span) and one executive measure (Simon Task reaction times) regressed on the difference in proportions correct on the 2-choice and 3-choice conditions (WM load Effect), n = 21 participants with aphasia (original data).

Triplet Judgment Task	Multiple R, Adjusted R ²	F and p value of ANOVA	Category Probe Span (Semantic STM)		Digit Pointing Span (Phonological STM)		Simon Task (Inhibition)
					t	Statistic and p value	
Synonymy (Concrete and Abstract items)	R = .708 R ² = .543	F (3, 17) = 8.792 p = .001	t = -3.263 p = .005	t = .999 NS	t = 4.339 p = .000		
Concrete items only	R = .680 R ² = .367	F (3, 17) = 4.864 p = .013	t = -2.975 p = .028	t = .673 NS	f = 2.73 p = .010		
Abstract items only	R = .763, R ² = .508	F (3, 17) = 7.875 p = .002	t = -2.631 p = .018	t = 1.037 NS	t = 4.360 p = .000		
Rhyming	R = .558, R ² = .190	F (3, 17) = 2.567 p = .089	t = -1.084 NS	t = -.885 NS	t = 1.661 NS		

Table 8

Summary of Regression Analysis: Category Probe Span and difference score (reaction times) on Simon Task regressed on the difference between proportions correct on the 2-choice and 3-choice conditions (WM load Effect), $n = 21$ participants with aphasia. (original data)

Triplet Judgment Task	Multiple R, Adjusted R ²	F and p value of ANOVA	Category Probe Span (Semantic STM)	Simon Task (Inhibition)
			t Statistic and p value	
Synonymy (Concrete and Abstract items)	R = .765 R ² = .506	F (2, 18) = 7.290 p = .005	t = -3.106 p = .003	t = 4.422 p = .000
Concrete items only	R = .669 R ² = .448	F (2, 18) = 11.659 p = .001	t = -2.956 p = .008	t = 2.869 p = .010
Abstract items only	R = .745 R ² = .539	F (2, 18) = 11.228 p = .001	t = -2.423 p = .026	t = 4.414 p = .000
Rhyming	R = .529 R ² = .280	F (2, 18) = 3.501 p = .052	t = -1.441 p = .167	t = 2.425 p = .026