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Relations between Short-term Memory Deficits, Semantic Processing, and Executive Function

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Abstract

Background—Previous research has suggested separable short-term memory (STM) buffers for the maintenance of phonological and lexical-semantic information, as some patients with aphasia show better ability to retain semantic than phonological information and others show the reverse. Recently, researchers have proposed that deficits to the maintenance of semantic information in STM are related to executive control abilities.

Aims—The present study investigated the relationship of executive function abilities with semantic and phonological short-term memory (STM) and semantic processing in such patients, as some previous research has suggested that semantic STM deficits and semantic processing abilities are critically related to specific or general executive function deficits.

Method and Procedures—20 patients with aphasia and STM deficits were tested on measures of short-term retention, semantic processing, and both complex and simple executive function tasks.

Outcome and Results—In correlational analyses, we found no relation between semantic STM and performance on simple or complex executive function tasks. In contrast, phonological STM was related to executive function performance in tasks that had a verbal component, suggesting that performance in some executive function tasks depends on maintaining or rehearsing phonological codes. Although semantic STM was not related to executive function ability, performance on semantic processing tasks was related to executive function, perhaps due to similar executive task requirements in both semantic processing and executive function tasks.

Conclusions—Implications for treatment and interpretations of executive deficits are discussed.

One of the long-standing debates in the short-term memory (STM) literature concerns the cause of forgetting and whether it results from time-based decay or interference (e.g., McGeoch, 1932; see Jonides et al. (2007) for a recent review). Interestingly, data from patients with verbal STM deficits have suggested that the source of information loss may depend on the type of STM being assessed. The language-based model of STM of R. Martin and colleagues (R. Martin & He, 2004; R. Martin & Romani, 1994; R. Martin, Shelton, & Yaffee, 1994) has proposed two buffers for the retention of verbal material. The phonological buffer is involved in the maintenance of phonological information in STM, playing a role similar to the phonological loop proposed by Baddeley (e.g. Baddeley, 1986; Baddeley & Hitch, 1974). In contrast, the lexical-semantic buffer is involved in the maintenance of lexical-semantic information in STM (N. Martin & Saffran, 1997; R. Martin,

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Lesch & Bartha, 1999; R. Martin et al., 1994). This multiple capacities view of STM is supported by dissociable patterns of patient performance on STM tasks (R. Martin & He, 2004; R. Martin & Romani, 1994; R. Martin et al., 1994); patients with phonological STM deficits have difficulty maintaining phonological information, while patients with semantic STM deficits have difficulty maintaining lexical-semantic information. Although these patients generally have reduced STM spans (typically ranging from 1-3 items), they have relatively intact single word and semantic processing. Critically, the dissociation between retention of one type of information, but not another, cannot be easily explained by models that assume verbal STM processing occurs in a single phonological store (e.g., Baddeley, 1986).

Research has suggested that phonological STM deficits result from an overly rapid decay of phonological information (R. Martin et al., 1994; R. Martin & Lesch, 1996; N. Martin & Saffran, 1997). Although semantic STM deficits were initially thought to result from an overly rapid decay of semantic information (e.g. Freedman, R. Martin & Biegler, 2004; N. Martin & Saffran, 1997; R. Martin & Lesch, 1996), more recent research suggested that executive function (EF) deficits may be the source of semantic STM deficits, with failures in executive control causing excessive interference in semantic STM (Hamilton & R. Martin, 2005, 2007) or an inability to manipulate semantic representations in a task appropriate fashion (Hoffman, Jefferies, Ehsan, Hopper, & Lambon Ralph, 2009; cf. Barde, Schwartz, Chrysikou, & Thompson-Schill, 2010). Hamilton and R. Martin (2005, 2007) found that semantic STM patient ML demonstrated normal interference patterns on two nonverbal inhibition tasks (spatial Stroop, anti-saccade), but showed significantly exaggerated interference effects on two verbal inhibition tasks (standard Stroop, recent negatives probe task). In the recent negatives probe task, subjects are presented with a list of items and asked to judge whether a probe item was in the list. On some of the “no” trials, the probe appeared in an immediately preceding list. Standard findings with healthy subjects show longer reaction times and higher error rates in rejecting these recent negative probes than in rejecting probes that did not appear in a recent list. ML showed exaggerated interference in multiple versions of the recent negatives task, including a version with only letters, as well as a word version that manipulated the semantic and phonological relatedness of the probes to the list items (Hamilton & R. Martin, 2007). These exaggerated interference effects on verbal inhibition tasks were taken as evidence that ML’s STM deficits result from an abnormal persistence of previously relevant information, caused by a deficit to control processes acting on STM. Specifically, ML’s semantic STM deficits were hypothesized to be associated with failures of verbal inhibition, suggesting a critical role of executive control in semantic STM.

Relatedly, Hoffman et al. (2009) have suggested that semantic STM deficits stem from an impairment in the control processes utilized to manipulate semantic representations. This conclusion was derived from a case-series comparison of semantic STM patients and persons with comprehension-impaired stroke aphasia (SA). Previous research suggested that SA patients have intact amodal semantic knowledge, but show semantic impairments due to impaired executive control over semantic activations (Jefferies & Lambon Ralph, 2006); while this impairment does not affect semantic representations, it does affect the use of semantic information in a task-appropriate fashion. Specifically, SA patient performance on both verbal and nonverbal semantic tasks was found to depend on the control demands of the task: patients showed consistent performance on semantic tasks that made the same semantic control requirements, but inconsistent performance across tasks with varying semantic processing requirements. For example, while SA patients may have been able to successfully utilize semantic information for picture naming, they may have had more difficulty utilizing semantic knowledge on a test of semantic associations, which requires not only object recognition and identification, but also attention to relevant features of the target item. Additionally, the SA patients also showed impairments on several executive/attention tasks, and this impairment was correlated with semantic task performance.

Hoffman et al. (2009) compared these comprehension-impaired SA patients to two patients with semantic STM deficits, JB and ABU, by investigating the STM, semantic processing, and executive abilities of both groups. Similar to previous findings (Jefferies & Lambon Ralph, 2006), the SA patients showed impaired performance on various verbal and nonverbal semantic processing tests. The two semantic STM patients, on the other hand, performed well on verbal and non-verbal semantic tests, replicating previous research demonstrating that these patients have intact semantic processing abilities (e.g., R. Martin & He, 2004; R. Martin & Lesch, 1996). In contrast to their relatively intact performance on standard semantic tasks, however, the two semantic STM patients showed mild semantic impairments when performing tasks that required speeded judgments or high semantic control demands. For example, in a speeded synonym judgment task, the semantic STM patients had accuracy levels within the range of the mildly impaired SA patients, and response times significantly slower than controls. They also showed impairments (relative to controls) on verbal fluency and verb generation tasks. Critically, these semantic STM patients also showed mild impairments on tests of executive function and attention, though their impairments were milder than those of the SA patients.

Given the qualitative performance similarities between the two patient groups, Hoffman and colleagues (2009) concluded that executive control of semantic information is at the source of both patterns of patient impairment. Patients with semantic STM deficits are hypothesized to have a less severe form of the control deficit, relative to the SA patients, but the difference is one of degree. That is, the semantic control deficits shown by the semantic STM patients are of a milder form than the impairments shown by the SA patients, such that the two patient groups fall along a continuum of impairment. Mild control impairments result in impairments on tasks requiring maintenance and manipulation of several word meanings (semantic STM), as well as more difficult semantic tasks involving speeded judgments. More severe impairments in semantic control result in semantic deficits that are evident in semantic tasks assessed at the single-word level.

This model of an underlying severity continuum that connects two seemingly independent disorders was first introduced by N. Martin and colleagues (N. Martin, 2008; N. Martin & Ayala, 2004; N. Martin & Gupta, 2004; N. Martin, Saffran, & Dell, 1996;) as part of their account of STM deficits in aphasia. Before a role for executive function was considered as part of the verbal STM deficit in aphasia, some theorists postulated that verbal STM impairments could occur independently of verbal impairment in aphasia (e.g., Shallice, 1988). Early evidence for this model came from Warrington and Shallice’s (1969) seminal case study of patient KF, who demonstrated a verbal STM impairment with minimal language impairment. In contrast, N. Martin et al. (1996) demonstrated that changes (quantitative and qualitative) in both verbal STM span and word repetition abilities were associated in a single case (patient NC) over the course of his recovery from aphasia, suggesting that a single impairment was underlying each ability. Specifically, N. Martin et al. proposed activation decay as the source of both impairments. Consistent with this idea, his exaggerated rate of decay lessened during recovery and his STM span and word repetition abilities improved. In a larger group of individuals with aphasia (N = 46), N. Martin and Ayala (2004) demonstrated significant correlations between severity of language impairment (both phonological and lexical-semantic measures) and digit and word span (repetition and pointing response conditions), providing additional evidence for a single underlying impairment that yields a profile of aphasia plus verbal STM impairment (more severe) or a profile limited to verbal STM impairment (milder). As accounts for the STM deficit in aphasia expand to include executive functions (the control impairment proposed by

Hoffman and colleagues (2009), among others), it follows that the severity continuum model could apply to these abilities as well.

Accordingly, two separate research endeavors have converged on the hypothesis that semantic STM deficits are related to disorders in executive control. Hamilton and R. Martin (2005, 2007) suggested that semantic STM deficits are related to a deficit in a specific component of executive function (verbal inhibition), while Jefferies, Lambon Ralph and colleagues (Hoffman et al., 2009; Jefferies & Lambon Ralph, 2006) have suggested that semantic processing and semantic STM deficits fall along a continuum, both resulting from a deficit in the control processes that allow for the flexible use semantic representations. However, the nature of the executive/attentional tasks used by Jefferies and Lambon Ralph and Hoffman et al. should be noted. These tests included the Brixton test of spatial anticipation (Burgess & Shallice, 1996), the Elevator Counting subtests of the Test of Everyday Attention (Robertson, Ward, Ridgeway, & Nimmo-Smith, 1994), the Wisconsin Card Sorting Test (e.g., Milner, 1964; Stuss et al., 2000), and the Raven's Colored Progressive Matrices (Raven, 1962). With the exception of the Raven's test, which is considered a measure of fluid intelligence, the other tasks, while being standard tasks used to assess executive dysfunction, are considered "complex" as they involve a variety of cognitive processes. Although some of these processes are agreed to be executive processes (e.g., switching attention to relevant stimuli or rules, updating the contents of working memory), others are not (e.g., phonological retention and rehearsal). Consequently, this complexity makes poor performance difficult to interpret (Berman et al., 1995; Dunbar & Sussman, 1995). Furthermore, even within those aspects that might be considered part of executive control, there is evidence that inhibition, shifting, and updating are at least partially separable components of executive function (e.g., Lehto, 1996; Miyake et al., 2000). From the Hoffman study, then, one cannot draw conclusions about which aspect(s) of executive function may be the source of the correlation with semantic task performance and thus arguably critical to the control of semantic information.

In contrast to the previously mentioned accounts implicating executive control in semantic STM deficits, Barde and colleagues (Barde, Schwartz, & Thompson-Schill, 2006; Barde et al., 2010) found exaggerated interference effects in STM tasks for patients with *both* semantic STM deficits *and* phonological STM deficits, suggesting the exaggerated interference effects found by Hamilton and R. Martin (2005, 2007) may not be limited to patients with semantic STM deficits. Specifically, Barde et al. (2010) assessed semantic and phonological interference in probe tasks similar to the recent negatives task, discussed above. In their probe tasks, probes could be semantically or phonologically related to items in previous lists: on some trials, previous lists contained lure items – words that were either semantically or phonologically related to the current trial's probe word. Interestingly, patients with both types of STM deficits and healthy, age-matched adults demonstrated interference effects on both lure types. Critically, however, for the patients, the pattern of interference effects was predicted by their degree of STM deficit: "the magnitude of phonological interference effects was predicted by the extent of phonological STM deficit alone, while the magnitude of semantic interference effects was predicted by the extent of the semantic STM deficit alone" (Barde et al., 2010, p. 916).

To accommodate their findings, Barde et al. (2010) proposed the reactivation hypothesis. Importantly to the present discussion, this hypothesis does not draw on executive control mechanisms to explain STM deficits. According to the reactivation hypothesis, memory items do not persist over time to result in excessive interference in short-term memory, as predicted by an inhibition deficit. Instead, exaggerated interference arises from difficulty discriminating degraded representations of current list items and reactivated representations of prior list items. According to Barde and colleagues, both phonological and semantic STM deficits result from difficulty maintaining "lexical features in a state of temporary activation" (Barde et al., 2010, p. 918). Although temporary activation of current list items may not be strong, they assume that incremental learning occurs for each list item that is presented such that the lexical representations of these items are strengthened, increasing the likelihood that these representations will be retrieved or reactivated in the future. Thus, when a related probe is presented (whether semantically or phonologically related) in a subsequent list, it is likely that the lure word from the prior list will be reactivated, given the assumption of spreading activation to semantic and phonological neighbors. As a result, patients will have difficulty discriminating a match to the current list from a match to a previous lure. They argued that their hypothesis better accommodated their findings of a selective relation between phonological STM deficits and interference from phonologically but not semantically related lures, and the reverse for semantic STM deficits. In order for an inhibition deficit to accommodate these findings, one would have to assume that inhibition can be selectively impaired for semantic vs. phonological information. Thus, they argued that their approach provided a more parsimonious account.

Thus, while both Hamilton and R. Martin (2005, 2007) and Hoffman et al. (2009) have proposed a critical role for executive control as the source of semantic STM deficits, Barde et al. (2010) have taken a different approach, instead emphasizing traditional decay-based explanations for both types of STM deficits. Given these different hypotheses, a number of issues remain. First, Hamilton and R. Martin (2005, 2007) only tested a single patient with a semantic STM deficit; if inhibition is, in fact, important to semantic STM deficits, it is critical to show that this same inhibition deficit is manifested across a larger group of patients. The arguments of Barde and colleagues suggest that exaggerated interference effects will not necessarily be related to inhibition deficits. Second, the patient studied in Hamilton and R. Martin was only tested on one aspect of executive control (inhibition). If semantic STM deficits are associated with impairments to executive control in general, then testing of additional patients may reveal global executive control deficits (i.e., deficit to other aspects of executive control such as updating and task switching; Miyake et al., 2000), as proposed by Hoffman and colleagues (2009). Third, only Hoffman and colleagues have investigated the relationship between executive function and semantic processing ability; their theory predicts that more severe executive control impairments should be associated with semantic processing deficits, as executive control is important for the flexible manipulation of semantic representations. As a result, one might expect patients with severe executive control deficits to also show greater semantic processing deficits. The present study investigates this prediction with a large group of patients.

In summary, the nature of the executive impairment in semantic STM patients remains an open question and is investigated in the present study. The data from Hamilton and R. Martin predict a relationship between semantic STM and inhibition, though not necessarily with other aspects of executive control. The data from Hoffman and colleagues (2009) predict that all executive impairments should be related to both semantic STM and semantic processing. Conversely, the data from Barde et al. (2010) predict no necessary relationship between executive control and semantic STM. The predictions of these accounts are summarized in Table 1.[1]

Finally, only the Barde et al. (2010) study has extended their investigation to both patients with semantic and phonological STM deficits; both Hamilton and R. Martin (2005) and Hoffman et al. (2009) focused on patients with semantic STM deficits. As a result, little

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[1] It should be noted that neither the inhibition hypothesis of Hamilton and Martin (2005; 2007) nor the reactivation hypothesis of Barde et al. (2010) rule out a role for executive function in the performance of semantic processing tasks per se. However, neither approach necessitates that such relations be found.

research has investigated patients with phonological STM deficits to determine whether executive deficits are related to both semantic *and* phonological STM deficits, and prior work has come to mixed conclusions on this issue. Barde et al. found that patients with phonological STM deficits did show exaggerated interference effects, though they argued these were not due to an inhibition deficit. On the other hand, other work has proposed a causal relation in the other direction. That is, instead of proposing that deficits in aspects of executive functioning cause deficits in phonological retention, researchers have argued that phonological retention and rehearsal play a supportive role in various aspects of executive function, and this supportive role may be revealed depending on the memory demands of the EF task (Baldo et al., 2005; Baldo, Bunge, Wilson, & Dronkers, 2010; Dunbar & Sussman, 1995; Lehto, 1996). In summary, if phonological STM deficits derive from overly rapid decay of phonological information as has been argued by various researchers (Barde et al., 2010; R. Martin et al., 1999), we would predict no necessary relation between phonological STM deficits and EF deficits, at least to the extent that the EF tasks do not rely on phonological retention and rehearsal (e.g., as for Stroop task). Some relation between phonological STM deficits and performance on EF tasks might be observed, however, for tasks in which verbal codes are involved and the task draws on memory resources (e.g., as for updating tasks and complex verbal EF tasks).

The present study includes patient data on a variety of tasks, including screening assessments, STM measures, semantic tasks, complex executive function tasks, and simple executive function tasks, which tap more basic components of executive function such as inhibition, updating, and shifting (Miyake et al., 2000); each category of tasks is motivated and discussed in turn, below (see Table 2 for a summary of the tasks included). This battery of tasks allows us to assess the relationship between STM, semantic processing, and executive function abilities in a large group of patients to better examine the remaining questions elucidated above. Specifically, the present study investigates the different predictions of the various accounts, addressing whether deficits in inhibition and other components of executive function are related to a) semantic, but not phonological, STM deficits and b) semantic processing abilities in a large group of patients with aphasia. The relationship between executive ability and STM retention is examined with correlational analyses, using a variety of executive function tasks; unlike previous patient studies, the present study includes both complex executive tasks and tasks tapping more basic components of executive control.

Method

The present study investigated the STM, semantic, and executive function abilities of 20 patients with aphasia to explore the relationship between measures of these abilities. All patients were right-handed, Native English speakers, had no history of psychiatric illness, and were diagnosed as persons with aphasia as per referring speech-language pathologists on the basis of standardized aphasia tests such as the Western Aphasia Battery (Kertesz, 1982) and the Boston Diagnostic Aphasia Exam (Goodglass & Kaplan, 1972). With the exception of one patient (TUBC2), all patients experienced aphasia secondary to stroke. Additionally, at testing, all patients were in the chronic phase, at least 12 months post brain damage (Table 3). Patients were selected on the basis of relatively intact speech perception, but reduced short-term memory capacities. Speech perception abilities were measured by single-word processing tasks, including a single picture-word matching and auditory discrimination (described in detail below); all patients performed above 80% correct on the speech perception test and above 85% correct on the picture-word matching task, with all patients performing at 90% correct or above on at least one of the two measures (see Table 3). Semantic and phonological retention were assessed via two probe recognition tasks – the category probe and rhyme probe task (described in detail below). These two measures have been used in several studies in various labs (e.g., Barde et al., 2010; Wong & Law, 2008; Hoffman et al., 2009; R. Martin et al., 1994; R. Martin & He, 2004) and have been found to relate in plausible ways to phonological and semantic aspects of short-term retention (Barde et al, 2010). Rather than classifying patients as having either a semantic or phonological STM deficit, their performance on these two continuous measures was used to reflect the degree to which either or both of these capacities might be affected (e.g., Barde et al., 2010). That is, semantic and phonological patients do not have an all-or-none deficit – instead, patients have different degrees of STM deficits. In order to improve the reliability of the STM measures, we also tested the patients on three other STM tasks in order to develop composite measures that would tap phonological and semantic retention capacities. The variation in patient STM performance allowed us to investigate the relationships between degree of semantic and phonological STM deficit and executive function abilities. Patient background information including age at testing, years post-brain damage, education, lesion location, and single word processing ability are shown in Table 3. All patients were tested in multiple sessions lasting from 1 to 1.5 hrs, typically with at least one week separating sessions. Language, STM, and semantic processing tasks took approximately two months to complete and were administered prior to the EF tests. Once EF testing was started, it was completed within two to six sessions (depending on the number of tasks the patient could complete) over the course of approximately three months. Where possible, EF tasks were completed in the same order.

Screening Assessments

Patients were selected on the basis of intact single word processing and speech perception to rule out both factors as potential causes of patient STM deficits. Single word processing was assessed with a single picture-word matching task and speech perception was assessed with an auditory discrimination task.

Single picture-word matching (PWM)—In the picture-word matching task patients saw a picture and were asked, “Is this a ____?” (shortened 54-item version of that used in R. Martin et al., 1999). Patients indicated whether a spoken word matched the presented picture by saying ‘yes’ (the word and picture do match) or ‘no’ (the word and picture do not match). This task contained four conditions, representing the relationship between the word and the picture: a correct condition (word and picture were the same, e.g., cat, cat), a semantically related condition (cat, dog), a phonologically related condition (cat, hat), and an unrelated condition (cat, table). The dependent variable was mean accuracy across all trials.

Auditory discrimination—In the auditory discrimination task, patients indicated whether pairs of auditory stimuli were the same or different (N. Martin, Schwartz & Kohen, 2006). Of the 40 items, half were pairs of words (e.g., road-road; road-rope) and half were pairs of nonwords (/mErd/-/mErd/; /mErd/-/mErg/). Items included in the non-matching pairs differed by one phoneme. The dependent variable was mean accuracy across trials.

Short-term Memory Measures

In addition to the category and rhyme probe tasks mentioned earlier, two standard memory span tasks (digit span and word span) were also administered to allow performance on these measures to be combined with rhyme and category probe performance. These tasks required list output, consequently tapping output phonological and articulatory abilities in addition to any input phonological and semantic STM abilities. As digits have relatively little meaning in isolation, one might assume phonological retention would be most critical for performance on this task. In contrast, semantic STM might play more of a role for the word span task. A synonymy judgment task was also used as a measure of semantic STM.

Word span—The word span task used lists drawn from a closed set of ten items, with the lists presented in a fixed order (R. Martin et al., 1999). All items were one syllable, three-letter words presented at an approximate rate of one word per second (for multi-item list lengths); each list length contained ten lists. Items were presented aurally, starting with single-item lists, anditems were repeated in serial order. Testing continued until lists correct accuracy dropped below 50% on a given list length. Span was calculated by using linear interpolation to find the list length at which patients would score 50% correct.

Digit span—Digit span was assessed with the forward digit span task from the WAIS-R (Wechsler, 1981); lists were composed of digits (0-9) presented aurally at an approximate rate of one digit per second. Patients recalled the lists in serial order. Testing started at two-item lists, and each list length contained two trials. Testing continued until patients failed both trials at a given list length. Span was calculated based on the last list length at which patients maintained correct recall; if they were correct on both those trials, their span was a whole number (e.g., 3, given they passed both trials at list length three but failed both trials at list length four); if they failed one of those trials, their span was a decimal (e.g., 2.5, given they passed one trial at list length three, but failed both trials at list length four).

Category and rhyme probe tasks—The category and rhyme probe tasks measured the short-term retention of semantic and phonological information, respectively (R. Martin et al., 1994). Testing began at one-item lists and continued until patients scored less than 75% correct on a given list length. Each list length contained between 20 and 28 lists, half of which were yes trials. Items in the category probe task came from 10 different categories, with each category containing 24 items. All categories and category members were presented before the start of the task to familiarize patients with each item’s correct category classification. For both tasks, patients heard a list of words followed by a probe word. Patients pressed yes if the probe item was in the same category as any items in the most recently presented list, or no if the probe item was not in the same category as any of the list items. In the rhyme probe task, patients pressed yes if the probe word rhymed with any items in the most recently presented list, or no if there was no rhyme. For both tasks, span was calculated by using linear interpolation to find the list length at which patients would score 75% correct.

Synonymy judgment—Patients indicated which two of three visually presented words were synonyms by pointing to the correct pair (N. Martin et al., 2006). Across the 48 items, all words were nouns; half of the word sets consisted of all concrete words, and half consisted of all abstract words. The dependent variable was percent correct across all trials.

Semantic Tasks

As previously discussed, Hoffman and colleagues (2009) claim that semantic impairments for stroke patients, including both semantic STM deficits and semantic processing deficits, derive from executive control deficits; such control deficits impair the ability to use semantic information in a task-appropriate manner. The present study included semantic tasks to investigate whether their findings could be replicated, and if so, determine whether the nature of the control deficits could be better specified.

Picture naming task (PNT)—Patients named a 30-item subset (Walker & Schwartz, 2008) of individually presented pictures from the Philadelphia Picture Naming Test (Roach, Schwartz, N. Martin, Grewal & Brecher, 1996). Short-form items are matched in lexical property distributions of the full, 175-item PNT. The dependent variable was proportion correct, using patients’ first response.

Single picture-word matching (PWM)—Task description was detailed under Screening Assessments. For the present purposes, this task served as both a screening measure for single-word processing ability, as well as a measure of semantic knowledge.

Peabody Picture Vocabulary Test-R (PPVT, Form-L)—The Peabody Picture Vocabulary Test-Revised (Dunn & Dunn, 1981) is a standardized word-to-picture matching test that assesses vocabulary. Patients heard a spoken word and chose the correct corresponding picture from one of four pictured alternatives. As per standard administration, testing was continued until six errors were made over eight consecutive trials. Standard scores were estimated based on normed data for forty-year old adults.

Pyramids and Palm Trees (PRYPT)—Pyramids and Palm Trees (Howard & Patterson, 1992) is a published test of semantic knowledge; in the picture subtest (used here), three pictures are displayed in a match-to-sample format. Patients pointed to the single picture deemed to be associated with the sample; there were 52 items. The dependent variable was percent correct. In contrast to the other semantic processing measures, the PRYPRT does not involve verbal processing. The claims of Jefferies and Lambon Ralph (2006) and Hoffman et al. (2009) about control deficits concern the processing of amodal semantic representations and thus executive function deficits should result in poor performance on both verbal and nonverbal semantic tasks.[2]

Complex Executive Function Tasks

To measure executive function abilities, patients performed both complex and simple executive function tasks. Complex executive tasks, such as the Wisconsin Card Sorting Task (Heaton, Chelune, Talley, Kay, & Curtiss, 1993) and the Tower of Hanoi (Simon, 1975), have traditionally been used to access frontal lobe function in patients thought to have dysexecutive syndrome (e.g., Baddeley & Wilson, 1988). As previously mentioned, complex tasks may tap more than one executive function and may also make demands on STM and language abilities (e.g., Baddeley, 1996; Baldo et al., 2005; Baldo et al., 2010; Handley, Capon, Copp, & Harper, 2002; Miyake et al., 2000). Hoffman et al. (2009) used a variety of complex tasks, including executive/attention tasks and a non-verbal intelligence task to assess the executive ability of their two patients with semantic STM deficits. The present study included two traditional complex executive tasks in order to provide a comparison with the findings of Hoffman and colleagues.

Wisconsin Card Sorting Task (WCST)—Patients performed a computerized version of the Wisconsin Card Sorting Task (Heaton et al., 1993; adapted from Miyake et al., 2000). In this task, patients sorted a target card into categorized piles according to different sorting rules. A single target card, which changed on every trial, was displayed below four piles (Figure 1, top). To sort a target card, patients moved the mouse and clicked on the pile into which they wanted to place the target card. Target cards were sorted according to three criteria: shape (circle, square, star, or cross), number (1, 2, 3, or 4), or color (red, blue, yellow, or green). The correct sorting criterion was determined by placing a card onto a pile and receiving feedback: the words “RIGHT” or “WRONG” appeared below the most recently sorted card to indicate whether the target was correctly sorted. If correct, patients continued sorting by that category (shape, color, or number) until they made an error. The sorting criterion changed after patients correctly sorted eight consecutive target cards. The

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[2] Although the synonymy judgments and PYRPT test are similar in requiring processing the relations among three items, the synonymy triples had greater STM demands because subjects had to determine which of the three items were most related and thus had to consider three possible pairs of relations. In contrast, in the PYRPT task, subjects only had to consider two relations – that between the sample and the two possible choices.

task continued until either 15 categories were correctly completed, or a total of 288 cards were sorted; there was no time limit. Patients first performed practice trials with experimenter instruction and feedback. The dependent variables were the number of categories completed (out of 15 possible) and the total number of perseverative errors. Perseverative errors were defined as the continued sorting by a category that was no longer correct.

Tower of Hanoi (TOH)—Patients performed a computerized version of the Tower of Hanoi task (Simon, 1975; adapted from Miyake et al., 2000). In this task, patients saw three pegs and four disks of consecutive sizes (Figure 1, bottom). Patients saw the initial disk state on the computer screen and the goal state of the disks on a piece of paper. Their task was to move the disks from the initial state to the goal state in as few moves as possible by clicking on a disk and dragging it to a different peg while abiding by three rules. First, disks could only be moved one at a time. Second, disks always had to be moved onto pegs (as opposed to being left in mid-air). Third, larger disks could not be placed on top of smaller disks. These rules required some counterintuitive moves, such as temporarily moving a disk away from its final target location. Patients first performed two practice trials, each of which involved arranging three disks. After practice, patients performed four critical trials, each with four disks to arrange. There was no time limit. The dependent variable was the total number of moves taken to reach the goal state across the four trials.

Simple Executive Function Tasks

While the complex tasks tap a variety of cognitive processes, simple executive tasks are argued to measure primarily a single component of executive control (Miyake et al., 2000). Thus, performance on simple executive function tasks should provide information on the nature of global executive impairments, and any relation this impairment may have with STM and semantic processing. Also, whereas some patients may be unable to perform or have great difficulty with complex executive tasks, most patients were able to complete at least some of the simple executive tasks. In the present study, we included measures of the inhibition, updating, and shifting components of executive function, similar to Miyake et al. (2000). Where indicated below, some patients received shortened versions of the simple executive function tasks due to time constraints associated with off-site testing.

Inhibition Tasks

Verbal Stroop task—In the verbal Stroop task (Stroop, 1935; adapted from Miyake et al., 2000), patients saw a series of words (RED, GREEN, BLUE, PURPLE, ORANGE, or YELLOW) or strings of asterisks in the center of the screen. The words or asterisks were presented in the color red, green, blue, purple, orange, or yellow. Patients named the color of the string as quickly as possible while ignoring the string's written text. Items appeared in one of three conditions: incongruent (word RED in blue ink, 42% of trials), congruent (word RED in red ink, 8% of trials), and neutral (string of asterisks in blue ink, 50% of trials). The standard version of this task contained 154 items; the shortened version contained 76 items. Patients completed practice trials and voice key calibration for recording response times (RTs; in milliseconds). The experimenter recorded errors and responses were recorded digitally. The dependent variable was the log-transformed Stroop interference effect, measured as the difference between incongruent and neutral trials in RTs.

Spatial Stroop task—The spatial Stroop task (Hamilton & R. Martin, 2005; similar to Clark & Brownell, 1975) was used as a nonverbal analogue of the original Stroop task (Stroop, 1935). Patients saw a left- or right-pointing arrow on the left, center, or right side of the computer screen. Patients pressed a button according to the direction the arrow was pointing while ignoring the arrow's location. Similar to the standard Stroop task, trials were incongruent, congruent, or neutral. On incongruent trials, the direction of the arrow did not match the arrow's location (right-facing arrow on the left side of the screen). On congruent trials, the direction of the arrow matched the arrow's location (right-facing arrow on the right side of the screen). On the neutral trials, the arrow was displayed in the center of the screen. Patients completed practice trials to acquaint themselves with the correct buttons; following practice, all patients completed 240 trials. The dependent variable was the RT interference effect, measured as the difference between the incongruent and neutral trials.

Picture-word interference task (PWI)—In the picture-word interference task (e.g., Lupker, 1979; Schriefers, Meyer & Levelt, 2002), patients saw a picture with a super-imposed word in the center of the computer screen. Half of the picture/word pairs were related (i.e., from the same category) and half were unrelated; all distractor words were items not pictured for naming. Prior to beginning the PWI task, patients were exposed to the pictures in two practice trials. They first named the picture while seeing both the picture and the correct name; they then practiced naming the same pictures without the correct name. For non-practice trials, patients were instructed to ignore the super-imposed word and name the picture as quickly as possible. Pictures were presented in two blocks (90 items/block), and each picture was seen in both related and unrelated conditions. The proportional interference effect, measured as the RT difference between related and unrelated trials divided by the unrelated RT, served as the dependent variable.

Recent negatives probe task—In the recent negatives probe task (e.g., Monsell, 1978), patients heard a list of words followed by a probe word and indicated whether the probe word was in the previous list; all patients completed 96 items. On positive trials, the probe word was presented in the most recently presented list (list n). On recent negative trials, the probe word was not presented as an item in the most recent list (list n), but in the previous trial (list n-1). On non-recent negative trials, the probe word was not presented as an item in the most recent list (list n), nor in any of the previous five lists. It takes more time to reject a recent negative, relative to a non-recent negative, suggesting proactive interference from more recently presented information (D'Esposito, Postle, Jonides & Smith, 1999; Jonides, Smith, Marshuetz, Koeppe & Reuter-Lorenz, 1998). The dependent variable was the difference between two sensitivity (d') measures: one for the sensitivity for correctly rejecting non-recent negative items (calculated using performance on positive and non-recent negative trials) and one for the sensitivity for correctly rejecting recent negative items (calculated using performance on positive and recent negative trials). Using the difference in sensitivity between the two trial types allowed us to account for overall performance on all trial types.

Updating Tasks

Verbal and nonverbal 1-back tasks—The verbal 1-back task (Hull, Martin, Beier, Lane, & Hamilton, 2008) required patients to continually monitor a stream of individually presented letters. Similarly, the nonverbal 1-back task required patients to continually monitor a stream of individually presented tones. Patients pressed the spacebar when the stimulus of the current trial was exactly the same as the stimulus of the immediately previous trial (i.e., the trial 1-back). In both tasks, practice trials preceded experimental trials; all patients completed 60 items/task. Additionally, before beginning the nonverbal task, patients were exposed to the five tones used in this task. The dependent variable was percent correct, calculated as the sum of the proportion of misses and false positives. While performance on 2-back versions of these tasks was attempted, many patients performed at floor on these tasks and thus testing was discontinued.

Verbal and nonverbal keep-track tasks—In the verbal keep-track task (Hull et al., 2008), patients were first shown six categories (animals, colors, countries, distances, metals, relatives) and four familiar exemplars from each category, being told they should be able to identify the category to which an item belongs. In the verbal keep-track task, patients saw a target category that remained on the screen for the duration of the trial. Presented below the visually presented category were 16 individually presented items from the previously specified categories. Patients remembered the last item from the target category, requiring that the contents of working memory be modified each time a new item in the target category was presented. In the nonverbal keep-track task, patients saw four quadrants (one quadrant in each corner of the computer screen). Patients saw a target color patch and their goal was to keep track of the last location in which that target color appeared. Over the course of one trial, 16 individually presented color patches (either red, blue, yellow, or green) appeared serially in different quadrants. For both the verbal and nonverbal keep track tasks, patients were given several practice trials with feedback. The standard version contained 40 items; the shortened version contained 20 items. The dependent variable was percent correct. Trials on which subjects had to retain the identity of the last member of two separate categories or the last location of two different colors were also attempted. However, as with the 2-back tasks, patient performance was very poor on the more difficult tasks and data from those tasks were not analyzed further.

Shifting Tasks

Plus-minus task—The plus-minus task (Jersild, 1927; Hull et al., 2008) was a paper and pencil task that consisted of three blocks. In each block, 30 two-digit numbers were presented in a column. In the first block, patients added 1 to each two-digit number. In the second block, patients subtracted 1 from each two-digit number. In the third block, subjects alternated between adding and subtracting 1 from each two-digit number. Practice trials were administered for each block, and the experimenter used a stopwatch to record the time (in seconds) taken to complete each block. The dependent variable was the switch cost, measured by subtracting the mean (RT) on the single task blocks from the total time for the alternating block.

Cued shifting—In the cued shifting task (e.g., Jersild, 1927; Rogers & Monsell, 1995), patients completed one of two tasks: in the “Life” task, patients judged whether the referent of a word was living (e.g., elephant) or non-living (e.g., spoon); in the “Size” task, patients judged whether the referent of a word was small (e.g., spoon) or large (e.g., elephant). On each trial, a cue indicating which of the two tasks should be performed was presented in black font 650 ms prior to target onset; following this 650 ms cue-stimulus interval, the target was presented in red font. This was a computerized task consisting of three blocks. In pure blocks, patients performed a single task based on the cued category (either “Life” or “Size”). In the mixed block, patients alternated between performing the “Life” and “Size” tasks using an alternating runs paradigm (e.g., AAAABBBBAAAA; Rogers & Monsell, 1995). In the standard version, each patient completed three sets, with each set containing two pure blocks and one mixed block; each set used a different cue-stimulus interval. For this version, only data from the 650 ms cue-stimulus interval was used; pure blocks contained 64 items and the mixed block contained 128 items. In the shortened version, patients received only one set (2 pure blocks, 1 mixed block at the 650 ms cue-stimulus interval); each pure block contained 84 items and the mixed block contained 152 items. Global switch costs (Jersild, 1927) served as the dependent variable, and were calculated by subtracting the mean RT for the two single task blocks from the mean RT for the mixed task block. Global switch costs are argued to measure the manipulation of multiple tasks in working memory.

Results

Patient Performance on STM and Semantic Tasks

The category probe, synonymy judgments, and word span tasks were hypothesized to measure semantic retention, while the rhyme probe and digit span tasks were hypothesized to measure phonological retention. Accuracy on the PNT, PWM, and PRYPT tasks and standard score on the Peabody Picture Vocabulary Test were used as measures of semantic processing. Patient performance on the STM and semantic tasks is shown in Table 4.

As indicated in Table 4, patients showed a wide range of performance on both STM and semantic tasks. As an example, category probe spans range from 1.67 to 5 items, while rhyme probe spans range from 1.31 items to 6.97 items, indicating large individual variability in short-term retention, as well as varying degrees of semantic and phonological retention deficits. As can be seen by comparing the category and rhyme probe spans of various patients, some patients have reduced semantic *and* phonological STM spans, while others show more clear semantic or phonological retention deficits. For example, patient SH has a category span of 3 items and a rhyme probe span of 2 items, suggesting an impairment in both semantic and phonological retention (relative to normal). In contrast, patient TUHN8 has a category probe span of 2.93 items, but a much larger rhyme probe span, 6.97 items. Patients also showed various degrees of impairment on semantic processing tasks. Critically, this variability in STM and semantic ability enabled us to investigate executive skill as it relates to a continuum of STM and semantic impairments.

Correlations Between STM Measures and Semantic Processing Measures

We used a correlational analysis (using Pearson product-moment correlations) to investigate the relationship between STM and executive function, as well as semantic assessments and executive function. Prior to doing so, we reduced the data by combining tasks tapping a single process into composite measures. These composite scores should have greater reliability and validity in tapping the underlying mental construct than measures derived from a single task (Nunnally & Bernstein, 1994; Wainer, 1976).

Correlations among STM measures—We first investigated the relationships among the five STM measures. Of particular interest were the correlations between tasks hypothesized to tap semantic retention (category probe, synonymy judgments, word span) and tasks hypothesized to tap phonological retention (rhyme probe, digit span). As would be expected of measures proposed to tap separate STM buffers, Barde and colleagues (2010) found a low correlation between category and rhyme probe performance in their sample of 20 patients with aphasia. Additionally, the two probe measures correlated in theoretically predicted ways with phonological similarity effects and lexicality effects in STM. In the present analyses, we looked at the pairwise correlations of category and rhyme probe with each of the other STM measures (Table 5).

As shown in Table 5, the correlation between the category and rhyme probe tasks was small and non-significant. Given these tasks have similar design, memory, and response requirements, it can be hypothesized that the lack of correlation between these two tasks represents a difference in processing requirements – specifically the retention of semantic vs. phonological information. The category probe task, which is hypothesized to measure semantic retention, was not significantly correlated with any of the other STM measures, though the correlation with synonymy triples was marginal ($p = .10$). In contrast, the rhyme probe task, which is hypothesized to assess phonological retention, correlated significantly with both the digit span task (as predicted) and the word span task. The correlation between the rhyme probe and word span task was not predicted, but may result from the materials used in this task. That is, this task utilized a closed set of ten, one-syllable, three-letter words. The repetition of these words and the need to recall them in order may have encouraged patients to rely on phonological retention (similar to digits, for example), as opposed to utilizing the semantic features inherent in words.

We also carried out multiple regressions in which single STM measures were regressed on both category and rhyme probe to determine the independent contribution of each measure while controlling for the other; predictors were entered into the model simultaneously. The multiple regression results are shown in Table 6. As can be seen in the table, synonymy judgment was significantly predicted by a combination of the category and rhyme probe measures with a significant positive contribution of category probe and a significant negative contribution of rhyme probe, suggesting the rhyme probe measure is acting like a suppressor variable. When the contribution of phonological storage to performance on the synonymy judgments task is statistically factored out, the relation between category probe and synonymy triples increases and becomes significant. (Equivalently, the partial correlation between synonymy triples and category probe with rhyme probe partialled out is .50 (p =.03), which is greater than the pairwise correlation of synonymy triples and category probe (r = .38, p =.10.) For both the digit and word span measures, only the regression weights for rhyme probe were significant. Thus, there was no independent contribution of category probe to either digit span or word span.

The results of these correlational and regression results suggest that we have two STM measures tapping semantic retention (category probe and synonymy judgment) and three STM tasks tapping phonological retention (rhyme probe, word span, digit span). In order to reduce the data, we computed two composite scores: a semantic STM composite consisting of the category probe and synonymy triples measures[3] and a phonological STM composite consisting of the rhyme probe, word span, and digit span measures. To compute these composites, z-scores for each of the measures were calculated; these z-scores were then averaged across the variables going into the composite. The correlation between the semantic and phonological STM composites was near zero (r = .007). For the remainder of the paper, these composites will be used to relate to performance on semantic tasks and executive function.

Relations among semantic measures and their correlation with STM measures

—We investigated the relationships between the four semantic processing measures, anticipating that all would be at least moderately correlated with each other (Table 7). This proved not to be the case. While the PPVT and PYRPT tests were highly correlated and the PNT and PWM were highly correlated, correlations between the variables across these two sets failed to reach significance. The lack of correlations across these two sets indicates that there are dimensions across which the two sets differ. The PNT and PWM could be argued to have an important phonological component, as the PNT requires producing a name, and some of the trials on the PWM task involved phonologically related distractors. In contrast, neither the PYRPT or the PPVT tasks require retrieval of phonological representations for production, nor do phonologically related distractors appear in these tasks. Moreover, both the PPVT and PYRPT make greater demands on both working memory and reasoning. For the PPVT, many of the more difficult items are abstract words or adjectives, with the choice of the correct picture requiring some degree of inference (e.g., selecting which of four action pictures represents the word “laminated”) rather than straightforward object-name matching as in the PWM task. Similarly, for the PYRPT task, it is necessary to determine the

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[3] Instead of using the synonymy triples measure, one might instead use the residuals in this measure after factoring out the contribution of rhyme probe. However, the correlation between a composite using the synonymy triples directly and one using the residuals was very high (r = .98). Thus, using the synonymy triples directly was employed as it is more straightforward to explain and compute.

appropriate relation for judging which of two pictures is more related to the target picture (e.g., selecting a “canoe” over a “rowboat” picture as related to the target picture “Eskimo”).

Because of the pattern of correlations, two separate semantic composites were calculated – one combining the z-scores for the PNT and PWM and the other combining the z-scores for the PPVT and PYRPT. We assessed the correlation between these composites and the phonological and semantic STM composites. In line with our reasoning above, we found that the first composite (PNT + PWM) correlated highly with the phonological STM composite ($r = .64$, $p = .003$) but not with the semantic STM composite ($r = -.03$, $p = .91$). The reverse was found for the second composite (PPVT + PYRPT), as the correlation with the phonological STM composite was non-significant ($r = .14$, $p = .58$) whereas the correlation with the semantic STM composite was high and significant ($r = .60$, $p =.001$). Because the claims of Hoffman and colleagues (2009) relate to amodal semantic processing rather than access to lexical or phonological representations from semantics, we decided to use only the second semantic composite involving the PPVT and PPYRT as our measure of semantic processing ability.

Relations between STM and Semantic Processing and Complex Executive Function Tasks

Patient performance on the EF tasks is shown in Table 8, including patient means and ranges for each task; additionally, means and ranges for healthy older adult subjects are included for reference. Using the EF data, we next investigated the relationship of STM and semantic processing with complex executive tasks. That is, if semantic STM and semantic processing deficits result from a deficit in semantic control, as proposed by Hoffman et al. (2009), we would predict that semantic STM and semantic processing measures would be significantly correlated with performance on complex EF tasks. The correlations are shown in Table 9. Also indicated in Table 9 is the number of patients included in the correlations involving the complex EF tasks; for these tasks, the N included is less than the total number of patients because many patients were simply unable to complete these tasks.[4]

As can be seen in Table 9, performance on the semantic STM composite did not correlate significantly with any of the global executive function measures, with two of three correlations being close to zero and the third going in a direction opposite that predicted. However, performance on the semantic processing composite correlated significantly or marginally so with each of the global executive function measures. (Although two of these three measures of executive function were of only marginal significance, the combined probability of the null hypothesis assuming independence of the measures is .01 ($\chi^2(6) = 16.93$; Winer, 1971) given the three observed probabilities.) The failure to find a relation between the executive function measures with the semantic STM composite goes against the claims of Hoffman et al. (2009), as performance on semantic STM tasks was attributed to semantic control abilities – which is presumed to be related to executive function ability. On the other hand, the relation between semantic processing per se and the complex EF measures is in line with their hypothesis. One might then ask what aspect of executive control would be in common across the two complex EF task and the two semantic processing tasks that go into the semantic processing composite. One might hypothesize that general reasoning abilities are required in all of these tasks. This issue will be addressed in the next section by considering the relation between semantic processing and the simple EF tasks for which reasoning ability is less critical.

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[4] Because of the inability of some patients to complete complex EF tasks, we also examined complex EF task correlations with missing values filled in with estimates of performance at the extremes of the scales. For the number of categories sorted in the WCST, we assigned 1 to the missing values; similarly, for the TOH, we assigned a maximum value for the number of moves. Filling in these missing values did not alter the pattern of correlations from that reported above, with the exception that the correlation between the TOH and STM measures was closer to zero.

The only other significant correlation in Table 9 was that between the phonological STM composite and the WCST categories measure. The significant correlation between phonological STM and the WCST is consistent with previous findings from Baldo et al. (2005) and Dunbar and Sussman (1995) suggesting a role for verbal abilities in the WCST. Consistent with the arguments of these authors, we conclude that phonological STM contributes to successful task performance – for instance, aiding in keeping in mind the names of the dimensions along which matching is carried out. The fact that the correlation between phonological STM and the TOH and the correlation between the semantic STM composite and the WCST were smaller and non-significant are consistent with the notion that there is specifically a phonological storage component to the WCST.

Relations between STM and Semantic Processing and Simple Executive Function Tasks

Although relations with the two complex EF tasks were not consistent with general executive function deficits causing semantic STM deficits, it is possible that such relations might be observed for more specific components of executive function.

Patient performance on the simple EF tasks is shown in Table 8; intercorrelations among all of these tasks are shown in the Appendix. As can be seen in the Appendix, the updating measures all correlated with each other at fairly high levels with the exception of one correlation between the nonverbal keep track and the nonverbal 1-back tasks. Thus, all four updating measures were combined into a single updating composite by combining the z-scores for the four measures. The inhibition measures showed moderate intercorrelations with the exception of the verbal Stroop effect. In fact, the correlation between the verbal and nonverbal Stroop measures actually went in the wrong direction. As discussed elsewhere (R. Martin & Allen, 2008), the standard Stroop measure may not be a very useful measure of inhibition for patients with aphasia, given that these patients often have difficulty with color naming. Thus, the inhibition composite was calculated by combining the z-scores for the nonverbal Stroop, picture-word interference, and recent negatives task. The two shifting measures showed only a modest correlation with each other.[5] Thus, those two were not combined.

Table 10 shows the correlations between simple EF measures and measures of STM, semantic processing, and complex EF. In considering these correlations, the number of correlations and the small sample size should be taken into account in evaluating the strength of the findings. Clearly, further studies would be needed to ensure that the patterns of correlations reported here could be replicated. Nonetheless, it is the case that the findings across the global EF (Tables 9) and simple EF tasks (Table 10) point to similar conclusions, as elaborated below. As indicated in Table 10, the inhibition composite did not correlate significantly with either the phonological or semantic STM measures or the semantic processing measure. It did correlate marginally, however, with the number of perseverations in the WCST. Such a correlation is interesting because a failure to inhibit prior response selection (i.e., previously relevant categories) could plausibly lead to increased perseverations. The updating composite correlated with the phonological but not the semantic STM measure, which is consistent with the notion that subjects used a rehearsal strategy to maintain information during the updating tasks. If the updating measures represented a general ability to update all types of information in working memory, a correlation between updating and the semantic composite should have been obtained as well. Updating also correlated with the performance on the WCST and the TOH, similar to the findings obtained by Hull et al. (2008) for a large group of healthy older subjects. The plus-

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[5] The plus-minus task also failed to correlate with other shifting measures in a large executive function study of older adults (Hull et al., 2008).

minus task measure of global switch costs failed to correlate with any of the measures. The cued shifting measure, in contrast, was marginally correlated with WCST perseverations and significantly correlated with performance on the Tower of Hanoi. The relation to perseverations makes intuitive sense, as perseverative errors could result from both a failure to switch and a failure to inhibit. The relation to the TOH is less transparent, but it is possible that shifting ability is related to the ability to make counterintuitive moves away from the goal-state, which is required for solution of the puzzles (Bull, Espy, & Senn, 2004; Sorel & Pennequin, 2008).

Overall, the pattern of correlations between the simple executive function measures and the STM measures were in line with those found for the global EF measures: phonological STM, which was related to the WCST categories measure, was also correlated with the updating measure. Further, the updating measure was significantly correlated with the WCST. This suggests that both WCST performance and updating abilities rely to some extent on the retention of phonological information in STM. In contrast, the semantic STM composite did not correlate significantly with any of the simple or complex EF measures, contrary to the prior suggestions of Hamilton and R. Martin (2005, 2007) and Hoffman et al. (2009). Thus, a causal role for executive control or specifically inhibition in the capacity for short-term semantic retention can be ruled out. The findings could be accommodated, however, by the approach of Barde et al. (2010), which does not assume a role for executive function in semantic STM deficits. Interestingly, the semantic processing composite correlated significantly with all three of the complex EF measures, but did not correlate significantly with any of the simple EF measures. However, some of the correlations between semantic processing and simple EF measures are in the .30 - .40 range, which might become significant with larger sample sizes.

Discussion

The present study examined the relationship of executive control with semantic STM deficits, semantic processing, and phonological STM deficits. Motivated by hypotheses proposing a critical role for executive control in semantic STM deficits and semantic processing abilities, this research extended previous work by investigating a large number of patients on an extensive STM, semantic processing, and executive function battery. While Hamilton and R. Martin (2005, 2007) and Hoffman and colleagues (2009) have suggested that executive control plays a critical role in the cause of semantic STM deficits, Barde and colleagues (2010) have proposed an alternative account that does not hinge on executive control impairments. Additionally, we also included patients with phonological STM deficits to examine the relationship between phonological STM and executive control.

Semantic STM and Executive Function

As shown in Table 1, previous work by Hamilton and R. Martin (2005, 2007) and Hoffman et al. (2009) predicted a relationship between executive control and semantic STM deficits, as both groups of researchers have proposed a critical role for executive function as the source of semantic STM deficits. Specifically, Hamilton and R. Martin's account predicted that semantic STM should be related to inhibition, while the account of Hoffman and colleagues predicted that semantic STM should be related to all aspects of executive control. Contrary to both proposals, however, the semantic STM composite did not correlate significantly with any complex (Table 9) or simple (Table 10) measure of executive function. Thus, the present results suggest no relationship between semantic STM deficits and executive control abilities. The lack of relationship between semantic STM and aspects of executive function supports alternative views of semantic STM deficits, such as that proposed by Barde et al. (2010). As discussed in the introduction, Barde et al. posit a reactivation account, which explains interference effects in both semantic and phonological

STM deficit patients on the basis of incremental changes to lexical items due to their presentation in the memory lists. In this model, both semantic and phonological STM deficits result from an overly rapid decay of information (see also R. Martin et al., 1994), leading to difficulty in distinguishing between currently relevant and reactivated (via spreading activation to semantically and phonologically related information) representations. Such an account is consistent both with STM accounts that posit STM buffers for the short-term maintenance of information (e.g., R. Martin et al., 1994) and those that posit STM as a temporarily activated portion of long-term memory (e.g., N. Martin & Saffran, 1997).

Additionally, the present results extend those of Barde and colleagues (2010). Barde et al. asserted that their data did not rule out a less parsimonious alternative, in which inhibitory deficits contribute to their interference effects by operating at different stages. In this alternative, interference effects are caused by both modality-specific maintenance deficits and an inability to inhibit inappropriately activated representations. However, the present results speak against this possibility, as we found no relationship between either semantic or phonological STM capacity and inhibition.

Semantic Processing and Executive Function

As shown in Table 1, Hoffman et al.'s (2009) position regarding semantic control deficits in stroke patients predicted a relation between semantic processing and measures of EF whereas R. Martin and colleagues' (e.g., Hamilton & Martin, 2007; Martin, 2007) and Barde et al.'s (2010) approach to semantic STM deficits predicted no necessary relation in this regard. The results provided support for Hoffman et al.'s (2009) position as a correlation between complex EF measures and the semantic processing composite was obtained. Specifically, the semantic processing composite, which included performance on the PPVT and the PYRPT tasks, was correlated with performance on both the WCST and TOH (the complex EF measures). Given that the EF measures were related to semantic processing per se, and the semantic processing and semantic STM composite were highly correlated, the absence of a relation between semantic STM and the EF measures is intriguing. One possible explanation comes from a recent study by Oberauer and colleagues (Oberauer, Süß, Wilhelm, & Wittman, 2008). These authors have proposed that working memory capacity is broken down into three components – storage, relational integration, and supervision – and they argue that the relational integration component is most related to fluid intelligence. More specifically, relational integration consists of the ability to identify new relations between elements and thereby create new structured representations (Waltz et al., 1999). Given the type of tasks included in the semantic STM composite, one might hypothesize that our semantic STM composite predominately reflects semantic storage capacity. On the other hand, the semantic processing composite might predominately reflect relational integration, given the nature of the tasks that went into this composite. That is, both the PPVT and the PRYPT require the ability to reason about the appropriate semantic relations between picture choices. Additionally, we found a correlation between the semantic STM composite and semantic processing composite because semantic storage and relational reasoning play a role in each; however, storage predominates in the STM measures and relational reasoning dominates in the semantic composite measure. As suggested by the findings from Waltz et al. (1999), the relational reasoning component also plays an important role in complex executive function tasks like the WCST and the TOH. As a consequence, we observed a relation between the semantic processing composite and the complex executive function measures. No such correlations were obtained between semantic processing and simple EF measures, as these component EF tasks did not place heavy demands on relational reasoning. Thus, the present findings lend partial support to the hypotheses of Hoffman and colleagues (2009): some aspects of semantic processing do appear to involve executive control, specifically relational reasoning. More specifically, it may be that relational integration is an important factor in the control of semantic information (Jefferies et al., 2006), used to determine how semantic information should be used on a basis of task-related demands.

Phonological STM and Executive Function

The phonological STM composite also correlated with aspects of executive control, specifically the updating composite and the WCST (number of categories sorted). The relation between phonological retention and updating seems highly reasonable in that subvocal rehearsal is very likely involved in the updating tasks. Similarly, the relation between the WCST and the phonological STM composite would most likely be explained in a similar way, with phonological retention and rehearsal being used to support performance on this task. For example, phonological rehearsal could be used to keep in mind either the set of possible dimensions or the currently relevant sorting dimension. Thus, rather than executive function abilities being a causal factor in determining phonological retention capacity, we instead suggest that phonological retention supports performance on various measures of executive function, especially those with a verbal component. Supporting this line of reasoning is the fact that the phonological STM composite did not correlate with performance on the TOH task or the inhibition measure. For these tasks, a role for phonological retention and subvocal rehearsal seems less likely.

The results showing a relation between phonological STM and EF abilities are not the first to suggest that patient executive function abilities are dependent on more basic cognitive resources (e.g., Baldo et al., 2005, 2010). Baldo and colleagues have suggested that complex problem solving depends on intact language abilities. Specifically, they found language abilities to be a good predictor of both WCST performance (Baldo et al., 2005) and relational integration performance (Baldo et al., 2010) in patients with aphasia. Additionally, using voxel-based lesion symptom mapping (VLSM), Baldo et al. (2010) found relational reasoning performance to be associated with lesions to core language areas, including the left middle and superior temporal gyri. Consistent with the present results, relational reasoning was also associated with a smaller region in the left inferior parietal cortex (BA 40), an area associated with phonological STM (e.g., Baddeley, 2003; R. Martin, Wu, Freedman, Jackson, & Lesch, 2003; Romero, Walsh, & Papagno, 2006). In relation to the present study, this is in line with our correlation between phonological STM and aspects of executive control. Additionally, a number of studies have also suggested a supportive role for aspects of phonological STM in EF tasks. For example, Lehto (1996) found significant correlations between WCST and both simple and complex span measures in normal participants. Additionally, non-brain damaged participants perform significantly worse on the WCST under conditions of articulatory suppression, in which phonological rehearsal is disrupted (Baldo et al., 2005, Experiment 2; Dunbar & Sussman, 1995). These findings strongly suggest that at least one aspect of phonological STM – subvocal rehearsal – plays an important role in complex tasks such as the WCST, and other executive tasks with a verbal component, such as updating. In contrast, Lehto (1996) found no significant relationship between TOH and simple or complex capacity measures, similar to the present study. Unlike the WCST, it seems likely that the TOH does not depend on verbal processes, such as language and verbal STM. Future studies could use VLSM to provide converging evidence regarding the proposed relations (or lack of relations) between semantic and phonological STM, semantic processing, and aspects of executive function.

Previous work on the shifting component of EF has found a relation between phonological STM and shifting; however, this evidence indicates that the phonological loop is utilized in efficient task switching when tasks are not explicitly activated by an explicit cue (e.g., Baddeley, Chincotta, & Adlam, 2001; Emerson & Miyake, 2003). That is, when the cue unambiguously indicates which task is relevant on a given trial, phonological STM resources play little role; in contrast, when the cue is arbitrary, such that it does not automatically activate the relevant task (e.g., with nonsense symbols such as %%% serving as the cue for the 'Life' task, or no cues at all), phonological STM resources do play a role in task switching. Thus, in the present study, an absence of a relation between phonological STM and cued shifting is not surprising, given that this task had minimal STM demands: on each trial, patients saw not only the target but also an explicit cue which indicated which task should be performed on that trial. Thus, patients did not have to use STM resources to keep track of the current task set. Along similar lines of reasoning, however, the lack of relation between the plus-minus task and phonological retention was surprising and not predicted by previous research. In contrast to the cued shifting task, the plus-minus task is not cued; instead, patients are required to keep track of the relevant task being performed on each trial in the mixed block – and thus we would have expected phonological STM to be important. One possible explanation for the lack of correlation between this task and the measure of phonological STM is the requirement for arithmetic computations. It may be possible that the simple arithmetic required by this task utilized phonological STM resources (Andersson, 2007; Lee & Kang, 2002), wiping out other phonological STM contributions to task performance.

Broader Implications

Sentence processing—We can also ask what our findings imply for language processing beyond the single word level. Many previous studies in our lab have established an important role for semantic storage capacity in sentence comprehension and production (Martin & He, 2004). Based on some case study results, we hypothesized that a semantic STM deficit was related to an ability to inhibit irrelevant information and suggested some ways that our prior sentence processing results might be re-interpreted in terms of an inhibition deficit (R. Martin, 2007). However, the current findings (and those from Barde et al., 2010) suggest that there is no necessary relation between a semantic STM deficit and an inhibition deficit. Consequently, a semantic storage deficit per se may likely be the source of the sentence processing deficits we observed. Nonetheless, it remains possible, that executive function deficits involved in inhibition or the control of attention play a role in some aspects of sentence processing – in situations in which a predominant meaning or preferred syntactic structure must be suppressed and an interpretation developed based on a subordinate meaning or less frequent structure (Novick, Trueswell, & Thompson-Schill, 2005; Vuong & R. Martin, 2011). A high-level function like relational integration may not be important in such aspects of language processing, though it plausibly would be in reasoning about discourse (see Coelho, Liles & Duffy, 1995).

Assessment and rehabilitation—In recent years, aphasia rehabilitation research has witnessed a surge of interest in the role of non-linguistic cognitive processes in the treatment of language disorders. Aphasia is almost invariably accompanied by some degree of verbal STM impairment. Some aphasia tests in development include repetition span tasks designed specifically to assess span capacity (Marshall & Wright, 2007; N. Martin, Kohen & Kalinyak-Fliszar, 2010), and some treatment protocols specifically aim to improve STM capacity (e.g., Francis, Clark, & Humphreys, 2003; Kalinyak-Fliszar, Kohen, & N. Martin, in press; Majerus, Van der Kaa, Renard, Van der Linden, & Poncelet, 2005). Executive function is another domain of cognitive abilities that has been recently recognized as critical to language function (Keil & Kaszniak, 2002) and therefore, worthy of consideration in rehabilitation of language impairments. The findings reported here suggest that semantic STM deficits are separable from executive function deficits and thus treatment directed at the two would be different. With respect to the role of executive function in treatment of language deficits, the importance of executive function deficit may depend to a large extent on the aspect of language that was being treated and the treatment method that is employed.

For simpler language abilities like word comprehension or production, executive functions may not play a large role, although recent evidence suggests a possible role of inhibition in generalization of treated words to untreated words in anomia (Yeung & Law, 2010). Executive functions have also been studied extensively as a factor in impaired discourse processing of individuals with traumatic brain injury (e.g., Coelho et al., 1995) and more recently in persons with aphasia (Purdy, 2002; Frankel, Penn & Ormond-Brown, 2007). As research into the role of executive processing in language impairments proceeds, one useful outcome would be the identification of training regimens that place demands on executive function and relational integration in order for the patient to obtain the maximum benefit from the treatment. For example, well-known treatments for naming (e.g., Coelho, McHugh, & Boyle, 2000), discourse processing (e.g., Chapman & Ulatowska, 1989), and sentence processing (Thompson & Shapiro, 2005; Edmonds, Nadeau, & Kiran, 2009) depend implicitly or explicitly on patients' ability to infer and generalize relations. As we learn more about the relationship between executive functions and relational integration abilities, it will be important to find ways to diagnose the integrity of these abilities in aphasia, which may be crucial to the patients' ability to transfer training to new materials.

Lastly, the present results suggest that researchers should take caution when interpreting the source of patients' poor performance on EF tasks. The relationship between phonological STM and at least some measures of EF suggest that poor performance on executive control tasks may sometimes be better interpreted as a deficit to STM resources that support EF performance rather than to executive functions such as updating or relational integration per se. In this regard it would be preferable to employ simpler executive function tasks where the source of the deficit may be more precisely identified as opposed to using general complex tasks that may rely on a variety of cognitive functions.

Conclusions

The results have several implications for theoretical claims. Contrary to the claims of R. Martin and colleagues (e.g., Hamilton & Martin, 2005) and Hoffman et al. (2009), the present study found no evidence that semantic STM deficits are caused by deficits in executive function. Instead, the evidence is more consistent with claims that semantic STM deficits derive from overly rapid decay (e.g., Barde et al., 2010, N. Martin & Saffran, 1995; R. Martin & Lesch, 1996). Performance on executive function tasks was found to correlate with performance on some semantic processing tasks for the patients tested here, and it was argued that a relational integration function may underlie performance on both types of tasks. Finally, a correlation between phonological STM and some executive function tasks was found and it was argued that phonological storage and rehearsal play a role in executive function tasks with a verbal component. The results have important implications for the interpretation of the role of executive function in language processing tasks and, more speculatively, the possible contributions of STM and executive function deficits in treatment regimes.

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Appendix

Appendix:

Intercorrelations among simple executive function tasks. No values are reverse scored.

Variable	1	2	3	4	5	6	7	8	9
				Inhibition factor					
1. Verbal Stroop	-								
2. Spatial Stroop	−.45$^{(*)}$	-							
3. PWI	.14	.43$^{(*)}$	-						
4. Rec. Negatives	.13	.30	.36	-					
				Updating factor					
5. V 1-back	−.07	.06	.20	.19	-				
6. NV 1-back	.05	−.30	−.55*	−.08	.56*	-			
7. V Keep Track	−.34	−.24	−.33	.006	.71*	.58*	-		
8. NV Keep Track	−.38	.11	.22	.11	.79*	.26	.65*	-	
				Shifting factor					
9. Plus-minus	.44$^{(*)}$	−.12	.01	.18	.14	.32	−.33	−.20	-
10. Cued Shifting	.003	.48$^{(*)}$	.38	.25	−.29	−.36	−.29	−.28	−.18

***Note*. $p < .01$.

*$p < .05$.

$^{(*)}$$p \leq .10$.

References

Andersson U. The contribution of working memory to children’s mathematical word problem solving. Applied Cognitive Psychology. 2007; 21:1201–1216.

Baddeley, AD. Working Memory. Clarendon; Oxford: 1986.

Baddeley AD. Exploring the central executive. The Quarterly Journal of Experimental Psychology. 1996; 49:5–28.

Baddeley AD. Working memory: Looking back and looking forward. Nature Reviews Neuroscience. 2003; 4:829–839.

Baddeley A, Chincotta D, Adlam A. Working memory and the control of action: Evidence from task switching. Journal of Experimental Psychology: General. 2001; 130:641–657. [PubMed: 11757873]

Baddeley, AD.; Hitch, G. Working memory. In: Bower, GA., editor. Recent Advances in Learning and Motivation. Vol. Vol. 8. Academic; New York: 1974. p. 47-90.

Baddeley AD, Wilson B. Frontal amnesia and the dysexecutive syndrome. Brain and Cognition. 1988; 7:212–230. [PubMed: 3377900]

Baldo JV, Bunge SA, Wilson SM, Dronkers NF. Is relational reasoning dependent on language? A voxel-based lesion symptom mapping study. Brain & Language. 2010; 113:59–64. [PubMed: 20206985]

Baldo JV, Dronkers NF, Wilkins D, Ludy C, Raskin P, Kim J. Is problem solving dependent on language? Brain and Language. 2005; 92:240–250. [PubMed: 15721957]

Barde LHF, Schwartz MF, Chrysikou EG, Thompson-Schill SL. Reduced short-term memory span in aphasia and susceptibility to interference: Contribution of material-specific maintenance deficits. Neuropsychologia. 2010; 48:909–920. [PubMed: 19925813]

Barde LHF, Schwartz MF, Thompson-Schill SL. The role of left inferior frontal gyrus (LIFG) in semantic short-term memory: A comparison of two case studies. Brain & Language. 2006; 99:71–72.

Berman KF, Ostrem JL, Randolph C, Gold J, Goldberg TE, Coppola R, et al. Physiological activation of a cortical network during performance of the Wisconsin Card Sorting Test: A positron Emission tomography study. Neuropsychologia. 1995; 33:1027–1046. [PubMed: 8524452]

Bull R, Espy KA, Senn TE. A comparison of performance on the Towers of London and Hanoi in young children. Journal of Child Psychology and Psychiatry. 2004; 45:743–754. [PubMed: 15056306]

Burgess P, Shallice T. Bizarre responses, rule detection and frontal lobe lesions. Cortex. 1996; 32:241–259. [PubMed: 8800613]

Chapman SB, Ulatowska HK. Discourse in aphasia: Integration deficits in processing reference. Brain and Language. 1989; 36:651–668. [PubMed: 2720374]

Clark HH, Brownell HH. Judging up and down. Journal of Experimental Psychology: Human Perception & Performance. 1975; 1:339–352. [PubMed: 1185121]

Coelho CA, Liles BZ, Duffy RJ. Impairments of discourse abilities and executive functions in traumatically brain-injured adults. Brain Injury. 1995; 9:471–477. [PubMed: 7550218]

Coelho CA, McHugh R, Boyle M. Semantic feature analysis as a treatment for aphasic dysnomia: A replication. Aphasiology. 2000; 14:133–142.

D'Esposito M, Postle BR, Jonides J, Smith EE. The neural substrate and temporal dynamics of interference effects in working memory as revealed by event-related fMRI. Proceedings of the National Academy of Sciences. 1999; 96:7514–7519.

Dunbar K, Sussman D. Toward a cognitive account of frontal lobe function: Simulating frontal lobe deficits in normal subjects. Annals of New York Academy of Sciences. 1995; 769:289–304.

Dunn, L.; Dunn, L. Peabody Picture Vocabulary Test Revised. American Guidance Service; Circle Pines, MN: 1981.

Edmonds LA, Nadeau SE, Kiran S. Effect of verb network strengthening treatment (VNeST) on lexical retrieval of content words in sentences with persons with aphasia. Aphasiology. 2009; 23:402–424. [PubMed: 19763227]

Emerson MJ, Miyake A. The role of inner speech in task switching: A dual-task investigation. Journal of Memory and Language. 2003; 48:148–168.

Francis DR, Clark N, Humphreys GW. The treatment of an auditory working memory deficit and the implications for sentence comprehension abilities in mild "receptive" aphasia. Aphasiology. 2003; 17:723–750.

Frankel T, Penn C, Ormond-Brown D. Executive dysfunction as an explanatory basis for conversation symptoms of aphasia: A pilot study. Aphasiology. 2007; 21:814–828.

Freedman ML, Martin RC, Biegler K. Semantic relatedness effects in conjoined noun phrase production: Implications for the role of short-term memory. Cognitive Neuropsychology. 2004; 21:245–265. [PubMed: 21038203]

Goodglass, H.; Kaplan, E. Assessment of aphasia and related disorders. Lea & Febiger; Philadelphia: 1972.

Hamilton AC, Martin RC. Dissociations among tasks involving inhibition: A single case study. Cognitive, Affective, & Behavioral Neuroscience. 2005; 5:1–13.

Hamilton AC, Martin RC. Proactive interference in a semantic short-term memory deficit: Role of semantic and phonological relatedness. Cortex. 2007; 43:112–123. [PubMed: 17334211]

Handley SJ, Capon A, Copp C, Harper C. Conditional reasoning and the Tower of Hanoi: The role of spatial and verbal working memory. British Journal of Psychology. 2002; 93:501–518. [PubMed: 12519531]

Heaton, RK.; Chelune, GJ.; Talley, JL.; Kay, GG.; Curtiss, G. Wisconsin Card Sorting Test Manual – Revised and Expanded. Psychological Assessment Resource; Lutz, FL: 1993.

Hoffman P, Jefferies E, Ehsan S, Hopper S, Ralph M. A. Lambon. Selective short-term memory deficits arise from impaired domain-general semantic control mechanisms. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2009; 35:137–156.

Howard, D.; Patterson, K. Pyramids and Palm Trees Test. Thames Valley Test Company; Edmunds, England: 1992.

Hull R, Martin RC, Beier ME, Lane D, Hamilton AC. Executive function in older adults: A structural equation modeling approach. Neuropsychology. 2008; 22:508–522. [PubMed: 18590362]

Jefferies E, Ralph M. A. Lambon. Semantic impairment in stroke aphasia vs. semantic dementia: A case-series comparison. Brain. 2006; 129:2132–2147. [PubMed: 16815878]

Jersild AT. Mental set and shift. Archives of Psychology. 1927; 89

Jonides J, Lewis RL, Nee DE, Lustig CA, Berman MG, Moore KS. The mind and brain of short-term memory. Annual Review of Psychology. 2007; 59:15.1–15.32.

Jonides J, Smith EE, Marshuetz C, Koeppe RA, Reuter-Lorenz PA. Inhibition in verbal working memory revealed by brain activation. Proceedings of the National Academy of Science. 1998; 95:8410–8413.

Kalinyak-Fliszar M, Kohen FP, Martin N. Remediation of language processing in aphasia: Improving activation and maintenance of linguistic representations in (verbal) short-term memory. Aphasiology. (In press).

Keil K, Kaszniak AW. Examining executive function in individuals with brain injury: A review. Aphasiology. 2002; 16:305–335.

Kertesz, A. Western Aphasia Battery –Revised (WAB-R). Pearson; San Antonio: 2006.

Koenig-Bruhin M, Studer-Eichenberger F. Therapy of verbal short-term memory disorders in fluent aphasia: A single case study. Aphasiology. 2007; 21:448–458.

Lee K-M, Kang S-Y. Arithmetic operation and working memory: Differential suppression in dual tasks. Cognition. 2002; 83:B63–B68. [PubMed: 11934408]

Lehto J. Are executive function tests dependent on working memory capacity? The Quarterly Journal of Experimental Psychology. 1996; 49:29–50.

Lupker SJ. The semantic nature of response competition in the picture-word interference task. Memory and Cognition. 1979; 7:485–495.

Majerus S, Van der Kaa MA, Renard C, Van der Linden M, Poncelet P. Treating verbal short-term memory deficits by increasing the duration of temporary phonological representations: A case study. Brain and Language. 2005; 95:174–175.

Marshall RC, Wright HH. Developing a clinician-friendly aphasia test. American Journal of Speech-Language Pathology. 2007; 16:295–315. [PubMed: 17971491]

Martin N. Dynamic interactions of language with other cognitive processes. Seminars in Speech and Language. 2008; 29:167–168. [PubMed: 18720314]

Martin N, Ayala J. Measurements of auditory-verbal STM in aphasia: Effects of task, item and word processing impairment. Brain and Language. 2004; 89:464–483. [PubMed: 15120538]

Martin N, Gupta P. Exploring the relationship between word processing and verbal STM: Evidence from associations and dissociations. Cognitive Neuropsychology. 2004; 21:213–228. [PubMed: 21038201]

Martin, N.; Kohen, FP.; Kalinyak-Fliszar, M. A processing approach to the assessment of language and verbal short-term memory abilities in aphasia. Paper presented at the Clinical Aphasiology Conference; Charleston, SC. 2010.

Martin N, Saffran EM. Language and auditory-verbal short-term memory impairments: Evidence for common underlying processes. Cognitive Neuropsychology. 1997; 14:641–682.

Martin N, Saffran EM, Dell GS. Recovery in deep dysphasia: Evidence for a relation between auditory-verbal STM and lexical errors in repetition. Brain and Language. 1996; 52:83–113. [PubMed: 8741977]

Martin N, Schwartz MF, Kohen FP. Assessment of the ability to process semantic and phonological aspects of words in aphasia: A multi-measurement approach. Aphasiology. 2006; 20:154–166.

Martin, RC. Semantic short-term memory, language processing, and inhibition. In: Meyer, AS.; Wheeldon, LR.; Knott, A., editors. Automaticity and control in language processing. Psychology Press; Hove: 2007. p. 161-191.

Martin, RC.; Allen, CM. Relations between short-term memory deficits and executive function. Poster presented at the Annual Meeting of the Academy of Aphasia; Turku, Finland. 2008.

Martin RC, He T. Semantic short-term memory and its role in sentence processing: A replication. Brain & Language. 2004; 89:76–82. [PubMed: 15010239]

Martin, RC.; Lesch, MF. Associations and dissociations between language impairment and list recall: Implications for models of short-term memory. In: Gathercole, S., editor. Models of Short-term Memory. Erlbaum; Hove, U.K.: 1996. p. 149-178.

Martin RC, Lesch MF, Bartha MC. Independence of input and output phonology in word processing and short-term memory. Journal of Memory and Language. 1999; 41:3–29.

Martin RC, Romani C. Verbal working memory and sentence comprehension: A multiple-components view. Neuropsychology. 1994; 8:506–523.

Martin RC, Shelton JR, Yaffee LS. Language processing and working memory: Neuropsychological evidence for separate phonological and semantic capacities. Journal of Memory and Language. 1994; 33:83–111.

Martin RC, Wu D, Freedman M, Jackson EF, Lesch M. An event-related fMRI investigation of phonological and semantic short-term memory. Journal of Neurolinguistics. 2003; 16:341–360.

McGeoch J. Forgetting and the law of disuse. Psychological Review. 1932; 39:352–370.

Milner B. Effects of different brain lesions on card sorting: The role of the frontal lobes. Archives of Neurology. 1964; 9:100–110.

Miyake A, Friedman NP, Emerson MJ, Witzki AH, Howerter A, Wager TD. The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. Cognitive Psychology. 2000; 41:49–100. [PubMed: 10945922]

Monsell S. Recency, immediate recognition memory, and reaction time. Cognitive Psychology. 1978; 10:465–501.

Novick JM, Trueswell JC, Thompson-Schill SL. Cognitive control and parsing: Reexamining the role of Broca’s area in sentence comprehension. Cognitive, Affective & Behavioral Neuroscience. 2005; 5:263–281.

Nunnally, J.; Bernstein, I. Psychometric theory. 3rd edition. McGraw-Hill; New York: 1994.

Oberauer K, Süß H-M, Wilhelm O, Wittman WW. Which working memory functions predict intelligence? Intelligence. 2008; 36:641–652.

Purdy M. Executive function ability in persons with aphasia. Aphasiology. 2002; 16:549–557.

Raven, JC. Coloured progressive matrices sets A, AB, B. H. K. Lewis; London: 1962.

Roach A, Schwartz MF, Martin N, Grewal RS, Brecher A. The Philadelphia Naming Test: Scoring and rationale. Clinical Aphasiology. 1996; 24:121–133.

Robertson, IH.; Ward, T.; Ridgeway, V.; Nimmo-Smith, I. The Test of Everyday Attention. Thames Valley Test Company; Flempton, England: 1994.

Rogers RD, Monsell S. Costs of a predictable switch between simple cognitive tasks. Journal of Experimental Psychology: General. 1995; 124:207–231.

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. [PubMed: 16839288]

Schriefers H, Meyer AS, Levelt WJM. Exploring the time course of lexical access in language production: Picture-word interference studies. Journal of Memory and Language. 1990; 29:86–102.

Shallice, T. From Neuropsychology to Mental Structure. Cambridge University Press; Cambridge: 1988.

Simon HA. The functional equivalence of problem solving skills. Cognitive Psychology. 1975; 7:268–288.

Sorel O, Pennequin V. Aging of the planning process: The role of executive functioning. Brian and Cognition. 2008; 66:196–201.

Stroop JR. Studies of interference in serial verbal reactions. Journal of Experimental Psychology. 1935; 18:643–662.

Stuss DT, Levine B, Alexander MP, Hong J, Palumbo C, Hamer L, et al. Wisconsin Card Sorting Test performance in patients with focal frontal and posterior brain damage: Effects of lesion location and test structure on separable cognitive processes. Neuropsychologia. 2000; 34:388–402. [PubMed: 10683390]

Thompson CK, Shapiro LP. Treating agrammatic aphasia within a linguistic framework: Treatment of Underlying Forms. Aphasiology. 2005; 10-11:1021–1036. [PubMed: 17410280]

Vuong LC, Martin RC. LIFG-based attentional control and the resolution of lexical ambiguities in sentence context. Brain & Language. 2011; 116:22–32. [PubMed: 20971500]

Wainer H. Estimating coefficients in linear models: It don't make no nevermind. Psychological Bulletin. 1976; 83:213–217.

Walker, GM.; Schwartz, MF. Development of the Short Form Philadelphia Naming Test (PNT). Poster session presented at the 46th Annual Meeting of the Academy of Aphasia; Turku, Finland. Oct. 2008

Waltz JA, Knowlton BJ, Holyoak KJ, Boone KB, Mishkin FS, de Menezes Santos M, Thomas CR, Miller BL. A system for relational reasoning in human prefrontal cortex. Psychological Science. 1999; 10:119–125.

Warrington EK, Shallice T. The selective impairment of auditory verbal short-term memory. Brain. 1969; 92:885–896. [PubMed: 5364015]

Wechsler, D. Wechsler Memory Scale—Revised. Psychological Corporation; New York: 1987.

Winer, BJ. Statistical Principles in Experimental Design. 2nd ed. McGraw-Hil; New York: 1971.

Wong W, Law S-P. The relationship between semantic short-term memory and immediate serial recall of known and unknown words and nonwords: Data from two Chinese individuals with aphasia. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2008; 34:900–917.

Yeung O, Law S-P. Executive functions and aphasia treatment outcomes: Data from an ortho-phonolgoical cueing therapy for anomia in Chinese. International Journal of Speech-Language Pathology. 2010; 12:529–544. [PubMed: 21080778]

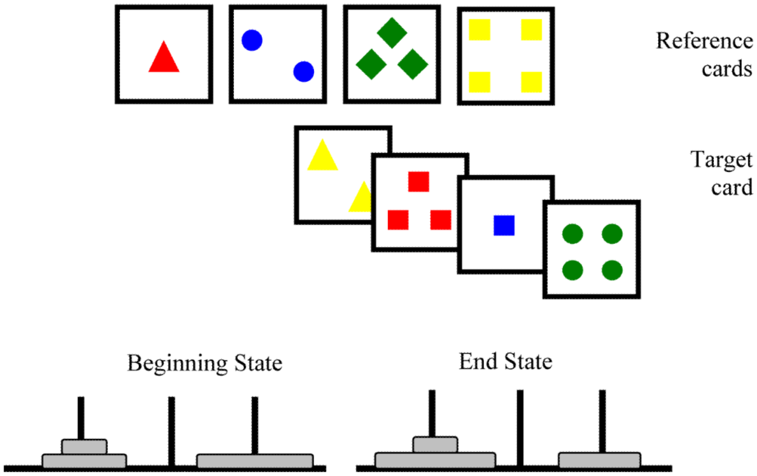

Figure 1.
Examples of the Wisconsin Card Sorting Task (top) and Tower of Hanoi (bottom).

Table 1

Predictions from the various accounts relating executive control impairments to semantic STM and semantic processing deficits. Correlation predicted: √. No relation predicted: X.

	Hamilton & R. Martin (2005, 2007)		Hoffman et al. (2009)		Barde et al. (2010)	
	Semantic STM	**Semantic Processing**	**Semantic STM**	**Semantic Processing**	**Semantic STM**	**Semantic Processing**
Inhibition	√	X	√	√	X	X
Updating	X	X	√	√	X	X
Shifting	X	X	√	√	X	X
Global Tasks	X[a]	X	√	√	X	X

[a] A relation with global tasks is predicted to the extent that the global task relies on inhibition.

Table 2

Summary of tasks included in the present study, including task abbreviations and indication of which tasks were combined into composites (as discussed in the Results).

Screening Assessments	Task composites (in gray)
Single picture-word matching (PWM)	None
Auditory discrimination	None
Short-term Memory Measures	
Category probe	Semantic STM composite
Synonymy judgment	
Word span	Phonological STM composite
Digit span	
Rhyme probe	
Semantic tasks	
Picture naming task (PNT)	None
Single picture-word matching (PWM)	None
Peabody Picture Vocabulary Test (PPVT)	Semantic processing composite
Pyramids and Palm Trees (PRYPT)	
Complex Executive Function Tasks	
Wisconsin Card Sorting Task (WCST)	None
Tower of Hanoi (TOH)	None
Simple Executive Function Tasks	
Inhibition Tasks	
Verbal Stroop	None
Spatial Stroop	Inhibition composite
Picture-word interference (PWI)	
Recent negatives probe task	
Updating Tasks	
Verbal 1-back	Updating composite
Nonverbal 1-back	
Verbal keep track	
Nonverbal keep track	
Shifting Tasks	
Plus-minus	None
Cued shifting	None

Table 3

Patient background information, including age at testing (Age), years post-stroke, years of education (Ed.), brain regions affected (Damage), single word processing ability (Picture-Word Matching; percent correct), speech perception (Speech Perception; percent correct).

	Age	Years post-stroke	Ed.	Damage	Picture-Word Matching	Speech Perception
BB	48	11	21	Left frontal, parietal and superior temporal lobes with some insular and subcortical damage	94%	100%
BQ	67	11	16	Left temporal-parietal lesion including superior temporal gyrus and majority of parietal lobe	92%	95%
ER	56	10	17	Left parietal lobe, sparing the angular gyrus	97%	100%
EV	53	11	16	Left frontal including BA 44 and 45, with extension into middle frontal gyrus; insular damage also present	95%	100%
KI	86	17	15	Left superior temporal gyrus, with posterior extension towards the supramarginal gyrus	97%	84%
MB	60	5	13	Left parietal; additional small subcortical infarcts of the posterior and lateral right parietal lobe	98%	100%
MV	75	8	12	Lesion information unavailable.	97%	81%
NC	55	10	16	Lesion information unavailable.	99%	100%
ML	68	21	14	Left inferior and middle frontal gyri and large lateral areas of the superior and inferior left parietal lobe, with some sparing of supramarginal & angular gyri	99%	100%
SH	81	6	11	Left temporal lobe and portions of the left posterior parietal lobe	98%	95%
SJ	61	5	13	Left posterior parietal regions, including angular and supramarginal gyri; slight posterior superior temporal damage	97%	-
HEQ	69	8	15	Left subcortical and deep white matter ischemic change; mild diffuse atrophy	99%	95%
MDD	61	6	16	Infarct of inferior latero-frontal lobe and small parietal infarct; left temporal abcess	89%	98%
TUFS1	55	1	12	Left intraparenchymal hemorrhage	94%	88%
TUHN8	58	9	16	Left thalamic CVA hemorrhage	-	90%

	Age	Years post-stroke	Ed.	Damage	Picture-Word Matching	Speech Perception
TUIU19	65	1	17	Left parieto-occipital infarct with probable newer left parietal embolic infarct in left MCA region	98%	98%
TUKL12	60	2.5	17	Left thalamic CVA	100%	100%
TUBC2	61	27[a]	14	TBI from gunshot (1981) and head trauma (2002)	100%	90%
TUXD9	65	16	16	Left perisylvian CVA	88%	90%
VA3KC	48	6	14	Left MCA infarct	93%	85%

[a] Refers to years since traumatic brain injury.

Table 4

Patient performance on STM and semantic tasks. Means and variability from older controls are shown in the final two rows; measure of variability is control range, unless otherwise indicated.

	STM Measures					**Semantic Measures**			
	Category Probe	**Word Span**	**Synonymy Judgments**	**Rhyme Probe**	**Digit Span**	**PNT**	**PWM**	**PPVT**	**PRYPT**
	Span est.	**Span est.**	**% correct**	**Span est.**	**Span est.**	**% correct**	**% correct**	**Std. score**	**% correct**
BB	1.5	2.71	85	3.34	4.5	73	94	92	88
BQ	3.76	1.8	85	4.17	4	87	92	99	96
ER	4	2.29	90	2.35	4.5	90	97	100	96
EV	1.8	3	81	3.34	5	90	95	73	83
KI	1.67	2	69	2	3.5	93	97	67	-
MB	2.45	2.6	96	5	3.5	77	98	120	96
MV	1.67	3.17	73	4.34	6	100	97	83	-
NC	3	3	81	3.5	4	93	99	102	96
ML	1.8	2	94	1.75	3.5	100	99	107	98
SH	3	2.2	98	2	4	83	98	115	94
SJ	2.38	1.3	100	3	3.5	90	97	94	98
HEQ	5	3.8	94	6	6	97	99	113	100
MDD	3.77	-	90	1.8	2.4	57	89	82	88
TUFS1	1.85	1.6	70	4.72	3.6	67	94	66	87
TUHN8	2.93	4.6	70	6.97	6.2	90	-	87	96
TUIU19	3.77	3.4	85	3.9	5.2	86	98	93	96
TUKL12	4.92	3.6	100	6.84	6	94	100	101	92
TUBC2	2.76	2.8	65	3.73	3.7	74	100	60	90
TUXD9	3.97	1.2	100	1.31	1	0	88	82	94
VA3KC	2.84	-	45	5.96	3	60	93	85	87
Controls	*5.38* *(3.4-7)*	*4.8* *(4-5.2)*	*95* *(SD=5.2)*	*7.02* *(5.8-9)*	*5.7* *(3-7.5)*	*96* *(SD=7)*	-	*100* *(SD=15)*	*98* *(94-100)*

Note. Except where noted below, control data is from the task reference cited in the Methods section. Word span control data from Freedman and Martin (2001). Digit span control data collected from N = 6 older adults (*M* age = 69). PNT control data from Roach et al. (1996), based on the full 175-item PNT. PWM data unavailable; Martin et al. (1999) assumed control subjects would obtain 100% correct.

Table 5

Correlations between STM tasks.

	1	**2**	**3**	**4**	**5**
1. Category probe	-	.24	.38$^{(*)}$	.25	.07
2. Word span		-	-.17	.68**	.80**
3. Synonymy judgment			-	-.32	-.09
4. Rhyme probe				-	.59**
5. Digit span					-

***Note*. $p < .01$.

*$p < .05$.

$^{(*)}$$p \le .10$.

Table 6

Multiple regression results for STM measures regressed on category and rhyme probe.

	Synonymy judgment		
	B	*SE B*	β
Category probe	.07*	.03	.49*
Rhyme probe	−.04*	.02	−.44*
	Digit span		
	B	*SE B*	β
Category probe	−.04	.25	−.03
Rhyme probe	.47**	.15	.61**
	Word span		
	B	*SE B*	β
Category probe	.06	.15	.07
Rhyme probe	.34**	.09	.07**

***Note*. $p < .01$.

*$p < .05$.

$^{(*)}$$p \leq .10$.

Table 7

Correlations between semantic processing tasks.

	1	**2**	**3**	**4**
1. PNT	-	.76[**]	.28	.31
2. PWM	-	-	.32	.41
3. PPVT	-	-	-	.69[**]
4. PRYPT				

[**] *Note*. $p < .01$.

Table 8

Patient performance on complex and component executive function tasks. Patient and control values show means and ranges (in parentheses). Shading identifies tasks that were combined into composites, as discussed in the Results (see also Table 2).

Complex Executive Function Tasks	**Patients**	**Controls**
WCST (categories completed)	10 (1-15)	15 (14-15)[a]
WCST (perseverative errors)	20 (3-38)	7 (0-21)[b]
TOH (number of moves)	95 (60-176)	88 (54-163)[b]
Simple Executive Function Tasks		
Inhibition Tasks		
Verbal Stroop (interference effect,ms)	1017 (131-2794)	244 (56-492)[b]
Spatial Stroop (interference effect, ms)	209 (10-865)	63 (−100-260)[b]
PWI (interference effect, ms)	199 (−286-676)	38 (−18-185)[a]
Recent negatives (interference effect, ms)	664 (−489-2835)	115 (−9-260)[a]
Updating Tasks		
Verbal 1-back (percent correct)	93 (62-100)	86 (65-97)[b, c]
Nonverbal 1-back (percent correct)	82 (52-96)	76 (41-98)[b, c]
Verbal keep track (percent correct)	84 (50-100)	93 (79-100)[b, c]
Nonverbal keep track (percent correct)	87 (5-100)	89 (51-100)[b, c]
Shifting Tasks		
Plus-minus (switch cost, sec)	86 (−1-284)	41 (27-74)[b, d]
Cued shifting (switch cost, ms)	1033 (19-3197)	155 (−55-468)[a]

[a] Control data collected at Rice University. WCST (categories): $N = 18$, $M_{\text{age}} = 67$ years. PWI: $N = 9$, $M_{\text{age}} = 66$ years. Recent negatives: $N = 10$, $M_{\text{age}} = 67$ years. Cued shifting: $N = 16$, $M_{\text{age}} = 64$ years.

[b] Control data from Hull et al. (2008).

[c] The updating tasks used by Hull et al. (2008) required subjects to update two items (e.g., keeping track of 2 colors in the nonverbal keep track task), as opposed to one item as used for the patients tested in the present study. Thus, the control data reflect 2-item updating; we assume accuracy would be very high were controls to complete the 1-item updating tasks.

[d] The plus-minus task used by Hull et al. (2008) required subjects to add or subtract 3 from each two-digit number (as opposed to adding or subtracting 1, as used in the present study). Thus, the control data reflect this task variation.

Table 9

Correlations between STM, semantic, and complex executive function tasks. WSCT (categories) measures the number of categories completed (out of 15 possible). WCST (perseverations) measures the number of perseverative errors. TOH measures the total number of moves to completion. Rev indicates an item that was reverse scored, and N indicates the number of patients included in the correlation.

		STM Measures		**Semantics Measure**
	N	**Semantic STM Comp.**	**Phonological STM Comp.**	**Semantic Processing Comp.**
WCST (categories)	17	.04	.55[*]	.48[(*)]
WCST (persev., rev)	14	−.08	−.05	.54[(*)]
TOH (rev)	16	−.35	.22	.54[*]

[*] *Note*. $p < .05$.

[(*)] $p \leq .10$.

Table 10

Correlations between simple EF tasks and measures of STM, semantic processing, and complex executive function. Rev indicates an item that was reverse scored.

	STM Measures		Semantics Measure	Complex EF Measures		
	Semantic STM Comp.	**Phono. STM Comp.**	**Semantic Processing Comp.**	**WCST (cat.)**	**WCST (persev.)**	**TOH**
Inhibition Composite (rev.)	.21	.21	.15	−.15	.53$^{(*)}$	.12
Updating Composite	.05	.58*	.39	.77**	−.23	−.56*
Plus-minus (shifting, rev)	.30	.02	−.01	.12	−.09	.10
Cued shifting (shifting, rev)	.12	−.13	.33	.08	.52$^{(*)}$	.58*

[**] *Note*. $p < .01$.

[*] $p < .05$.

(*) $p \leq .10$.