



Working Memory in Aphasia: Theory, Measures, and Clinical Implications

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Recently, researchers have suggested that deficits in working memory capacity contribute to language-processing difficulties observed in individuals with aphasia (e.g., I. Caspari, S. Parkinson, L. LaPointe, & R. Katz, 1998; R. A. Downey et al., 2004; N. Friedmann & A. Gvion, 2003; H. H. Wright, M. Newhoff, R. Downey, & S. Austermann, 2003). A theoretical framework of working memory can aid in our understanding of a disrupted system (e.g., after stroke) and how this relates to language comprehension and production. Additionally, understanding the

theoretical basis of working memory is important for the measurement and treatment of working memory. The literature indicates that future investigations of measurement and treatment of working memory are warranted in order to determine the role of working memory in language processing.

Key Words: aphasia, working memory, memory measures

Aphasia has been traditionally identified as a language-based impairment (Benson, 1994; Grodzinsky, 1990). However, language models are not able to account for some characteristics exhibited by individuals with aphasia, or variability in task performance by individuals presenting with similar behavioral patterns. A preserved working memory system is crucial for language processing. For example, it is essential for resolving lexical and structural ambiguity during sentence comprehension and discourse processing. Recently, researchers have suggested that a deficit in working memory capacity contributes to the language-processing difficulties seen in individuals with aphasia (Caspari, Parkinson, LaPointe, & Katz, 1998; Friedmann & Gvion, 2003; Wright, Newhoff, Downey, & Austermann, 2003). The purpose of this article is to provide clinicians and researchers with a brief review and discussion of working memory theories that have been influential in the aphasia literature, research findings of working memory in aphasia, and assessment measures. We offer this for clinicians to gain knowledge of some of the prominent theories in working memory and their application to clinical practice. Theory is discussed first, then working memory in aphasia, with assessment measures and clinical applications in conclusion.

Theories of Working Memory

Several theories of working memory have been proposed to account for linguistic presentations exhibited by adults with aphasia (e.g., Baddeley, 1986; Caplan & Waters, 1999a; Just & Carpenter, 1992). Limitations in linguistic performance have been argued to be constrained by the availability and allocation of resources (e.g., Caplan & Waters, 1995; L. L. LaPointe & Erickson, 1991; McNeil & Kimelman, 1986; McNeil, Odell, & Tseng, 1991; Murray, Holland, & Beeson, 1997a, 1997b; Slansky & McNeil, 1997; Tseng, McNeil, & Milenkovic, 1993). Some of these approaches are proposed to also account for the deficits observed in aphasia (Baddeley, 1986; Just & Carpenter, 1992). For example, Baddeley suggested a single resource model with a multi-component makeup that works to store and manipulate information (Baddeley, 1986). The single resource model theory refers to the idea that a single or central process is responsible for all language processing. Alternatively, Caplan and Waters (1999a) offered a dual resource model that focuses on a limited resource pool for either automatic tasks or more conscious processing. Relatedly, Just and Carpenter (1992) proposed that a limited capacity variation in working memory leads to comprehension discrepancies and individual differences. Though each of these approaches has unique components, each asserts that a person's working memory includes a maintenance component and

processing component that act simultaneously while processing language. By considering these theories in the context of assessment and intervention, clinicians will be better able to utilize the proper tools of measurement and, thus, more accurately treat clients with aphasia and their underlying working memory disorders.

Baddeley's Working Memory Model

Baddeley and Hitch (1974) proposed the original working memory model that formed the foundation of subsequent research in this area (Baddeley, 1986, 1992). The main components of this model include a *central executive system* (CES) and two slave systems. The central executive is considered the primary aspect of this system, as its job is to delineate control. This manager or supervisor is responsible for information processing and immediate storage, as well as for designating attention and resources to other components. The CES is seen as responsible for focusing, dividing, and switching attention (see Baddeley, 2002, for a discussion). The CES controls the two slave systems: the visuospatial sketchpad and the phonological loop. The visuospatial sketchpad retains visuospatial material in short-term memory. The phonological loop is composed of two systems as well: a phonological input store and an articulatory rehearsal process. The phonological loop is of particular interest when investigating linguistic processing deficits in aphasia. Here, verbally encoded information is rehearsed, recycling the verbal material, to refresh the memory trace. If the trace decays, the rehearsed information is lost. Baddeley hypothesized that the time limit for information to be rehearsed prior to decay is only 2 s. In other words, if more than 2 s of information enters the store and rehearsal is not allowed, this information could be lost because it exceeded the loop's capacity. The subvocal rehearsal of visual information (reading silently) is also considered to take place in the phonological loop as a part of articulatory rehearsal (Connor, MacKay, & White, 2000).

Studies have shown that word length can impact the number of words held in the rehearsal portion of the articulatory loop, due to its limited capacity (Baddeley, Chincotta, Stafford, & Turk, 2002; Baddeley, Thomson, & Buchanan, 1975; Henry, 1991). An example of this is the word length effect, where longer words lead to slower rehearsal times due to the fact that it takes longer to subvocally rehearse longer words. Additionally, there are other aspects that could cause a loss of information from the phonological loop. Interference at the various stages of information acquisition may impair verbal memory. For instance, interference from words that are phonologically similar could disrupt the items currently being rehearsed (Baddeley, 1986; Salame & Baddeley, 1982). This occurs as a result of a disruption in working memory performance due to an overlap of features stored in the phonological loop; it does not occur when items are phonologically dissimilar (Conrad, 1964). These data have been used as evidence that the information in the phonological loop is subvocally rehearsed in order to be remembered (Baddeley, 2003). Further, performance on working memory tasks may be hampered by the presentation of irrelevant information.

Recently, Baddeley (2000, 2002) has updated this model to include links to long-term memory (LTM) and a new subsystem. In 1999, Baddeley and Logie altered the CES to be more of an attentionally based system. However, this left a need for temporary storage, a way to combine visual and verbal information, and a link to information in the subsystems to LTM. Baddeley (2000, 2002, 2003) discussed the added links from working memory to LTM and proposed an "episodic buffer" that might link information from the slave systems to LTM. The episodic buffer was proposed as a storage structure that interfaces between the different systems. This recent addition alters the original 1974 model in an attempt to expand and update the model to fit with research that has occurred over the last 30 years. Regarding the 1974 model, Baddeley (2002) wrote that because of the limited capacity of the subsystems and the assumption that the CES's job relates solely to attention, explanations of various phenomena (such as recall of prose paragraphs) were difficult.

Basic knowledge about the ever-changing theoretical models in working memory is important for clinical application. For example, Vallar, Corno, and Basso (1992) found that patients with aphasia may demonstrate phonological loop deficits. This finding implies that speech-language therapy could differ for individuals with aphasia who have a preserved phonological loop working memory system versus individuals with a damaged phonological loop (Baddeley, 2003). Vallar et al.'s findings suggest that it would be important to assess auditory working memory in individuals with aphasia prior to treatment.

Daneman and Carpenter's Working Memory Approach

Although Baddeley has updated the original tripartite model, several other approaches were derived from the original 1974 theory. Daneman and Carpenter (1980) developed a measure to test the working memory capacity for language by looking at both the processing and storage functions of working memory in reading. They developed the concept of *working memory span*, which has been used extensively in the literature. Their approach is based on the assumption that working memory is of limited capacity, and this limited capacity must share resources between processing and storage (Baddeley & Hitch, 1974; Miller, 1956). Daneman and Carpenter (1980) argued that this could lead to individual differences in reading comprehension. For readers who are "more efficient," processes would be used more successfully, allowing more information to be stored and maintained. They argued that, by considering both processing and storage functions of working memory aspects in reading, their measure could differentiate a good reader from a poor reader. They posited that a good reader would be more likely to integrate information read, store it in LTM, and make it potentially available at more points of access for retrieval. The study required participants to read aloud sentences presented in sets, with the sets increasing in the number of sentences. The participant was required to recall the final word in each sentence, for a number of sentences. The greatest number

of words remembered equaled the working memory capacity of that individual, or the *reading span* (as it was termed). Daneman and Carpenter found that participants' performance on reading span tasks was consistent with limited working memory. In fact, participants reported attempting to retain the sentence-final words in working memory through various compensatory strategies (e.g., rehearsal). Their findings suggest that the reading span task taxed processing and storage capacity, was a predictor of reading comprehension in healthy individuals, and was a measure of individual differences.

Reading span has been used extensively in the literature as well as having been modified for use with other populations such as right hemisphere (RH) syndrome and closed-head injury (Schmitter-Edgecombe & Chaytor, 2003; Tompkins, Bloise, Timko, & Baumgaertner, 1994; Turner & Engle, 1989; Waters, Caplan, & Hildebrandt, 1987). For example, Tompkins and colleagues (1994) used a modified version to study individuals with RH syndrome to determine if working memory capacity deficits influence discourse comprehension. Tompkins et al. found that correlations of working memory capacity and comprehension for discourse were minimal; however, if processing requirements were increased, the magnitude of the effect increased for individuals with RH lesions. Work by various researchers on working memory span in different populations demonstrates the importance of individual differences and suggests that working memory span in aphasia be explored further.

Also, Just and Carpenter's (1992) work focused on working memory and how it relates to language comprehension. They focused on the CES and how language is stored and manipulated within working memory. Because language performance differed across individuals with different working memory capacities, Just and Carpenter argued that working memory capacity predicts performance on language comprehension tasks. Therefore, if an individual had limited working memory capacity, this would be expected to lead to poorer storage and processing efficiency, which would result in slower and less efficient processing of language comprehension. Again, the implication is that individual differences in working memory should be considered both in the non-brain-damaged population as well as in individuals with aphasia.

In relation to individuals with neurological deficits, Miyake, Carpenter, and Just (1994) studied decreased performance of healthy individuals by increasing task speed. They hypothesized that increasing the "load" required (i.e., limiting capacity) would elicit performance similar to that of individuals with aphasia. That is, if working memory capacity is reduced in healthy individuals, syntactic comprehension deficits like those seen in individuals with aphasia would result. In fact, it was found that similar patterns of breakdown occurred in healthy individuals, although some differences were noted as well. For example, it was found that even in a speeded reading task, healthy individuals were able to comprehend simple sentences while individuals with aphasia might not be able to do so. These findings suggest that decreases in working memory capacity may contribute to difficulty in syntactic comprehension that could be very important for individuals with aphasia.

Hasher and Zacks's Working Memory Approach

Another perspective on working memory that is different from the previously presented views is that of Hasher and Zacks (1988). They also assume that working memory is of limited capacity (resources) and that there is competition by the processes for this limited capacity (Baddeley & Hitch, 1974; Miller, 1956). However, Hasher and Zacks expanded this argument to include an explanation of what decreases the speed at which this limited capacity system operates. The premise of their theory is that irrelevant information in working memory takes up restricted space, thus limiting the space available for either processing or storage of relevant information. Much of their subsequent work (Connelly, Hasher, & Zacks, 1991; Zacks & Hasher, 1993) has focused on older adults and the decreased inhibition of task-irrelevant information. They have found that older adults do not perform as well on working memory measures as younger adults. They suggested that these older adults' working memory capacity reduction is not due to reduced capacity size, but rather to an inability to inhibit irrelevant information. The irrelevant information takes up processing space and leaves less space for the task-relevant information. In contrast, younger individuals are able to inhibit the irrelevant information, which allows working memory capacity to remain open for relevant information processing. In sum, predictions about performance on working memory tasks, according to Hasher and Zacks, could be made based on age and on inhibition problems. That is, because older people have more trouble inhibiting irrelevant information, their learning, retrieval, and comprehension performance will be poorer than that of younger people.

Over the years, research by Hasher and colleagues has centered on the idea that there are three functions of inhibition within working memory: It limits information that enters the system, it suppresses information already in working memory, and it restrains irrelevant information from taking over the working memory system. Support for Hasher and Zacks's work was found for older individuals (Gerard, Zacks, Hasher, & Radvansky, 1991). This research has demonstrated an age-related decrease in performance in relation to selecting which information is irrelevant in working memory. It has also been suggested that working memory capacity involves inhibitory control (Schelstraete & Hupte, 2002). If working memory capacity involves inhibitory control, and if older adults have decreased inhibitory control, then it is possible that individuals with aphasia may have reduced processing in part due to a decrease in inhibition.

Caplan and Waters's Working Memory Approach

Caplan and Waters (1999b) have disagreed with the idea of "an undifferentiated central executive ... model" (p. 121) as argued by Just and Carpenter (1992) and colleagues (King & Just, 1991; MacDonald, Just, & Carpenter, 1992; Miyake et al., 1994). Where Just and Carpenter argued for a single resource model, Caplan and Waters have stated that such a model fails to explain performance for syntactic processing for individuals with brain damage (Caplan & Waters, 1999b; Waters & Caplan,

TABLE 1. Summary of approaches presented.

Approach	Theoretical underpinning	Components/processes	Predictions on WM tasks	Relation to aphasia
Baddeley	Limited capacity attentional system; memory decays in about 2 s unless rehearsed; emphasis on structures versus processes.	CES and two slave systems (phonological loop and visuospatial sketchpad); episodic buffer.	Presentation of irrelevant information may impair immediate serial verbal memory.	People with aphasia may demonstrate phonological loop deficits.
Daneman & Carpenter	Limited capacity for computation and storage; individual differences account for variance in performance.	Comprehension consists of many processes that may occur simultaneously.	Poor performance and efficiency on WM tasks; increases in task speed or higher demands on activation produced deficits in performance.	Decreases in WM capacity may lead to problems in syntactic comprehension often seen in aphasia.
Waters & Caplan	Verbal WM is divided into several components; a collection of processes.	Separate language interpretation resource theory; initial or unconscious processing aspect and a conscious, postinterpretive processing component.	Increased syntactic complexity does not lead to decreased performance for those with decreased working memory capacity.	The ability to use syntactic structure to resolve sentence meaning is retained (Waters et al., 1991).
Hasher & Zacks	Limited capacity and competition for resources; inability to inhibit irrelevant information is the culprit of space reduction.	Three functions of inhibition: controls accessibility, deletion and suppression of information, and prevents some information from monopolizing WM.	Inability to inhibit is affected by age. Inhibition problems will affect learning, retrieval, and comprehension performance.	Processing deficits observed in people with aphasia may be due, in part, to decreased inhibitory control.

Note. WM = working memory; CES = central executive system.

1996). They have argued that in language comprehension there are separate aspects used in the working memory system. This view has been termed the “separate language interpretation resource theory” by Caplan and Waters (1999a, 1999b). This theory states that there are two parts of the working memory system that contribute to language comprehension. The first aspect focuses on the initial meaning of an utterance (unconsciously processed), whereas the second component involves a level of processing that is more conscious and controlled. Specifically, assigning and applying the syntactic structure of a sentence (assigning *boy* to *fell* in *The boy who chased the girl fell*) is separate from what is typically measured in verbal working memory. Therefore, the verbal working memory system is specialized to include different components, with one such process applicable to determining meaning (Waters & Caplan, 2004).

As mentioned previously, Just and colleagues (King & Just, 1991; MacDonald et al., 1992) have put forth the theory that limited working memory capacity leads to decreased performance for syntactically complex sentences if a concurrent memory load is required. Conversely, Waters, Caplan, and Hildebrandt (1991) found that individuals with aphasia performed poorly on Daneman and Carpenter’s (1980) Reading Span Test but retained the ability to use syntactic structure to resolve sentence meaning. Waters et al. have argued that individuals with limited working memory capacity do not demonstrate such a difficulty because the working memory system is distributed into different segments (Waters & Caplan, 1996, 1999; Waters, Rochon, & Caplan, 1998). Because patients demonstrated a preserved ability to manipulate intricate syntactic structures while still demonstrating impairments in working memory, Caplan

and Waters (1995) argued that these findings discount Just and Carpenter’s single process approach.

In summary, Baddeley’s theory is the touchstone for working memory research that has led to other approaches and measures which have influenced the literature. For instance, Baddeley’s work enabled Daneman and Carpenter to develop the Reading Span Test to measure working memory capacity. The Reading Span Test has been used extensively in either its original or modified form and has been important in the development of later research such as Just and Carpenter’s and Waters and Caplan’s (see Table 1 for an outline of these theories). The working memory approaches introduced in this review demonstrate that there are diverse, and sometimes discrepant, theories in the literature. One controversy outlined above is whether working memory is a unitary process or consists of subprocesses as suggested by Caplan and Waters (1999b). Despite this debate in the literature, several researchers still argue that there is a pool of resources in working memory that allows for the temporary storage and manipulation of activated information (see Connor et al., 2000).

Working Memory Impairment in Aphasia

Several researchers have presented findings of limitations in working memory (e.g., inhibition, interference, and speed of processing; Hasher & Zacks, 1988; Salthouse, 1994). These limitations have been argued to be constrained by the availability of resources or the allocation of available resources (e.g., Caplan & Waters, 1995; L. L. LaPointe & Erickson, 1991; McNeil et al., 1991). Although various theories may differ in details regarding the processing

of linguistic information, there appears to be a general consensus that individuals with aphasia have limited resources and/or disrupted allocation efficiency of resources (e.g., Caplan & Waters, 1995; L. L. LaPointe & Erickson, 1991; McNeil & Kimelman, 1986; McNeil et al., 1991; Murray et al., 1997a, 1997b; Slansky & McNeil, 1997; Tseng et al., 1993). Findings such as these have led to further questions regarding the role of working memory in language, specifically for individuals with aphasia. That is, researchers have found that individuals with aphasia present reduced working memory ability (e.g., Caspari et al., 1998; Friedmann & Gvion, 2003; Wright et al., 2003; Yasuda & Nakamura, 2000). In the following section, we will review the neural network for working memory capacity and its significance in aphasia, as well as results of previous investigations of memory function in adults with aphasia.

Neural Correlates for Working Memory

Functional neuroimaging techniques, such as functional magnetic resonance imaging and positron emission tomography, have been used by researchers to identify neural activation patterns occurring during working memory tasks (for reviews, see Baddeley, 1998; Carpenter, Just, & Reichle, 2000; McCarthy, 1995; Owen, 1997; Smith & Jonides, 1997). These techniques allow investigators to make hypotheses regarding brain regions involved in verbal working memory.

Baddeley's working memory model was applied to investigations of neural activation patterns as they related to behavioral performance on tasks of working memory. More specifically, studies reviewed included tasks designed to measure neural correlates for the phonological loop, which include frontal and parietal regions. Frontal regions include prefrontal cortex (i.e., dorsolateral prefrontal cortex [DLPFC]) and Broca's area. Investigators have hypothesized that the DLPFC is associated with active maintenance of information (Barch et al., 1997; Jonides, Lauber, Awh, Satoshi, & Koeppe, 1997; Newman, Just, & Carpenter, 2002). As task memory load increased, the involvement of the DLPFC increased. An increase in DLPFC suggests that this area is involved in maintaining information while additional information is processed. Broca's area has also been activated in several investigations, and its role is believed to be mediating verbal rehearsal (Braver et al., 1997; Cohen et al., 1997; Jonides et al., 1997; Newman et al., 2002; Smith, Jonides, Marshuetz, & Koeppe, 1998). Other frontal regions activated in working memory studies include the premotor and supplementary motor areas. Though these areas are not consistently discussed, it is hypothesized that these regions are also involved in mediating rehearsal and maintaining information (Fiez, Raichle, Balota, Tallal, & Petersen, 1996; Smith & Jonides, 1997). The parietal cortex also plays a significant role in verbal working memory and has been consistently activated across studies. Jonides et al. (1997) suggested that the posterior parietal cortex mediates storage of verbal material, and these findings have been supported by others (Newman et al., 2002; Smith & Jonides, 1997; Smith et al., 1998).

These findings have significant implications for adults with aphasia, though few investigations have been conducted to identify neural substrates recruited during working memory tasks in adults with aphasia. Individuals with aphasia frequently have brain damage in the left frontal or left parietal cortices and may demonstrate a working memory deficit. Alternatively, adults with aphasia may not present with lesions in these areas directly, but pathways to these areas may be damaged, which, in turn, could contribute to a deficit in working memory ability.

Investigations of neural substrates recruited during working memory activities in adults with aphasia are warranted for several reasons. For example, Price (2000) suggested that investigations with adults who have aphasia could further strengthen cognitive and linguistic models by identifying (a) brain regions sufficient and necessary for specific tasks, (b) brain regions that are task dependent, and (c) activation patterns that correspond to language recovery. Though further investigation is needed in this area, there are limitations to using functional neuroimaging techniques with individuals who have aphasia as well as limitations with interpretation of results of these studies. Results of studies comparing activation patterns between adults with and without brain damage are interpretable only if the participants are able to perform the task (Price, 2000). This may be a challenge for individuals with aphasia by limiting who can participate in these studies. For example, adults with severe aphasia presentations would not be appropriate for such investigations. Another challenge is developing tasks that are appropriate for individuals with and without aphasia. Finally, findings from neuroimaging studies should be interpreted conservatively. As Carpenter et al. (2000) conclude from reviewing the executive function and working memory functional neuroimaging literature, "There is no one-to-one mapping of process to cortical region" (p. 197), and the goal of the research needs to be modified to determine the "cortical mosaic" (p. 197).

Impaired Working Memory

As suggested from results of functional neuroimaging investigations, adults with aphasia may present with a working memory deficit. Researchers have been investigating memory function, specifically long- and short-term memories, in adults with aphasia for over 30 years. Thus, the notion that individuals with aphasia have impaired memory systems in conjunction with their language comprehension and production deficits has been well documented (e.g., Burgio & Basso, 1997; L. L. LaPointe & Erickson, 1991; Meier, Cohen, & Koemeda-Lutz, 1990; Ronnberg et al., 1996; Warrington & Shallice, 1969). For example, Ronnberg and colleagues (1996) studied memory ability in adults with mild aphasia. They measured short-term memory function by performance on digit and word span tasks. From the results of the study, they reported that verbal short-term memory was impaired in their participants with mild aphasia; these findings are supported by others (e.g., Ween, Verfaellie, & Alexander, 1996). On average, the participants with aphasia recalled one less digit or word than their

neurologically intact (NI) counterparts, which resulted in a statistically significant difference.

Working memory ability of adults with aphasia has received a lot of attention in the literature in recent years, such that, in some investigations, it has not been specifically measured but has been identified as a possible contributor to aphasic adults' poor performance on language-processing tasks (e.g., Hough, Vogel, Cannito, & Pierce, 1997; Wright & Newhoff, 2004). For example, in these investigations it is suggested that providing redundant information improves comprehension performance by allowing for adequate distribution of the limited processing resources available to adults with aphasia so that task demands are met. That is, individuals with aphasia presumably present with a limited working memory capacity, and redundant information is a strategy to enhance language comprehension by overcoming this limitation.

Caspari et al. (1998) measured working memory ability in adults with aphasia. They were interested in whether a relationship existed between working memory and reading and listening comprehension abilities in individuals with aphasia. They included 22 individuals with aphasia who ranged in severity and type of aphasia. Included were individuals presenting with severe ($N = 5$), moderately severe ($N = 2$), moderate ($N = 3$), mild-moderate ($N = 3$), and mild ($N = 9$) forms of aphasia. A modified Daneman and Carpenter (1980) Reading Span Test was used to measure working memory. In its current form, the task was not appropriate for use with adults who had aphasia. Modifications included (a) shortening the sentences from 13 to 16 words to 5 to 6 words, (b) changing the recall task to a recognition task, and (c) changing the recognized word from the final word of the sentence to a separate word from the sentence, similar to L. B. LaPointe and Engle (1990). An example sentence and final word were *The man played poker* and *car*. Two versions of the task were administered: a reading version and listening version. Language function was measured by participants' performance on the Aphasia Quotient subtests of the Western Aphasia Battery (WAB; Kertesz, 1982), and reading comprehension ability was measured by performance on the Reading Comprehension Battery for Aphasia (RCBA; L. L. LaPointe & Horner, 1979). Several participants were too impaired to complete the reading span task; thus, correlation results between the reading span and RCBA scores are based on 14 participants: 13 with fluent aphasia and only 1 with nonfluent aphasia.

Results indicated significant, positive correlations between listening span and WAB Aphasia Quotient scores and reading span and RCBA scores. Caspari et al. (1998) concluded that working memory capacity is an accurate predictor of language comprehension performance, adding empirical evidence to the notion that a preserved working memory system is necessary for successful comprehension. However, these conclusions should be interpreted conservatively for several reasons. The working memory and language measures may be measuring similar functions, contributing to the significant correlations. For example, the working memory task required comprehension skills at the word (recognition task) and sentence level, two skills measured by the WAB. Finally, individuals without brain

damage were not included in the study to compare performance, which would allow for a stronger argument that the participants presented with reduced working memory capacity.

Tompkins et al. (1994) investigated working memory ability in adults with right and left hemisphere brain damage as one part of their study. They included 25 adults with right hemisphere brain damage (RHD), 25 with left hemisphere brain damage (LHD), and 25 NI individuals. Only 16 of the LHD participants had been previously diagnosed with aphasia; all LHD participants answered personally relevant yes-no questions with 100% accuracy. Further, the LHD group performed significantly more poorly on the auditory comprehension measure compared with the RHD and NI groups. To measure working memory, Tompkins et al. developed a listening span task similar to Daneman and Carpenter's (1980) Reading Span Test; however, the sentences were shorter and simpler. Participants were instructed to judge the truthfulness of each sentence, then retain the final word of each sentence for subsequent recall. They found that both brain-damaged groups made more errors on the task than the control group. For example, there were 42 opportunities to recall final words, and mean errors for the groups were 12.4 for the RHD, 16.8 for the LHD, and only 6.4 for the NI group. Participants within the LHD group were also divided into high and low auditory comprehension subgroups, and additional analyses were performed. Results indicated that the low comprehension group made significantly more word errors ($M = 23.6$) on the working memory measure compared with the high comprehension group ($M = 11.7$), suggesting that severity of comprehension impairment affected performance on the working memory measure, or, alternatively, working memory capacity affected comprehension ability.

Tompkins et al. (1994) reported that this working memory measure might be a useful predictor of individuals' performance on tasks high in information-processing load. That is, if a task does not maximize the individual's working memory capacity limits, then no relationship between performance on the task and working memory capacity should occur. Conversely, if the task does maximize capacity limits, then a significant relationship is expected. Tompkins et al. found that their participants with brain damage had reduced working memory capacities. Tasks that might not tax the non-brain-damaged individuals' working memory capacity may tax the working memory limits of individuals with brain damage, resulting in poor performance on that task. For example, comprehending ambiguous or incongruent sentences might require a high processing load for adults with brain damage, but not for those without brain damage.

Wright et al. (2003) investigated working memory performance in adults with aphasia using Tompkins et al.'s (1994) listening span task. Participants included 10 adults with fluent aphasia, 10 adults with nonfluent aphasia, and 10 NI adults. Severity and type of aphasia were determined by performance on the WAB. All participants presented with good auditory comprehension ability, and aphasia severity was mild to moderate. The participants with aphasia made significantly more errors on the measure as compared with

their NI counterparts. Also, similar to Caspari et al.'s (1998) findings, performance on the working memory measure significantly correlated with oral language ability, as measured by WAB Aphasia Quotients. Similar cautions raised when interpreting the results of Caspari et al.'s study apply here as well. That is, the working memory measure and WAB may share some linguistic and cognitive properties that may have contributed to the significant correlation.

In a recent investigation, Friedmann and Gvion (2003) studied the relationship between verbal working memory and sentence comprehension in adults with aphasia. Participants included 3 adults with conduction aphasia, 3 adults with agrammatic aphasia, and an NI group. Measures of working memory included several span measures: digit, word, and nonword, a listening span task similar to Tompkins et al. (1994), and a 2-back task (see below for description). Friedmann and Gvion reported that the results of the study indicated both aphasia groups presented with limited working memory abilities but performed differently on the sentence comprehension task. The participants with agrammatic aphasia performed poorly in comprehending object-relative sentences, whereas the participants with conduction aphasia did well comprehending these sentences. Friedmann and Gvion concluded that the effect of a verbal working memory deficit on sentence comprehension is dependent on the type of processing (i.e., semantic, syntactic, or phonologic) required in the sentence, adding support to Caplan and Waters's (1999a) theory that there are separate verbal working memory systems.

Results of the previous investigations indicate that individuals with aphasia have impaired working memory systems. Further, the working memory deficit does affect language performance as indicated by significant correlations between measures of working memory and language function. However, the working memory tasks used were not specifically designed for use with adults who have aphasia; consequently, performance on these tasks may be attributed to other problems, such as difficulty performing tasks requiring two activities (e.g., comprehension and recall) or requiring a verbal response, rather than solely a deficit in working memory. Other issues to consider that have not been addressed in the literature are the relationship between performance on working memory measures and communication situations experienced everyday, and the relationship between impaired performance on working memory measures and breakdowns in everyday communicative activities.

Measures of Working Memory

The ability to follow directions to a friend's house while driving might be affected by a working memory deficit. Likewise, remembering to ask the doctor all the questions you needed answers for regarding medicines and health issues might be affected by working memory ability. Working memory capacity can be considered a measure of resources available for storing, processing, and integrating information; in other words, there is a limit to the amount of resources available. Referring to the second example, there

is a limit for the amount of resources available for temporarily storing the questions for later recall while processing the information presented by the doctor during the exam. If the individual has a reduced working memory capacity and not enough resources available, then questions may be lost or information the doctor presents may not be processed or may be forgotten (Just & Carpenter, 1992). Results of investigations comparing individuals who have aphasia with NI adults suggest that the former demonstrate a reduced capacity and have reduced resources available to perform linguistic tasks (e.g., Tompkins et al., 1994; Wright et al., 2003). Further, researchers have suggested that limited resources are available for storing, processing, and integrating linguistic information (e.g., Caplan & Waters, 1995; Murray et al., 1997a, 1997b; Slansky & McNeil, 1997; Tseng et al., 1993). Consequently, a purpose for measuring and assessing working memory in adults with aphasia is to determine the resources available for storing, processing, and integrating information. A challenge, however, is finding an appropriate measure.

Researchers have modified several available measures for use with this population. For example, modifications for measuring working memory ability in adults with aphasia have included changing a recall activity to a recognition task (Caspari et al., 1998; Friedmann & Gvion, 2003) or simplifying a measure designed for use with NI individuals (e.g., Caspari et al., 1998; Friedmann & Gvion, 2003; Tompkins et al., 1994). We will review several measures currently available for use with adults who have aphasia and discuss strengths and weaknesses of each, as well as what they purportedly measure. Refer to Table 2 for aphasia data and NI data for the measures.

Wechsler Memory Scale—Third Edition (WMS-III)

The WMS-III (Wechsler, 1997) has three subtests that measure aspects of working memory. These include forward digit span, backward digit span, and letter-number sequencing. Span tasks have been used extensively in research to measure working memory storage, and several researchers have developed their own as well (e.g., Friedmann & Gvion, 2003). Span tasks used in the literature have included digits, words, letters, and nonwords. The task has been modified for use with adults with aphasia in several studies by changing the response type for digit span, for example, from recall to recognition (e.g., Friedmann & Gvion, 2003; Sakurai et al., 1998). When using the WMS-III, however, response type is verbal recall only. A benefit to using the WMS-III is that the test is standardized and has normative data for adults up to age 89 to compare individuals' performance. See Table 2 for WMS-III raw scores for older adults. For the forward digit span, digits are presented auditorily and recalled in the order they were presented. The subtest increases in complexity by increasing the number of digits for recall, starting with two and continuing through nine. For each level, participants have two opportunities to recall digits presented. If both sets are missed at a level, then the subtest is discontinued. Administration for the backward digit span is identical, but participants recall the digits in the reverse order in which they were presented. The

TABLE 2. Summary of performance by individuals with and without aphasia on measures of working memory.

Measure	Participants	Scoring system	Participants' performance
WMS-III digit span total (FDS and BDS)	NI adults age 55–64 years ^a	Raw score max = 30	Raw score 11–21 represents 16–84 percentile range
WMS-III LNS	NI adults age 55–64 years	Raw score max = 21	Raw score 7–12 represents 16–84 percentile range
Caspari et al. (1998) listening span task	Aphasic adults age (<i>M</i>) 62.8 years; mild to severe aphasia (<i>N</i> = 22)	Span score max = 6.0	<i>M</i> = 2.68, <i>SD</i> = 1.4, range = 0.5–6.0
Caspari et al. (1998) reading span task	Aphasic adults age (<i>M</i>) 59.4 years; mild to mod/severe aphasia (<i>N</i> = 14)	Span score max = 6.0	<i>M</i> = 3.07, <i>SD</i> = 1.38, range = 1.0–5.5
Tompkins et al. (1994) listening span	LHD age (<i>M</i>) 63.8 years (<i>N</i> = 21); RHD age (<i>M</i>) 64.5 years (<i>N</i> = 25); NI age (<i>M</i>) 65.6 years (<i>N</i> = 25)	Word recall errors (max = 42) and true/false (t/f) errors (max = 42)	LHD: word recall <i>M</i> = 16.8, <i>SD</i> = 10.8, range = 1–36; t/f <i>M</i> = 0.8, <i>SD</i> = 1.6, range = 0–3 RHD: word recall <i>M</i> = 12.4, <i>SD</i> = 5.9, range = 2–22; t/f <i>M</i> = 1.0, <i>SD</i> = 2.0, range 1–10 NI: word recall <i>M</i> = 6.4, <i>SD</i> = 4.6, range = 0–17; t/f <i>M</i> = 0.3, <i>SD</i> = 0.5, range = 0–2
Wright et al. (2003) listening span	Aphasic adults ^b age (<i>M</i>) 65.8 years (<i>N</i> = 20); NI adults age (<i>M</i>) 64.3 years (<i>N</i> = 20)	Combined error score (t/f errors + word recall errors) max = 84	Aphasic adults: <i>M</i> = 23.3, <i>SD</i> = 6.78, range = 11–37 NI adults: <i>M</i> = 10.3, <i>SD</i> = 4.8, range = 1–19

Note. WMS-III = Wechsler Memory Scale—Third Edition; FDS = forward digit span; BDS = backward digit span; LNS = letter-number sequencing; NI = neurologically intact; LHD = left hemisphere brain damaged; RHD = right hemisphere brain damaged.

^aRaw scores are reported for selected age range from the WMS-III. ^bIncluded aphasic adults mild to moderately impaired.

forward digit span is appropriate for measuring short-term memory or working memory storage; however, because of the heavy load placed on storage but not on manipulation, it is not an appropriate measure for determining an individual's working memory capacity limit (Connor et al., 2000). Though the backward digit span also places a heavy load on storage, it does require some manipulation.

The letter-number sequencing subtest is new to the third edition of the WMS. For this subtest, letters and numbers are intermixed. The letters and numbers are auditorily presented, and the participant is instructed to recall the numbers first, then letters, each in ascending order. Similar to the span subtests, it starts with two items and then increases in complexity by increasing the number of items. The most difficult level contains eight items—four letters and four numbers. There are three opportunities at each level, and the test is discontinued when the client makes an error on all three sets at a level. This subtest is a more appropriate measure of working memory due to the fact that it requires storage as well as manipulation of information. However, because of the complexity of the instructions, it may not be appropriate for many individuals with aphasia (Connor et al., 2000). The span subtests as well as the letter-number sequencing subtest require verbal responses; therefore, many individuals with aphasia or other acquired neurogenic disorders (e.g., dysarthria, apraxia of speech) may not be appropriate candidates for receiving the measures. However, these measures would be appropriate for individuals presenting with mild forms of aphasia. Further, Friedmann and Gvion (2003), Ronnberg et al. (1996), and Ween et al.

(1996) used digit span tasks with their participants who had aphasia.

Reading Span Test and Variants

The Reading Span Test was developed by Daneman and Carpenter (1980) as a measure of working memory capacity in adults without neurological impairments. Since its development, this measure has been modified, and several versions have been developed for use with individuals who have brain damage. The dual-task component of the measure (comprehension and recall/recognition) has remained consistent across the different versions. For the comprehension component, Tompkins et al.'s (1994) version requires participants to judge the truthfulness of each statement (e.g., "you sit on a chair") following each sentence, whereas Caspari et al. (1998) followed the recognition activity with comprehension questions.

The other component of the task—recall/recognition of the final word of the sentences, word selection in terms of frequency of occurrence, imageability, and part of speech—has varied. For Daneman and Carpenter's (1980) test, the final word type and frequency of occurrence were not controlled. Final words included nouns, verbs, adverbs, and pronouns. Caspari et al. (1998) selected final words that were high in frequency of occurrence and picturability, whereas Tompkins et al.'s (1994) final words represented common lexical items. Further, for recall versus recognition of the final word, Daneman and Carpenter (1980) and Tompkins et al. required verbal recall, whereas Caspari et al.

(1998) required recognition. Tompkins et al. developed their measure for use with adults with RHD and reported that several of the participants with LHD were not able to complete the task because of the verbal recall component. Tompkins et al. also cautioned that the task was not appropriate for individuals with severe aphasia or apraxia of speech, and, subsequently, impaired verbal abilities. Caspari et al. used a recognition task rather than a recall task for this reason, so they could administer the measure to adults with aphasia who had verbal production difficulties.

Scoring for these measures has varied as well. A common method used is computing a span score—this represents the highest number of items (e.g., the final word in a number of sentences) that the participant was able to recall/recognize (Caspari et al., 1998; Daneman & Carpenter, 1980; Friedmann & Gvion, 2003). If the participant correctly recalls the final words in order for a set containing five sentences but is unable to do so for a set containing six sentences, then the participant's span is five. Tompkins et al. (1994) used a combined error score, which included the total number of recall and judgment errors made by the participant. The combined error score allows for additional inspection of an individual's performance on the task. The examiner is able to determine the individual's ability to correctly comprehend the sentences while retaining the final word for later recall. Also, the entire test must be administered, which allows for additional assessment of any strategies the individual may use, such as when the test becomes more difficult, if the individual begins to "trade off" accuracy of comprehension for recall. The listening span task may be an appropriate measure for some individuals with acquired neurogenic disorders, but not all. Lehman and Tompkins (1998) have shown that Tompkins et al.'s (1994) listening span task is a valid and reliable measure of RHD individuals' working memory capacity. Nevertheless, it would not be an appropriate measure of working memory ability for adults with aphasia who present with a verbal production deficit. Alternatively, adults with aphasia who have severely impaired auditory comprehension may perform poorly on the activity requiring judging the truthfulness of the sentence and could then be misidentified as having a significant working memory deficit. If there are no concerns about the individual's verbal production abilities and they do not present with significantly impaired comprehension ability, then this test may be appropriate. However, this measure is not appropriate for individuals with severe aphasia.

N-Back Tasks

A common measure of working memory used in functional neuroimaging studies is the *n*-back task. This task has not been used extensively with adults who have aphasia, but it has been used extensively to investigate working memory ability in NI adults and adults with schizophrenia (e.g., Callicott et al., 2000) and to identify neural correlates for working memory (e.g., Jonides et al., 1997). The *n*-back task requires the individual to continually update and maintain information in his or her working memory. During this task, a stream of items is presented (verbally or visually)

and the participant is instructed to respond when the current item is the same as the one *n* back. For example, for a 1-back task the individual responds when the current item is the same as the one immediately preceding it.

This task is a commonly used measure of working memory ability in functional neuroimaging studies for several reasons. The task does not require a verbal response; participants can respond with a button press. Task difficulty can be increased by increasing the *n* back, thus increasing memory load and taxing the participant's working memory system. Also, by including several levels (i.e., 0-back, 1-back, 2-back), a baseline task is not needed; rather, comparisons can be made between the different levels, which allows for identifying brain regions associated with increasing memory load. For many of the same reasons, this task would be an appropriate measure of working memory ability in adults with aphasia (Downey et al., 2004).

A recent study of working memory ability in adults with aphasia used the *n*-back task as well as several other measures of short-term and working memory (Friedmann & Gvion, 2003). Friedmann and Gvion included a 2-back task in their study, but not other levels of *n*-back (i.e., 0-back or 1-back). Lists were presented auditorily, and three list types were included: digits, short animal names, and long animal names. The adults with aphasia performed less accurately than their NI counterparts on the 2-back task.

Inspecting performance of individuals with aphasia on an *n*-back task that includes multiple levels would allow for identifying baseline performance as well as identifying when the extent of working memory capacity is reached, which in turn would indicate whether adults with aphasia vary in terms of capacity size, as NI individuals do (Just & Carpenter, 1992). A challenge to using an *n*-back task is the limited data available with individuals who have aphasia for comparison. Also, the variability in task stimuli across studies makes it difficult to interpret what would be considered preserved versus impaired working memory ability. However, this measure could potentially be the most appropriate measure for use with individuals who have aphasia because those with more severe presentations as well as individuals with verbal production impairments would be able to perform the task.

There are several measures available that can be modified for individuals with aphasia; however, caution must be taken when interpreting these individuals' performance on these tasks. Several available measures, even after modification, may still require preserved language function for an accurate measure of working memory ability. Issues to consider when selecting a working memory measure, then, include response modality (i.e., verbal vs. nonverbal) and any comprehension requirements.

A necessary direction for future research in this area is to develop an appropriate measure of working memory ability for use with adults who have aphasia. Further, performance data by NI individuals on these modified measures as well as newly developed measures are needed to compare performance and determine whether an individual with aphasia has a working memory deficit. Another issue to consider is individual differences in working memory capacity size (Just & Carpenter, 1992). Studies are needed that

identify the range of normal performance on working memory measures. A concern with individuals who have aphasia is whether a decline in working memory capacity is due to the brain damage or representative of premorbid abilities. Daneman and Carpenter (1983) reported a relationship between verbal working memory ability and verbal Scholastic Aptitude Test scores with young adults. Masson and Miller (1983) reported a similar relationship, but with a standard test of reading comprehension. Tompkins et al. (1994) found a significant relationship between word recall errors on the working memory measure and estimated IQ (Wilson, Rosenbaum, & Brown, 1979). These findings suggest that, with patients who have aphasia, estimated IQ or some measure of premorbid general knowledge may be a useful predictor of premorbid working memory ability.

Conclusion and Clinical Implications

Theories of working memory are evolving in response to empirical findings of working memory ability in adults with and without aphasia. A theoretical framework of working memory can aid in our understanding of a disrupted system (e.g., after stroke) and how this relates to language comprehension and production. Additionally, understanding the theoretical basis of working memory is important for the measurement and treatment of working memory. Researchers investigating working memory ability in adults with neurogenic impairments have found that these participants present with reduced working memory capacities (Caspari et al., 1998; Friedmann & Gvion, 2003; Tompkins et al., 1994; Wright et al., 2003), and a relationship between working memory ability and language ability has been found (Caspari et al., 1998; Wright et al., 2003). Possibly, the relationship between working memory and language ability is attributed to allocation of resources. That is, working memory tasks may measure the amount of resources available for performing linguistic tasks.

Recently, several investigators have treated working memory deficits in adults with aphasia and achieved mixed results (Francis, Clark, & Humphreys, 2003; Mayer & Murray, 2002). Francis et al. (2003) used a repetition activity as their task for treating working memory in an adult with aphasia. During the course of treatment, the length of sentences repeated increased. Following treatment, they reported that the participant's performance improved on backward digit span, sentence repetition, and sentence comprehension tasks, but not forward digit span. They suggested that the participant's working memory improved, but short-term memory (i.e., storage component only) did not. Further, they suggested that the results support a capacity-constrained model. That is, capacity size did not change in response to treatment; however, processing efficiency did improve. In other words, the participant was able to allocate available resources more efficiently to perform the tasks.

Mayer and Murray (2002) treated working memory in an adult with aphasia and acquired alexia. An alternating-treatment-plus-baseline design was used; the participant received two treatments within each 2-hr session, and order of treatments was randomized across sessions. The two treatments used included one addressing text-level reading

ability and the other a cognitive treatment addressing the working memory deficit. The latter treatment was similar in design to Daneman and Carpenter's (1980) Reading Span Test. The participant performed two tasks: judging the grammaticality of each sentence and identifying the semantic category that matched the final words of the sentences in a set. Task complexity increased by increasing the number of semantic categories identified for each set of sentences. Results were inconclusive; though the participant's reading rates improved, minimal improvement was found in comprehension and working memory abilities. Further, because of the study design, improvement could not be attributed to a single treatment.

These studies are a step forward in addressing treatment of working memory ability in clinical populations. Future investigations of measurement and treatment of working memory are warranted; only then will we be able to determine the role of working memory in language processing, and vice versa. Some potential questions are: What is the exact nature of the relationship between working memory and language? Will an individual's language improve if working memory deficits are treated in therapy? If working memory is damaged, how can we alter therapy for individuals effectively? These potential questions are already being approached by researchers, and research needs to continue in this area to strengthen assessment and treatment approaches for adults with aphasia.

Acknowledgments

The authors would like to acknowledge the helpful comments from Carrah James on a previous version of this article. Portions of this article were presented at the annual convention of the American Speech-Language-Hearing Association in Chicago, November 2003.

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Received May 25, 2004

Revision received November 3, 2004

Accepted February 25, 2005

DOI: 10.1044/1058-0360(2005/012)

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