Working Memory in Adults with Aphasia: Considering Effort Invested to Verbal and Spatial Tasks through a Physiological Measure – Heart Rate Variability

by

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ABSTRACT

Working memory (WM) and attention deficits have been well documented in individuals with aphasia (IWA) (e.g. Caspari et al., 1998; Erickson et al., 1996; Tseng et al., 1993; Wright et al., 2003). Research into these cognitive domains has spurred a theoretical shift in how aphasia is conceptualized – from a purely linguistic disorder to a cognitive-information processing account. Language deficits experienced by IWA may result from WM impairments or from an inability to allocate cognitive effort to the tasks. However, how language impacts performance on these tasks has not been readily investigated. Further, there is a need for a more direct measure of effort invested to language tasks.

Heart rate variability (HRV) is a physiological measure of cognitive workload that has been used to measure effort in neurologically intact participants. Objectives of the study included: (1) determining the feasibility of using HRV as a measure of effort IWA invest into verbal compared with spatial WM tasks, (2) Comparing participants' performance on verbal and spatial WM tasks; and (3) determining the relationship among performance, perceived task difficulty, and HRV across verbal and spatial tasks. Eleven IWA and 21 age- and education-matched controls completed verbal and spatial n-back tasks at three difficulty levels. Difficulty ratings were obtained before and after each task.

Results indicated spatial WM was relatively preserved compared with verbal WM for the aphasia group. Additionally, the aphasia group was better at rating task difficulty after completing the tasks than they were at estimating task difficulty prior to completing the tasks. Significant baseline-task differences in

HRV were found for both groups. Relationships between HRV and performance, and HRV and task difficulty were non-significant.

Results suggest WM performance deficits in aphasia may be primarily driven by their language deficit. Baseline-task differences in HRV indicate effort is being allocated to the tasks. Difficulty ratings indicate IWA may underestimate task demands for both verbal and spatial stimuli. However, the extent to which difficulty ratings reflect effort allocated remains unclear. Additional research is necessary to further quantify the amount of effort IWA allocate to verbal and non-verbal tasks.

DEDICATION

To Charla Cotton for your great sacrifice, encouragement, wisdom, and love.

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INTRODUCTION

Aphasia is an acquired neurogenic disorder impacting a person's ability to comprehend and produce language. Although communication is affected, researchers suggest that the underlying deficit may not be solely linguistic (McNeil, Odell, & Tseng, 1991; Erickson, Goldinger, & LaPointe, 1996; Murray, Holland, & Beeson, 1997a; Murray, Holland, & Beeson, 1997b; Wright, Newhoff, Downey, & Austerman, 2003). Individuals with aphasia also show impairments on attention and working memory tasks (Caspari, Parkinson, LaPointe, & Katz, 1998; Erickson et al., 1996; Murray, 2004; Tseng, McNeil, & Milenkovic, 1993; Wright, et al., 2003; Wright & Shisler, 2005). According to the resource allocation theory of aphasia, impaired performance by individuals with aphasia on attention and working memory tasks is at least partially due to an impaired ability to allocate cognitive resources to the tasks. However the term "resources" represents a vague construct that is difficult to directly measure (McNeil, 1981; McNeil, et al., 1991). Others have explained this deficit as an impaired ability to match effort with task demands (e.g. Murray et al., 1997a; Clark & Robin, 1995; LaPointe & Erickson, 1991). There is some evidence that individuals with aphasia misperceive the demands of cognitive-linguistic tasks (e.g. Murray et al., 1997a; Tseng, et al., 1993), and do not invest the effort necessary for successful completion of these tasks (Murray et al., 1997a; Clark &

Robin, 1995; LaPointe & Erickson, 1991). This evidence comes primarily from subjective self ratings of task difficulty/effort invested, but also from evidence that individuals with aphasia were impaired in their ability to utilize probability information to enhance performance on lexical decision tasks (e.g.Tseng, et al., 1993).

However, investigations of attention and working memory performance and of effort and task difficulty evaluation have included measures that could be considered “language heavy.” That is, the tasks require semantic, syntactic, and/or phonological processing to follow the task instructions and/or formulate a response. Because language is known to be impaired in aphasia, it is difficult to distinguish deficits in cognitive processes underlying language from the language deficits germane to individuals with aphasia. To better understand the nature of underlying cognitive deficits in aphasia, it is essential that language processing is not required for successful task performance.

Baddeley’s model of working memory provides a useful construct for investigating working memory in individuals with aphasia. According to this model, verbal and visual-spatial information are stored separately in the phonological and spatial buffers and function to temporarily hold and manipulate information. Although verbal and spatial information are stored separately, these two components share an executive system that directs and monitors information storage and manipulation within the buffers. This executive component is limited in capacity and corresponds closely with the executive control system specified in attention models (e.g. Kahneman, 1973; Norman & Shallice, 1986) which have been reported to account for deficits in attention/effort allocation in individuals with aphasia (McNeil, 1981; McNeil, et al., 1991).

Although verbal working memory has been demonstrated to be impaired in individuals with aphasia (Caspari, et al., 1998; Christensen, & Wright, 2010; Erickson et al., 1996; Murray, 2004; Tseng, et al., 1993; Wright et al., 2003; Wright & Shisler, 2005), spatial (i.e., non-verbal) working memory has not been readily investigated and may be relatively preserved in individuals with aphasia. Consistent with Baddeley's model, working memory tasks can be manipulated so that processing requirements are manipulated (e.g. verbal versus spatial) while all other task requirements remain constant. Inclusion of verbal and spatial working memory tasks may reveal whether working memory deficits in individuals with aphasia are specific to verbal information or if deficits extend to non-verbal (spatial) stimuli. Further, in order to understand how perception of task difficulty relates to the effort individuals with aphasia expend during cognitively challenging tasks, a more objective measure of effort is needed. Heart rate variability (HRV) is the amount of fluctuation around the mean heart rate. It has been shown to be a physiological measure of the mental workload demanded from cognitive tasks (Hansen, Johnsen, & Thayer, 2003; Porges, 1992; Veltman &

Gaillard, 1993) and could provide an objective measure of the effort individuals with aphasia allocate to cognitive-linguistic tasks.

The objective of the current research study is to determine the relationship among perceived level of difficulty, physiological effort allocated (measured via HRV), and working memory performance for verbal versus non-verbal (spatial) tasks. Verbal and spatial working memory tasks will be used to determine whether deficits are specific to verbal information or if deficits extend to non-verbal (spatial) stimuli. Heart rate variability will be the measure of physiological effort expended to the working memory tasks and will be compared to ratings of task difficulty and behavioral performance on the working memory tasks. In this study effort is operationally defined as the difference in HRV (.07-.14 Hz range) measured during an n-back working memory task from HRV measured during a resting state.

Review of Literature

The following is a review of the literature which led to the research questions in this study. The components of Baddeley’s (2007) model of working memory will be discussed as they provide the basis for the task selection. This review includes research investigating working memory in individuals with aphasia that reveals deficits in the phonological loop and central executive components of Baddeley’s (2007) model of working memory. In addition, literature related to effort individuals with aphasia allocate to cognitive tasks will be reviewed including perceptual ratings of effort, task difficulty, and stress, as well as physiological measures used with this population. Finally, the utility of HRV as a measure for investigating whether deficits in the ability to allocate effort are present in individuals with aphasia will be discussed. This section is concluded with the statement of the problem and specific aims of this research.

Baddeley's Working Memory Model.

The ability to maintain information in an active state while manipulating and using that information for mental operations is termed working memory. In Baddeley and Hitch's (1974) original model, working memory included three components that enable the flexible deployment of attention to verbal and visuospatial information, as well as the activation, maintenance, manipulation, and storage of that information. These components which are limited in capacity include the domain-general central executive, and two domain-specific slave systems – the phonological loop and the visuospatial sketchpad. The domain-specific components are responsible for activation and maintenance of verbal and visuospatial information. In contrast, the domain-general central executive oversees these two systems by directing and focusing attention to the relevant tasks in order to maintain a goal. More recently, Baddeley (2000) added another component to his working memory model which he termed the episodic buffer. The episodic buffer helps to account for the evidence that items processed through separate modality-specific channels are perceived as coherent and cohesive unitary episodes (Baddeley, 2000). Baddeley's (2000) model of working memory provides the theoretical motivation for the current study; the components of this model are further reviewed here.

Phonological loop.

Baddeley and Hitch's (1974) original model and Baddeley's subsequent modifications to the model (2007) include two domain-specific systems responsible for the short-term storage of stimuli-specific information: a phonological loop and visuospatial sketchpad. The phonological loop is composed of a phonological store and an articulatory rehearsal mechanism. The phonological store holds rapidly decaying phonological information; but this information can be maintained indefinitely through active subvocal rehearsal (Baddeley, 2007). The *phonological similarity effect* provides evidence for the specificity of the phonological loop for phonological information, and is thought to reflect activation within the phonological store (Baddeley, 2007). The phonological similarity effect refers to the fact that it is easier to recall strings of letters or words presented orally or visually that are phonologically dissimilar (e.g. F, K, Y, W, R, Q) than it is to immediately recall phonologically similar stimuli (e.g. B, G, T, C, P, V) (Conrad & Hull, 1964; Baddeley, 1966a). In contrast, semantic information has minimal impact on the immediate recall of word lists (Baddeley, 1966a).

Due to the limited capacity of the phonological loop, word length also has an effect on the immediate recall of verbal material. Longer words which take longer to rehearse (overtly or covertly) are not recalled as well as shorter words (Baddeley, 1975). This word length effect provides evidence for a second component of the phonological loop – the articulatory rehearsal mechanism. Additional evidence for the articulatory rehearsal mechanism is provided through studies that require immediate recall of word lists (short term memory (STM) tasks) while repeating an unrelated word or syllable, such as “the”. This task condition is known as articulatory suppression. The repetition task requires minimal additional memory load, but interferes with the rehearsal mechanism which is necessary for recalling items as list length increases (Baddeley, 2007). This is demonstrated by the elimination of the word length effect for STM tasks performed under articulatory suppression (Baddeley, et al., 1975; Baddeley et al., 1984a). Because the word length effect is dependent on the articulatory rehearsal mechanism, articulatory suppression eliminates this effect for both aurally and visually presented word lists (Baddeley, et al., 1975; Baddeley et al., 1984a).

In addition to blocking access to the rehearsal mechanism, articulatory suppression also blocks access to the phonological store for written stimuli but not for aurally presented stimuli (Murray, 1968). This occurs because aurally presented verbal information has direct access to the phonological store, but visually presented verbal information does not. It must be transferred from its visual form into a phonological form via an articulatory code (Baddeley, 2007). Evidence for the direct activation of the phonological store for aurally presented, but not visually presented information is provided by the fact that articulatory suppression eliminates the phonological similarity effect only for visually presented verbal stimuli (e.g. Baddeley, et al., 1975; Baddeley et al., 1984a). The phonological similarity of items does not impact recall when the person is asked to read and recall word lists during articulatory suppression because the words are never entered into the phonological store. Repetition of the irrelevant word prevents the formation of an articulatory code which is necessary for the transfer of visual information into a phonological code (Baddeley, 2007). In contrast, when the task is to listen to the word lists, articulatory suppression eliminates the word length effect because rehearsal is needed, but the phonological similarity effect remains because aurally presented words have automatic access to the phonological store (Baddeley, 2007). To summarize, articulatory suppression prohibits visual information from entering the phonological store, and prohibits the rehearsal of verbal information regardless of the modality of presentation.

Additional evidence for the separation of the phonological store from the articulatory rehearsal mechanism is provided by patient FA (Jacquemot, Dupoux, & Bachoud-Lévi, 2010). As reported by Jacquemot and colleagues (2010), FA is a person with conduction aphasia who has a selective deficit in the ability to convert codes from the phonological input buffer to phonological output effectively rendering him unable to rehearse (i.e. a natural case of articulatory suppression). Jacquemot and colleagues tested FA for a phonological similarity effect and a word-length effect and predicted that because FA was not able to convert phonological input codes into a phonological output buffer, he would display a phonological similarity effect, but no word-length effect in STM tasks. As predicted and similar to control participants, FA demonstrated a phonological similarity effect. He had a longer memory span for phonologically dissimilar non-word strings compared to phonologically similar non-word strings. However, also as predicted, FA who is not able to utilize subvocal rehearsal (i.e. a natural case of articulatory suppression), did not display a word length effect for monosyllabic and quadrisyllabic words (Jacquemot et al., 2010). He performed similarly to how neurologically intact participants perform when under articulatory suppression. These findings are similar to those reported by other researchers who have studied similar types of patients (e.g. Vallar and Cappa, 1987, Cubelli and Nichelli, 1992, as cited in Jacquemot et al., 2010).

To summarize, there are two components to the phonological loop: a rapidly decaying phonological store to which auditory information has direct access and an articulatory mechanism. The articulatory mechanism has two responsibilities: 1) transferring visual information into a phonological code via subvocalization, and 2) rehearsing phonological information that would otherwise rapidly decay. Immediate recall of verbal information (i.e. STM span) is thought to be set by two factors: the rate at which the trace decays and the speed at which information can be rehearsed (Baddeley, 2007). Although the integrity of the phonological loop is usually tested through STM span tasks, it is one of the primary components of the working memory model, and is an essential component for performance on other working memory tasks that require maintenance and rehearsal of verbal information (e.g. verbal n-back tasks, verbal complex span tasks, etc).

Visuospatial sketchpad.

The other domain-specific component of Baddeley’s working memory model, which is also under the control of the central executive, is the visuospatial sketchpad. The visuospatial sketchpad is responsible for storing and manipulating visuospatial information. Similar to the phonological loop, the visuospatial sketchpad also has two components – a rapidly decaying visual sensory component that stores the visual features of objects, and a spatial or sequential component that enables active maintenance of visuospatial information (Logie, 1995). Evidence for the separation of these two components is provided by studies demonstrating that visual feature discrimination tasks (e.g. color feature) disrupt performance on shape recall, but not location recall; likewise, a movement discrimination task disrupts performance on location recall, but not shape identity (Tresh, Cinnamon, & Seamon, 1993; as cited in Logie, 1995).

Support for the separation of the phonological loop and visual spatial sketchpad comes from dual-task studies, as well as dissociations of verbal and spatial span found in individuals with neuropsychological impairments. Dual-task paradigms require simultaneous performance of two tasks. When two tasks share a common domain, performance on the tasks decreases during the dual task condition in comparison to performance on the tasks when they are completed in isolation. In contrast, it is thought that when two tasks tap different processing domains, individuals can maintain performance during the dual-task condition (Baddeley, 2007). Repetition of an irrelevant word during a verbal immediate recall task is an example of a dual-task. This condition, known as articulatory suppression, significantly limits verbal STM span (e.g. Baddeley et al., 1975; Baddeley et al., 1984a), but only minimally impacts performance on spatial span tasks (Baddeley, 2000). Spatial span tasks require maintenance of sequential information about object location rather than object identity. To further demonstrate the dissociation between verbal and visuospatial systems, completing a secondary visuospatial task that requires visual imagery (Logie, Zucco, & Baddeley, 1990) or perceptual-motor tracking (e.g. Cocchini, Logi, Della Sala, & MacPherson, 2002) impairs performance on visuospatial STM tasks to a much greater extent than performance on verbal STM tasks (e.g. Logie et al., 1990; Cocchini et al., 2002).

Dissociations between verbal and visuospatial span in individuals with brain injuries provide additional evidence of the separation between verbal and visuospatial components of working memory (e.g. Basso, Spinnler, Vallar, and Zanobia, 1982; DeRenzi & Nichelli, 1975; Hanley, Young, & Pearson, 1991). For example, DeRenzi and Nichelli (1975) found a dissociation between verbal and spatial span in brain injured participants. Two participants with left hemisphere damage (one with conduction aphasia, and one with anomia) had preserved spatial spans, as indicated by their ability to accurately imitate the examiner's pointing sequence to a series of cubes (spatial span). However, when the participants were asked to listen to a sequence of numbers and point to the correct sequence of numbers printed on cubes (digit pointing task), the participants were not able to correctly recall the verbally presented sequences. This was not the result of a comprehension deficit as the participants were able to correctly identify the numbers when presented verbally in isolation. Oral recall of the numbers was also impaired in comparison to the participants' spatial spans. DeRenzi and Nichelli (1975) described two other patients with right hemisphere damage who demonstrated the opposite disassociation. These participants scored very high on digit pointing and verbal digit span tasks, but were severely impaired on the spatial block-tapping task. The impaired spatial performance was not a result of visuoperceptual deficits or hemi-neglect; these conditions were not present.

Other researchers have reported similar findings of disassociations between verbal and visuospatial short term memory. For example, Basso, Spinnler, Vallar, and Zanobia (1982) described a patient with left hemisphere damage with preserved visuospatial STM span, but impaired verbal STM span. In contrast, Hanley, Young, and Pearson (1991) described a patient with right hemisphere brain damage who displayed the opposite pattern; preserved verbal STM span, but impaired spatial STM span. Both dual task studies and double dissociations found in neurologically impaired participants provide support for the separation of the phonological loop and visuospatial sketchpad as conceptualized in Baddeley and Hitch's (1974) model of working memory.

Central executive.

The domain-general central executive is the 'heart' of Baddeley's (2000) model; it is frequently referred to as the controller of the working memory system. The functions of the central executive are primarily attentional in nature and include focusing, dividing, and switching attention, as well as activating information in long-term memory (Baddeley, 2003). The central executive is responsible for selecting appropriate incoming information and rejecting inappropriate information (Baddeley, 1996), a function requiring attentional control. The central executive plays a supervisory role to the short-term storage slave systems - the phonological loop and the viosuospatial sketchpad – and is thought to be responsible for coordinating performance on tasks that utilize the slave systems. Similar to the phonological loop and the visuospatial sketchpad, the central executive is also limited in capacity; however, it is domain-general rather than domain specific. Support for the domain-general coordinating function of the central executive comes from impaired dual-task performance by individuals with Alzheimer’s disease for verbal and visuospatial tasks that is disproportionate to any modality specific STM deficits (Baddeley, 1996). That is, individuals with Alzheimer’s disease were impaired in the domain-general function of coordinating performance on two tasks simultaneously (Baddeley, 1996). Dual tasks are commonly used to assess central executive function. Another task thought to tap central executive function is the attention network task (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002). In this non-verbal task, the participants view an arrow on a computer screen and press one of two buttons to indicate the direction the arrow points. This center arrow, the target for responses, is surrounded by arrows on its right and left pointing either in the same direction (congruent trials) or in the opposite direction of the central target arrow (incongruent trials). Performance on the incongruent trials reportedly reflects executive attention - the ability to resist environmental-attention capture, and attend to the task-critical event (Engle, 2010). Many researchers believe individual differences in working memory capacity are due to differences in the ability to control attention in spite of internal or external distractions (e.g. Engle & Kane, 2004; Kane, Conway, Hambrick, & Engle, 2007). For example, Redick and Engle (2006) found that individuals with low working memory spans (defined as the lower quartile performers on an operation span task) responded significantly slower than high working memory span participants (defined as upper quartile performers on the operation span task) on the incongruent trials of the ANT. No differences between groups were found on the congruent trials which are reported to tap automatic rather than controlled processing (Redick & Engle, 2006).

Similar relationships with working memory performance have been reported on other controlled attention tasks like Stroop (1935; Kane & Engle, 2003; Long & Prat, 2002), antisaccade (Kane, Bleckley, Conway, & Engle, 2001; Unsworth, Schrock, & Engle, 2004), and flanker interference tasks (Heitz & Engle, 2007; Redick & Engle, 2006) which require suppression of irrelevant information. The ecological validity of these findings has been noted as well. For example, Conway, Cowan, and Bunting (2001) found that participants with low working memory spans were more susceptible to the cocktail party effect during a dichotic listening task than participants with high working memory spans. The cocktail party effect refers to the ability to hear important information, such as one’s name, in unattended stimuli (e.g. a conversation to which one was not attending). The working memory span measure used by Conway et al. (2001) was the operation span task. In this task, participants viewed a series of displays on the computer screen which contained a math problem and an unrelated word (e.g. Is

6+4/2 = 5? Dog). They had to say the equation aloud, respond “yes” or “no” to its truthfulness, and then say each word. After the series of 2 to 6 displays ended, participants wrote all the words on a response sheet. A total of 15 series of displays were presented (3 of each span length). Span was calculated as the cumulative number of words that were recalled in correct serial order. Participants were then partitioned into two groups (high span and low span) based on their performance on the task. Participants in the middle two quartiles of the range of span scores were omitted from the study and the remaining 40 undergraduate college students participated in the experimental task. In the experimental task, the high- and low-span participants listened to relevant and irrelevant messages consisting of 330 or 300 monosyllabic words presented through headphones at a constant volume. Onset of the irrelevant message began 30 seconds after onset of the relevant message. The relevant message was a monotone female voice presented to the right ear and the irrelevant message was a monotone male talker presented to the left ear. Relevant and irrelevant words were presented simultaneously. Four or five minutes into the task, a word from the irrelevant message was replaced by the participants’ name. Participants were instructed to listen to the message presented to the right ear and repeat (shadow) each word while ignoring the message presented to the left ear. Shadowing errors were recorded by the researcher. After the shadowing task, participants completed a questionnaire in which they indicated if anything unusual was detected in the irrelevant message, and if so, what it was. All participants who detected something unusual reported that it was their name.

Results indicated that the participants with low working memory spans detected their name in the irrelevant message more often; that is 65% compared to only 20% for the high span participant group (Conway et al., 2001). The results of this study are somewhat counterintuitive. The participants with poorer performance on the working memory task were better at detecting their name in the irrelevant message. This is not a performance trade-off issue because the working memory measure was performed separately from the verbal shadowing tasks. Conway et al. (2001) and others (e.g. Engle & Kane, 2004; Kane, Conway, Hambrick, & Engle, 2007) interpret these and similar findings as evidence for the importance of attentional control (a domain general central executive function) to working memory performance. It seems individuals with high working memory spans are better able to focus their attention on the goal-relevant task in the presence of competing irrelevant information as compared to individuals with low working memory spans.

According to Baddeley (1996), the domain-general ability to focus attention in the presence of distractions is a primary function of the central executive. Findings of a relationship between such a low-level ability and a complex working memory task (Redick & Engle, 2010) are interesting and may have implications for understanding working memory performance in individuals with aphasia. In fact, attentional processes have been investigated with individuals with aphasia (e.g. Laures, Odell, & Coe, 2003; LaPointe & Erickson, 1991; Laures, 2005; Korda & Douglas, 1997; Murray, Holland, & Beeson, 1997) with mixed results reported. These studies involved either simple vigilance tasks, or dual tasks involving at least one linguistic processing component. Additional research in this area is needed in order to understand the cause of impaired performance by individuals with aphasia on tasks thought to tap the central executive. For example, it is not clear whether such deficits simply reflect the primary language deficit in aphasia which prevents verbal mediation necessary for successful task performance (Baldo, Dronkers, Wilkins, Ludy, Raskin, & Kim, 2005); impaired perception of task demands (Murray, Holland & Beeson, 1997a); an impaired physiological stress response (Laures-Gore, Heim, & Hsu, 2007) that is perhaps resulting in impaired mobilization of effort (Clark & Robin, 1995); or a true domain-general central executive deficit as suggested by the resource allocation deficit account of aphasia (e.g. McNeil, 1981; McNeil, et al., 1991).

Episodic buffer.

Up to this point, this review has referenced Baddeley and Hitch’s (1974) model of working memory. However, in 2000, Baddeley added a fourth component to the original model. The episodic buffer was added to account for the integration of phonological and visuospatial information that results in a coherent perception of items or events as cohesive unitary episodes, even though they are sensed through the separate modality-specific channels (Baddeley, 2000). The episodic buffer helps to account for instances where there is integration of perceptual representations in the phonological loop with conceptual representations in the semantic system. For example, it explains why meaningful sentences are more easily remembered than random lists of words, and how individuals can memorize long verses of prose that extend way beyond the constraints of the phonological loop. The episodic buffer serves as the interface between the two slave systems and long term memory (Baddeley, 2000).

To summarize, working memory is a multi-component system comprised of domain-specific systems involved in the activation and maintenance of verbal and visuospatial information, as well as domain-general systems responsible for directing and focusing attention to maintain a goal. These components which are limited in capacity include the domain-general central executive, two domain-specific slave systems, and an episodic buffer (Baddeley, 2000). According to this model, performance on working memory tasks can be impacted by any one of these components.

Working Memory and Aphasia

Domain specific (verbal) deficits.

Working memory has become increasingly interesting to researchers studying neurologically intact adults with recent findings linking working memory performance with performance on higher level intellectual tasks such as reading and listening comprehension (Daneman & Carpenter, 1980; Daneman & Mericle, 1996), reasoning (Kane, Hambrick, Tuholski, Wilhelm, Payne, & Engle, 2004; Sub, Oberauer, Wittman, Wilhelm, & Schultz, 2002), and intelligence (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999). The relationship found between working memory and language in neurologically intact adults is particularly relevant for those interested in understanding aphasia. Aphasiologists are interested in working memory because it may point to an underlying deficit in aphasia that potentially can be remediated to improve language skills and communication ability. Although communication impairments are the most obvious disability in aphasia, researchers suggest that the underlying deficit may be in working memory (Caspari et al., 1998; McNeil, et al., 1991; Erickson, Goldinger, & LaPointe, 1996; Murray, Holland, & Beeson, 1997a; Murray, Holland, & Beeson, 1997b; Tompkins, Bloise, Timko, & Baumgaertner, 1994; Wright, et al., 2003). The idea that working memory deficits may explain some of the language problems in individuals with aphasia has risen in part from significant correlations found between performance on verbal working memory tasks and language tasks. For example, working memory complex span tasks such as reading and listening span have been used with individuals with aphasia. Performance on these measures has been found to vary with performance on language tasks (Tompkins, et al., 1994; Caspari et al., 1998).

Tompkins and colleagues adapted Daneman and Carpenter’s (1980) reading span task for use with brain damaged individuals. In Tompkins and colleagues’ study, they included 21 participants with left hemisphere brain damage (LHD) and 25 with right hemisphere brain damage (RHD). The modified working memory measure required participants to listen to short (3-5 word) sentences, judge the truthfulness of the sentences, and then retain and recall the final word of the sentences. The number of sentences and final words to recall increased from two sentences to a maximum of five. Participants also completed paragraph-length listening comprehension tasks. The LHD group was divided into low and high comprehension groups based on their performance on the listening comprehension tasks. Tompkins et al. then examined differences in working memory performance between the low and high comprehension groups. The low comprehension group recalled significantly fewer words on the working memory measure than the high comprehension group, indicating a link between working memory and language comprehension. However, the correlation between language comprehension performance and working memory performance was not analyzed for the LHD group because the distribution was bimodal with the majority of participants scoring between the 87.5 and 98th percentiles. These results may indicate that the poorer scores by the low comprehension group on the working memory task were related to their difficulty comprehending the language stimuli, rather than reflecting a decreased working memory capacity. Perhaps the

LHD participants had less time to store the sentence final words due to increased processing time needed to comprehend the sentences. This is consistent with Martin's (1995) view of aphasia as described in her response to Miyake, Carpenter, and Just's (1994) paper which attributed syntactic comprehension deficits in individuals with aphasia to a reduced working memory capacity. In contrast, Martin (1999) asserted it is the opposite; the language deficit drives the lower working memory scores on complex span tasks like the reading span task. That is, the participants with the least efficient sentence processing (i.e. more severe language comprehension deficit) require more time to process the sentences and will therefore have less time available to process the sentence final words. Unfortunately, due to the verbal nature of both the paragraph-length listening comprehension task and the reading span working memory task, it is not possible to determine whether a working memory deficit exists in isolation of the language deficit or vice versa. It was also not readily apparent which of the LHD participants in Tompkins and colleagues' study presented with aphasia, so further interpretation for this population is not appropriate.

In a similar study, Caspari, et al. (1998) adapted the reading span task specifically for use with individuals with aphasia. The purpose of this study was to determine whether working memory performance correlated with performance on language measures in participants with aphasia in a way similar to that found by Daneman and Carpenter (1980) in college students without brain injury.

Several modifications were made for administration of the task with individuals with aphasia. The processing task included short 5-6 word declarative sentences, followed by a to-be-remembered word. The target word was presented after the sentence, rather than as the final word in the sentence. Also, the expressive requirement of the task was removed by having participants select correct targets from a series of pictures (a recognition rather than recall task). The final modification was that comprehension of the sentences was assessed at the end of a span length rather than after each sentence. Sentence comprehension performance was not included in the data analysis.

Each span length was presented five times. A span length of 1 indicated participants correctly selected the final word from pictures following presentation of a single sentence-word pair on three out of five occasions. A span length of two indicated participants correctly recognized the terminal words after presentation of two sentence-word pairs on three of five occasions. Responses were correct if all the words were recognized regardless of the order. Participants included 22 individuals with aphasia ranging in aphasia severity from mild to severe classified according to the Western Aphasia Battery (WAB; Kertez, 1982). All participants were at least six months post-onset of a unilateral left hemisphere CVA. In addition to a reading only version of the task in which the participants orally read the sentence-word pairs (reading span), participants were administered an identical version that included the experimenter orally reading the sentences viewed by the participants (listening span).

Caspari et al. found that both working memory span measures significantly correlated with overall measures of reading comprehension (Reading Comprehension Battery for Aphasia; LaPointe & Horner, 1979) and language performance (WAB Aphasia Quotients, Kertez, 1987). This finding is not surprising given the verbal nature of the working memory tasks. As the memory load of the tasks increase, so do the linguistic demands. In spite of the correlational nature of the data, Caspari et al. (1998) interpret their results as support for a working memory capacity deficit and a reduction of processing resources as contributing to the language comprehension deficits in individuals with aphasia. For example, they report that data from two participants who could not accurately answer the yes/no comprehension were included in the data analysis *because* their working memory scores were also low. However, this may indicate a primary language deficit as contributing to low working memory scores, rather than the opposite effect as suggested by the researchers. Further, many of the items on the RCBA and WAB are single word items, not expected to tax working memory. A relationship between performance on these tasks and performance on the working memory measure more likely reflects the common construct that underlie both measures (e.g. language comprehension). An equally plausible interpretation of the results reported by Caspari et al. is that the more severe the language deficit a person with aphasia has, the more difficulty they will have with a working memory measure that depends on language (semantic, syntactic, and phonological) processing.

This possibility is supported by results from a study by Friedmann and Givon (2003) which indicated that individuals with different types of aphasia have specific language comprehension deficits that cannot be explained by a general working memory deficit. Friedmann and Gvion had six participants with aphasia perform an n-back working memory task (2-back), several span measures (digit, word, and non-word span), and a listening span task similar to that used by Tompkins and colleagues (1994). The participants included three individuals with agrammatic aphasia and three with conduction aphasia. In addition to the working memory measures, participants also completed sentence comprehension tasks which required different types of linguistic processing for successful performance. Although all participants demonstrated impaired performance on working memory tasks, only the individuals with agrammatic aphasia had difficulty comprehending sentences including an object relative clause. In contrast, the participants with conduction aphasia, in spite of severe working memory impairments, had no difficulty with object relative clause sentences regardless of the antecedent-gap distance. Instead, they were impaired in their comprehension of sentences requiring phonological reactivation. Although this study included a small *n*, and no statistical comparisons were performed, results suggest that a general working memory deficit cannot account for the linguistic specific deficits (e.g. grammatical vs. phonological) that characterize these different types of aphasia.

Although complex span tasks, such as reading and listening span tasks have been a commonly used working memory measure with individuals with aphasia, other methods for estimating working memory ability in adults with aphasia are becoming more prevalent. One such task that appears ideal for evaluating working memory in individuals with aphasia is the n-back task (Wright, Downey, Gravier, Love, & Shapiro, 2007). The n-back is frequently used to assess working memory in functional neuroimaging studies, and has been used recently with individuals with aphasia (Wright et al., 2007; Christensen & Wright, 2010). It is ideal for individuals with aphasia because a simple button press is all that is required to indicate a response, thereby, eliminating the complication of an expressive component external to the processes under investigation. To complete the n-back, participants view stimuli one at a time on a computer screen. They press a button when the current item is identical to the one presented n-back. The difficulty of the n-back can be parametrically manipulated by varying the number of items (*n*) to be recalled. Thus, successful performance requires temporarily storing and manipulating the temporal order of items. The temporal order of newly presented items must be updated while activation of previously relevant items is suppressed. With its strong parallel with the definition of working memory, the n-back has strong face validity, and construct validity has also been demonstrated (e.g. Schmiedek, Li, & Lindenberger, 2009; Shamosh, DeYoung, Green, Reis, Johnson, Conway, Engle, Braver, Gray et al., 2008). It is particularly ideal because different working memory processes can be parametrically manipulated depending on the processes under investigation. For example, one can compare rhyming and non-rhyming words to gain information about the phonological loop by simply changing the lexical stimuli, or compare spatial with verbal working memory by using the same stimuli but changing the directions (e.g. respond when object is in same location vs. same in identity as the one *n* back).

Wright, Downey, Gravier, Love, and Shapiro (2007) used a verbally presented n-back working memory task to investigate working memory for different types of linguistic stimuli in individuals with aphasia. They manipulated the stimuli to investigate working memory performance for semantic (*SemBack),* syntactic (*SynBack*) and phonological (*PhonoBack)* information. In addition, they examined the relationship between syntactic working memory (*Syn*back) and performance on a measure of syntax assessed through sentence comprehension (accuracy on the Subject-relative, Object-relative, Active, Passive Test of Syntactic Complexity; SOAP, Love & Oster, 2002). Relationships between the SOAP and the other n-back tasks were not investigated; nor were relationships between n-back performance and overall language severity.

Nine individuals with a variety of aphasia types and severities participated in this study. A 1-back and 2-back task was administered for all stimuli types. Conditions were further manipulated by requiring participants to respond when the target item was the same as the item n-back (identity condition), or when the target item belonged to the same category as the item *n*-back (depth condition). In the depth condition for the *PhonoBack*, participants responded when the target item rhymed with the word presented *n*-back. The depth condition for the *SemBack* required participants to respond when the target item belonged to the same category as the item *n*-back. The *SynBack* was only presented at the identity level. For this task participants responded when the sentence was the same as the one heard *n*-back.

Wright and colleagues (2007) found a significant relationship between *Synback* performance and accuracy on the SOAP. Accuracy data from the *n*-back tasks indicated that performance declined as more items had to be retained in memory. The 1-back tasks were easier than the 2-back tasks. This is consistent with other studies using the *n*-back with individuals with aphasia using different types of stimuli (e.g. Christensen et al., 2010). They also found that participants were more accurate at the identity level than at the depth level. Further, participants were more accurate on the *SemBack* than they were on the *PhonoBack.* The finding of reduced performance by individuals with aphasia on the *PhonoBack* compared with the *SemBack* is likely due to impaired phonological processing in individuals with aphasia. It has been consistently demonstrated that individuals with aphasia have an impaired phonological loop (e.g. Ronnberg, Larsson, Fogelsjoo, Nilsson, Lindberg & Anguist, 1996; Laures-Gore, Marshall, & Verner, 2010). Specifically, an impairment at the level of the phonological store would be reflected with better performance with phonologically dissimilar items such as the *SemBack,* than with items that are phonologically similar (e.g. *PhonoBack*). This is consistent with a study by Ronnberg, Larsson, Fogelsjoo, Nilsson, Lindberg, and Angquist (1996) that had participants with mild aphasia recall lists of digits, rhyming, and non-rhyming words, as well as other short-term and working memory tasks. In this study, non-rhyming words were easiest for the participants with aphasia to recall, followed by digits, and the phonologically similar word lists were most difficult. Although this component of the study only included short-term memory tasks, these tasks are known to tap the phonological loop which is a primary component in Baddeley's (2000) model of working memory. Numerous other researchers have reported that the phonological loop is impaired in individuals with aphasia (e.g. Heilman et al., 1976; Martin, 1987; Rothi & Hutchinson, 1981). In fact, it may be that these deficits are responsible for decreased performance of individuals with aphasia on the verbal working memory tasks reported thus far in the literature. In support of this notion, Ronnberg et al. (1996) found that both digit span and non-rhyming word span correlated with a complex reading span task similar to the

Tompkins et al. (1994) reading span task described previously. Ronnberg et al (1996) stated that the degree to which the phonological loop is impaired is crucial to the execution of reading span (the working memory task). Similarly, the notion that deficits in the phonological loop are related to overall language deficits, particularly comprehension deficits, is not new (e.g. Caramazza, Basili, Koller, & Berndt, 1981; Ostrin & Schwartz, 1986; Saffran & Martin, 1975; Vallar & Baddeley, 1984).

In a recent study, Laures-Gore, Marshall, & Verner (2010) investigated the relationship between the integrity of the phonological loop and severity of aphasia (WAB-AQ score, Kertesz,1982). Twenty-two individuals with aphasia and 14 participants with right hemisphere brain damage (RHD) completed forward and backward digit span tasks. Digits were presented verbally with cards containing the printed numbers present during the span tasks. Participants were allowed to point to the numbers on the cards in lieu of a verbal response. The purpose of the study was to investigate differences in forward and backward digit span across these groups, as well as to investigate the relationship among span measures with overall severity measures for aphasia (WAB-AQ) and RHD (Mini-Inventory for Right Brain Injury-2 (MIRBI-2; Pimental & Knight, 2000).

As expected, results indicated all participants performed better on the forward span tasks than backward span tasks. Individuals with aphasia performed significantly worse than RHD participants on both span measures. For individuals with aphasia, both forward and backward span correlated significantly with overall language ability as measured by WAB-AQ scores. But for RHD participants, only backward digit span significantly correlated with the measure of overall severity of cognitive impairment for individuals with RBD – the MIRBI-2.

As suggested by Laures-Gore and colleagues (2010), their results support the notion that the working memory impairment in individuals with aphasia may be a reflection of an impaired phonological loop. That is, both forward and backward digit span rely on the phonological loop, but, forward digit span is less dependent on central processing resources than backward digit span (Rypma, Prabhakaran, Desmond, Glover, & Gabrieli, 1999). This could explain why RHD participants known to have deficits in the central executive (Mecklinger, von Cramon, Springer, & Matthes-von Cramon, 1999) but a relatively preserved phonological loop (Gainotti, Cappa, Perri, & Silveri, 1994; Hanley, et al., 1991) performed worse on backward digit span than forward digit span. In contrast, both forward and backward digit spans of individuals with aphasia correlated with scores of overall language severity indicating either predominantly deficits in the phonological loop or both phonological loop and central executive deficits.

Because individuals with aphasia show impairments on STM tasks which minimize central executive processing and reflect deficits in the phonological loop, it is possible that impaired performance on verbal working memory tasks is simply a reflection of the deficient phonological processing/rehearsal mechanism.

However, there is some research to suggest that individuals with aphasia may have more domain-general deficits consistent with problems at the level of the central executive.

Domain general (central executive) deficits.

Individuals with aphasia also show impairments on attention tasks which have been suggested as reflecting domain-general deficits at the central executive level (e.g. Erickson, Goldinger, & LaPointe, 1996; Glosser & Goodglass, 1990; LaPointe & Erickson, 1991; Laures, 2005; Murray, 2004; Tseng, et al., 1993). Two functions of the central executive (Baddeley, 1996) which have been reported to be impaired in individuals with aphasia are the ability to focus attention for an extended period of time in the presence of distractions (e.g. Glosser & Goodglass, 1990; Laures, 2005) and the ability to divide attention between two tasks (e.g., LaPointe & Erickson, 1991; Erickson, Goldinger, & Lapointe, 1996; Murray, Holland, & Beeson, 1997a; Murray, Holland, & Beeson, 1997b).

Laures (2005) investigated the accuracy and reaction time of 10 individuals with aphasia and 10 age- and education-matched participants on two different 32 minute focused attention tasks (verbal and non-verbal). The verbal task included a verbal target (the word “myth”) presented among other low frequency occurring abstract words. The non-verbal vigilance task required participants to identify a complex harmonic sound presented among pure tones.

Laures (2005) found a significant difference between groups for accuracy, with individuals with aphasia being less accurate than controls, but no difference in response time between groups. However, 91% of the false alarms produced by individuals with aphasia occurred on the item that followed the target. Laures (2005) explained this as indicating that individuals with aphasia recognized the target item but were more variable in their ability to respond within the 2500msec time frame. Citing McNeil (1997, 1991) she reported “the observed variability is most often thought to support a hypothesized inefficiency in accessing elements of the linguistic system” (p. 356). Laures expanded on this, reporting that the accessing difficulty may extend to non-linguistic information as well, since an interaction between verbal and non-verbal stimuli was not found. A condition where participants responded to all stimuli was not included.

In contrast to the results reported above indicating a deficit in the ability of individuals with aphasia to sustain attention, most studies contrast the relatively intact vigilance skills of participants with aphasia with their impaired performance on dual tasks (e.g. LaPointe & Erickson, 1991; Erickson, Goldinger, & LaPointe, 1996; Murray, Holland, & Beeson, 1997a; Murray, Holland, & Beeson, 1997b). In most dual task studies conducted with individuals with aphasia, participants have been required to complete a linguistic task alone, and in combination with another linguistic or non-linguistic task. Participants’ performance accuracy and/or reaction time on the tasks when performed alone is compared to that during the dual-task. Individuals with aphasia typically perform more poorly than non-brain damaged participants during dual tasks (e.g. LaPointe & Erickson, 1991; Erickson, et al., 1996; Murray, et al., 1997a; Murray, et al., 1997b; McNeil, et al., 1991). This finding has led aphasia researchers to hypothesize that individuals with aphasia are impaired in their ability to properly allocate cognitive resources during the dual tasks (a central executive function) (e.g. Murray, et al., 1997a; McNeil, 1981; McNeil, et al., 1991; Shuster, 2004). This theory has been popularly applied to aphasia because it could explain the moment-to-moment variability in performance by individuals with aphasia on language tasks– the fact that when sitting in a quiet room, a person with aphasia may be able to retrieve a word one minute and a moment later when the conditions are exactly the same, not be able to produce the same word.

However, the term “resources” represents a vague construct that is difficult to directly measure. Others have better explained this deficit as an impaired ability to match effort with task demands (e.g. Murray et al., 1997a; Clark & Robin, 1995, LaPointe, & Erickson, 1991). In fact the terms “effort” and “resources” are frequently used interchangeably (Kahneman, 1973; McNeil, Doyle, Hula, & Rubinsky, 2004). If language performance by individuals with aphasia is related to effort allocated, this could have important clinical implications.

Effort and Aphasia

Perceived effort, task demands, and stress.

Clark and Robin (1995) observed the relationship between sense of effort ratings and reaction time during a lexical decision task for eight participants with aphasia and 13 age- and education-matched control participants. The stimuli for the lexical decision task included concrete and abstract words, and non-words. In addition, stimuli were presented in either a non-degraded or degraded visual condition. Participants rated effort by using a computer mouse to move a cursor, centered on a line, either right or left. The line was anchored with 0 and 200, with 200 indicating maximal effort.

Clark and Robin (1995) found that sense of effort ratings by individuals with aphasia did not reflect the difficulty of the task. That is, although the participants with aphasia had increased reaction time compared to neurologically intact participants for the more difficult items, they did not report a greater sense of effort than control participants. In fact, for some participants with aphasia, sense of effort ratings were lower than those of the control participants.

Murray and colleagues (1997a) hypothesized that individuals with aphasia do not appropriately invest effort because they misperceive the demands of the tasks. Instead of having participants rate effort, Murray et al. had 16 individuals with aphasia and eight control participants, matched for age, education and estimated IQ, rate task difficulty. The tasks included a lexical decision task performed alone, and in combination with a verbal (semantic distractor) task or non-verbal (tone discrimination) task. Although the individuals with aphasia performed more poorly than control participants in the dual task conditions indicating the dual task conditions were more difficult for individuals with aphasia, there were no differences between groups in their ratings of task difficulty.

Both of these studies compared perceptual post-task ratings to behavioral performance and results seem to suggest that individuals with aphasia misperceive the demands of the verbal tasks. That is, although differences in performance were noted between individuals with aphasia and the neurologically intact participants, the groups did not differ in their evaluation of the difficulty of the tasks (Murray et al., 1997a) nor in their ratings of how much effort was allocated to the tasks (Clark & Robin, 1995). However, the lack of a finding of a significant difference in perceptions of task difficulty/effort may have been related to insufficient statistical power. In addition, these studies compared perceptual ratings to performance on lexical decision tasks. It is less clear whether these same deficits would appear if the behavioral task did not require language processing. Further, the finding of a mismatch between the performance of individuals with aphasia and their ratings of effort/difficulty is interesting, but there is need for a more objective physiological measure of effort.

Physiological measures used with individuals with aphasia.

Laures-Gore and colleagues (2007) took a related approach in their attempt to understand the underlying nature of aphasia. However, rather than evaluating perceived effort or task difficulty, they had participants with aphasia rate their stress after completing verbal and non-verbal tasks. In addition, they obtained physiological measures of stress by measuring salivary cortisol. They had participants with aphasia and age- and education-matched control participants complete a public speaking task and a non-linguistic mirror drawing task. After each task, participants completed a self-evaluation of perceived stress. Contrary to studies of perceptual ratings of task difficulty and effort (e.g. Clark & Robin, 1995; Murray et al., 1997a) in which ratings of task difficulty did not match their performance, the aphasia group in Laures-Gore and colleagues' study perceived greater stress than did the control group on the linguistic task; but there was no difference between groups for perceived stress on the non-linguistic task. Although performance differences between groups on the tasks were not reported, it is assumed that the verbal, but not the non-verbal task was more difficult for the participants with aphasia. Therefore, in this study, participants with aphasia seemed to be able to accurately rate task-related stress. Assuming that tasks that are more difficult are more stressful, these results seem to indicate that individuals with aphasia were accurate in their ability to rate stress. They perceived the verbal, but not the non-verbal task to be more stressful than did the neurologically intact participants.

Laures-Gore et al. (2007) took the study a step further and evaluated actual stress elicited from the tasks by measuring the participants' salivary cortisol. To assess cortisol response to the verbal and non-verbal tasks, all participants first completed a resting baseline condition in which they sat quietly in a room and were instructed to relax for half an hour. Salivary cortisol levels were measured at the beginning and end of the 30 minute baseline period. Immediately following the baseline, the experimental task began and cortisol was measured at 10 minute intervals for 90 minutes. Although a salivary cortisol response was found for the control group during the linguistic task, the individuals with aphasia demonstrated no response to the task. Despite self reports of higher levels of stress on the verbal task for individuals with aphasia, they did not display cortisol reactivity during either the verbal or the non-verbal task. These results seem to suggest a mismatch between perceived stress and a physiological measure of stress for individuals with aphasia (Lores et al., 2003). The lack of a physiological stress response seems to support the findings of Clark and Robin (1995) and Murray et al. (1997a) that suggest individuals with aphasia have a decreased mobilization of effort for cognitive-linguistic tasks. However, although salivary cortisol is a measure of the physiological stress response, it may not be appropriate for individuals with aphasia. For example, it has been suggested that the mechanism involved in the production of cortisol, the hypothalamic-pituitary-adrenal (HPA) axis, is impaired in brain injured populations (Fassbender, Schmidt, Mossner, Daffershofer, & Hennerici, 1994; Franceshini, Tenconi, Zoppoli, & Barreca, 2001; Johansson, Ahren, Nasman, Carlstrom, & Olsson, 2000; Olsson, 1990). Further, cortisol takes time to build up in the bloodstream and is a slower responding measure of stress (Everly, & Sobelman, 1987; Backs & Seljos, 1994); therefore, cortisol may not be appropriate for detecting immediate changes in stress experienced during short experimental tasks frequently used with individuals with aphasia.

Laures-Gore et al. (2007) suggested cardiovascular measures as an alternative indicator of the physiological stress response during cognitive tasks. In fact, in an earlier study, Laures, Odell, and Coe (2003) found that differences in blood pressure distinguished individuals with aphasia from controls; and, for both groups the cardiovascular measure was sensitive to differences between a baseline condition and a vigilance task. However, although participants with aphasia performed worse than neurologically intact participants on the behavioral vigilance measure, the magnitude of difference in blood pressure across the baseline versus experimental task was not significant. The finding that the cardiovascular measure (blood pressure) was sensitive to baseline versus experimental measures for both groups is promising; it may be that a more sensitive cardiovascular measure (e.g. HRV) will detect smaller between-group and between-task differences, particularly for more cognitively demanding tasks. In addition, unlike cortisol which is typically used in tasks that have high social-evaluative threat, HRV is thought to measure the mental workload demanded from cognitive tasks and reflects the effort allocated to those tasks (e.g. Capa, Audiffren, & Ragot, 2008; Mulder, Van Roon, Veldman, Elgersma, & Mulder, 1995). HRV is the amount of fluctuation around the mean heart rate. It has been shown to reflect the mental workload required during cognitive tasks (e.g. Kalsbeek, 1971; Porges, 1992; Backs & Seljos, 1994; Veltman & Gaillard, 1993; Hansen, Johnsen, & Thayer, 2003) and is a commonly used measure of effort (Aasman, Mulder, & Mulder, 1987). Cognitively challenging tasks elicit a stress response measured as a drop in HRV from baseline to task conditions (Kalsbeek, 1971). This decrease in HRV occurs because the parasympathetic system, normally working to slow the heart in opposition to the sympathetic system which speeds heart rate, is inhibited during cognitively challenging tasks. The resulting decrease in HRV provides an objective physiological measure of the effort allocated to cognitively challenging tasks. This measure has not yet been used with individuals with aphasia.

Utility of HRV for use with individuals with aphasia.

There are several theoretical issues regarding aphasia that having a non-subjective, reliable physiological measure may help resolve. A primary issue is related to the underlying cause of their performance deficits on cognitive and linguistic tasks. It has been suggested that an inability to properly allocate attention/effort to the tasks, and an inability to properly perceive the task demands, is the cause of poorer performance on dual tasks by individuals with aphasia compared with neurologically intact participants (Murray, Holland, & Beeson, 1997; McNeil, Odel, & Tseng, 1991). This has been investigated in several studies, but the issue remains unresolved. For example, Murray and her colleagues (1997) found that inaccurate perceptual ratings of task difficulty made by individuals with aphasia seemed to support this hypothesis. However, a similar study in which individuals with aphasia perceived greater stress than controls following a linguistic task but not after a mirror-tracing task (Laures-Gore, Heim, & Hsu, 2007) seemingly does not indicate a lack of effort or a misperception of task demands. Although the same dimension was not measured in these studies (task difficulty vs. stress), there are many conflicting findings related to participants with aphasia's perceptions of task difficulty, effort allocated, performance accuracy, and perceived stress (e.g. Murray, et al., 1997, Clark & Robin, 1995, LaPointe & Erickson, 1991; Laures-Gore et al., 2007). Most researchers purporting to provide support for the notion that individuals with aphasia have impaired perceptions of difficulty or effort invested often conclude this based on finding a lack of significant difference between individuals with aphasia and controls in their perceptual ratings. That is, in spite of performing more poorly on cognitive-linguistic tasks than non-language impaired participants, participants with aphasia do not report greater difficulty than that reported by controls. However, an inability to find significant results (i.e. an inability to reject the null hypothesis) is weak support for a theory. Further, if individuals are impaired in their mobilization of effort, there is a need to examine the relationship among perceptions of task difficulty, performance accuracy, and a physiological measure of effort invested.

In summary, debate about the nature of the underlying deficit in aphasia continues. Studies of self-perceptions of accuracy, task difficulty, and perceived stress provide conflicting results, particularly when combined with physiological measures such as salivary cortisol. The cardiovascular system may provide better insight into the cognitive workload demanded from different tasks, and the effort allocated to those tasks. The cardiovascular system has been suggested as a more accurate, faster-responding measure of physiological stress during cognitive tasks than slower reacting cortisol (Laures-Gore, 2007). Specifically, HRV is a measure of the physiological stress response elicited during cognitively demanding tasks and may provide a more sensitive tool for understanding the nature of the underlying deficit in aphasia.

Rationale for use of HRV as measure of effort with individuals with aphasia.

Cognitively challenging tasks elicit a stress response measured as a drop in HRV from baseline to task conditions (Kalsbeek, 1971). This decrease in HRV occurs because the parasympathetic system, normally working to slow the heart in opposition to the sympathetic system which speeds heart rate, is inhibited during cognitively challenging tasks. The resulting decrease in HRV provides an objective physiological measure of the effort allocated to cognitively challenging tasks and may provide insight into the effort allocated by individuals with aphasia to verbal versus spatial working memory tasks. HRV has shown to be a valid physiological measure of attentional capacity (Porges, 1992), memory (Hansen, Johnsen, Thayer, & Thayer, 2003), and mental effort or workload (Althaus, Mulder, Mulder, van Roon, & Minderaa, 1998; Backs & Seljos, 1994; Hansen, et al., 2003); all cognitive measures which are difficult to reliably assess in adults with language disorders. When combined with ratings of task difficulty and performance on verbal and non-verbal tasks, HRV measurements have promise for uncovering whether the findings of a mismatch between individuals with aphasia's perceptions of task difficulty and performance are the result of a physiological impairment in the mobilization of effort, or because of a perceptual problem with adequately assessing the demands of the tasks.

Higher levels of resting respiratory sinus arrhythmia (RSA), indicating greater parasympathetic outflow, have been associated with better performance on working memory (Hansen, Johnsen, & Thayer, 2003) and other cognitive tasks (Porges, 1972, 1973). Additionally, a consistent pattern of cardiovascular responses has been found to occur in response to mental workload when compared to baseline values during rest: an increase in heart rate and blood pressure, decreased HRV and blood pressure variability, and often a decrease in baroreflex sensitivity (van Roon, Mulder, Althaus, & Mulder, 2004). Further the mid frequency band (.07-.14 Hz) of the heart rate variability spectrum, as revealed by spectral power analysis, has shown to be sensitive, not only to differences between resting baseline and cognitive task performance, but also to differences among conditions of differing mental loads (Althaus, et al. 1998; Redondo & Del Valle-Inclan, 1992; Veltman & Gaillard, 1993). For example, Redondo and Del Valle -Inclan (1992) had college students perform a Sternberg memory search task with memory set sizes of one, two, and four elements and a display load of one. They collected heart rate variability and subjective measures for each experimental period. Spectral analyses revealed that only the mid frequency band (.07 - .14) was sensitive to differences between the tasks. The amplitude of the mid frequency band was maximum during rest, and minimum during the task. This mid frequency band is thought to reflect short-term changes in the sympathetic modulation of arterial pressure (Althaus, et al. 1998). Further, demonstrating the sensitivity of the mid frequency band to small changes in cognitive load (sympathetic input), this mid frequency band was lower for the memory set size of four than the memory set size of three. In this study more global measures of heart rate variability in both time and frequency domains (e.g. mean inter-beat-interval, variation coefficient, and total spectral energy) were sensitive only to rest versus task condition but were not sensitive to variations in task demands.

Global measures of HRV should be sensitive to task versus baseline conditions for individuals with aphasia. However, in order to obtain subtle differences in HRV based on tasks of varying difficulty levels, one may need to examine the different spectral frequency bands, specifically the mid frequency band. It is also possible that Redondo and Del Valle-Inclan (1992) did not find differences on more global measures of heart rate variability between the different tasks because their memory search task only tapped retrieval from storage and therefore, was less demanding than dynamic working memory tasks. Working memory tasks require rapid storage, manipulation, rehearsal, and retrieval of information (Baddeley, 2007). Thus, it is possible that global measures of HRV will be sensitive to differences between work loads on more cognitively demanding tasks such as those that tap working memory processes. Because these measures have not been measured with individuals with aphasia, both time and frequency domain measures will be extracted and analyzed. However, because of its response to mental workload, the frequency band between .07 - .14 Hz is of primary interest in this study.

Statement of the Problem.

Aphasia is an acquired language impairment impacting a person’s ability to comprehend and produce language. Approximately 100,000 people per year acquire aphasia (National Institute on Deafness and other Communication Disorders, 2010) and are profoundly handicapped in their ability to participate in daily activities due to their communication impairment. Although communication is affected, researchers suggest that the underlying deficit may not be solely language related (McNeil, et al., 1991; Erickson, et al., 1996; Murray, et al., 1997a; Murray, et al., 1997b; Wright, et.al., 2003). For example, individuals with aphasia also show impairments on attention and working memory tasks (Caspari, et. al., 1998; Erickson et al., 1996; Murray, 2004; Tseng, et al., 1993; Wright, et al., 2003; Wright & Shisler, 2005).

However, investigations of cognitive performance by individuals with aphasia have included measures that could be considered “language heavy” where overt lexical, semantic, and/or phonological processing is required to complete the tasks and/or to formulate a response. For example, the verbal complex span task, a measure commonly used to assess working memory in individuals with aphasia, requires participants to comprehend a sentence and recall a word presented after the sentence. Although the tasks have been simplified and modified for individuals with aphasia, successful performance is certainly dependent on language ability. Not surprisingly, most researchers noting working memory deficits in aphasia have also found a relationship between working memory performance and language ability (e.g. Caspari, et al., 1998; Wright et al., 2003; Tompkins, et al., 1994; Friedmann & Gvion, 2003; Sung, McNeil, Pratt, Dickey, Hula, Szuminsky, & Doyle, 2009). Because language is known to be impaired in aphasia, it is difficult to distinguish deficits in cognitive processes underlying language from the language deficits germane to individuals with aphasia. The same is true for much of the research indicating individuals with aphasia have attention deficits (e.g. McNeil, Doyle, Hula, & Rubinsky, 2004; Murray, 2000; Murray et al., 2997a; Murray et al., 1997b). These studies used dual task paradigms with at least one of the tasks having a language component. To better understand the nature of underlying cognitive deficits in aphasia, it is essential that language processing is not required for successful task performance.

The spatial n-back task is a working memory task that has been shown to tap spatial but not verbal processing (Jonides, Reuter-Lorenz, Smith, Awh, Barnes, Drain, Glass, Lauber, Patalano, & Schumacher, 1996). By manipulating the task stimuli, the executive component of the *n*-back task remains the same while the type of processing required (e.g. verbal/spatial) is manipulated (Jonides et al., 1996). The difficulty of the tasks is easily manipulated by increasing *n*. Thus, it is ideal for isolating performance differences across two different domains that are equivalent in difficulty and processing load.

According to the resource allocation theory of aphasia, impaired performance by individuals with aphasia on attention and working memory tasks is at least partially due to an impaired ability to allocate cognitive resources to the tasks (McNeil, 1981; McNeil et al., 1991). This theory has been popularly applied to aphasia because it could explain the moment-to-moment variability in performance by individuals with aphasia on language tasks– the fact that when sitting in a quiet room, a person with aphasia may be able to retrieve a word one minute and a moment later when the conditions are exactly the same, not be able to produce the same word. However, the term "resources" represents a vague construct that is difficult to directly measure. Others have explained this deficit as an impaired ability to match effort with task demands (e.g. Murray et al., 1997a; Clark & Robin, 1995; LaPointe & Erickson, 1991; Laures-Gore, et al., 2007). Further, the terms "effort" and "resources" are frequently used interchangeably (Kahneman, 1973; McNeil et al., 2004). If language performance by individuals with aphasia is related to effort allocated, this could have important clinical implications.

Clark and Robin (1995) reported this to be the case. They observed the relationship between sense of effort ratings and reaction time during a lexical decision task for participants with and without aphasia. Compared to control participants, those with aphasia had no change in sense of effort with increased reaction time to a lexical decision task. Similarly, hypothesizing that perhaps individuals with aphasia do not appropriately invest effort because they mis-perceive the demands of the task, Murray and colleagues (1997a) assessed individuals with aphasia's ratings of task difficulty. They compared the performance of individuals with aphasia on a lexical decision task to performance on the lexical decision task when combined with a semantic distractor task or a tone discrimination task. Although performance declined in the more difficult, dual task conditions, individuals with aphasia's ratings of task difficulty did not change. Both of these studies compared perceptual ratings to behavioral performance and results indicated that individuals with aphasia have an impaired perception of task demands possibly contributing to an impaired allocation of effort. However, the tasks used were lexical decision tasks. Comparing the relationship between difficulty ratings and performance on non-verbal (spatial) and verbal tasks would reveal whether any deficits in perceiving the task demands are specific to the verbal stimuli, possibly reflecting the primary language deficit, rather than a domain-general deficit in evaluating task demands. Further, the finding of a mismatch between the performance of individuals with aphasia and their ratings of effort/difficulty is interesting, but there is a need for a more direct physiological measure of effort.

Laures-Gore and colleagues' (Laures, et al., 2003; Laures-Gore, et al., 2007) utilized a physiological measure of stress – salivary cortisol – in their attempt to quantify the stress experienced by individuals with aphasia during verbal tasks compared with non-verbal tasks. They investigated change in cortisol during a vigilance task (Laures et al., 2003), a public speaking task, and during a mirror drawing task (Laures-Gore et al., 2007). In spite of poorer performance than control participants, individuals with aphasia did not display cortisol reactivity during these tasks. These results seem to suggest a disconnect between performance and a physiological measure of stress for individuals with aphasia (Laures et al., 2003). However, the salivary cortisol measurements are not an effective measure of effort for individuals with aphasia. For example, it has been suggested that the mechanism involved in the production of cortisol – the hypothalamic-pituitary-adrenal (HPA) axis – is impaired in brain injured populations (Fassbender, et al., 1994; Franceshini, Tenconi, Zoppoli, & Barreca, 2001; Johansson, et al., 2000; Olsson, 1990). Further, cortisol takes time to build up in the bloodstream and is a slower responding measure of stress (Backs, & Seljos, 1994; Everly, & Sobelman, 1987); therefore, cortisol may not be appropriate for detecting immediate changes in effort expended during short experimental tasks frequently used with individuals with aphasia.

An alternative, well-studied measure of effort allocated to cognitively demanding tasks is heart rate variability (HRV). HRV is the amount of fluctuation around the mean heart rate. It has been shown to reflect the mental workload required during cognitive tasks (e.g. Kalsbeek, 1971; Porges, 1992; Backs, & Seljos, 1994; Veltman, & Gaillard, 1993; Hansen, Johnsen, & Thayer; 2003) and, therefore, is considered a physiological measure of effort (Aasman, Mulder, & Mulder, 1987). Cognitively challenging tasks elicit a stress response measured as a drop in HRV from baseline to task conditions (Kalsbeek, 1971). This decrease in HRV occurs because the parasympathetic system, normally working to slow the heart in opposition to the sympathetic system which speeds heart rate, is inhibited during cognitively challenging tasks. The resulting decrease in HRV provides an objective physiological measure of the effort allocated to cognitively challenging tasks and may provide insight into the effort allocated by individuals with aphasia to verbal versus spatial working memory tasks. In this study effort is operationally defined as the difference in HRV measured during an *n*-back working memory task from HRV measured during a resting state.

Specific aims.

Specific Aim 1: To assess differences in behavioral performance for individuals with aphasia and neurologically intact participants on spatial and verbal working memory tasks. The study will address this aim by comparing the accuracy of individuals with aphasia and neurologically intact participants on a spatial working memory task with performance on a verbal working memory task.

Hypothesis: Individuals with aphasia will perform worse than neurologically intact participants on verbal, but not spatial working memory tasks.

Specific Aim 2: To assess the ability of individuals with aphasia to accurately perceive the difficulty of the verbal and spatial working memory tasks. This study will address this aim by assessing the relationship between perceived level of difficulty and behavioral accuracy for individuals with aphasia on verbal and spatial tasks. Pre- and post-task ratings of difficulty will be elicited.

Hypothesis: The relationship between difficulty and performance will be weaker for pre-task ratings than post task ratings of performance reflecting an impaired evaluation of task demands. Participants with aphasia's perceptions of difficulty will predict behavioral performance for spatial but not verbal tasks. This will indicate that individuals with aphasia are not accurate on verbal tasks because they don't perceive them as difficult.

Specific Aim 3: To assess differences in the relationship between task difficulty and level of effort (change in HRV from post-task baseline to task conditions) allocated by individuals with aphasia during verbal and spatial working memory tasks. This study will address this aim by comparing the relationship between task difficulty (n-back level) and change in HRV for verbal compared with spatial working memory tasks.

Hypothesis: A strong relationship between task difficulty and effort will be present for spatial but not verbal working memory tasks.

Specific Aim 4: To determine if level of effort dedicated to the working memory tasks relates with accuracy or perceived level of difficulty for verbal and spatial tasks for individuals with aphasia. This study will address this aim by comparing the relationship between HRV and perceived level of difficulty, and HRV and behavioral accuracy for individuals with aphasia and neurologically intact participants on verbal and spatial tasks.

Hypothesis: Effort allocated will correlate with perceived level of difficulty for both verbal and spatial tasks for individuals with aphasia and neurologically intact participants. Effort individuals with aphasia allocate to spatial, but not verbal tasks will correlate with behavioral accuracy.

Summary.

In summary, the nature of the underlying deficit impacting language in individuals with aphasia remains unclear. Impaired performance on working memory and attention tasks (e.g. Caspari et al., 1998; Erickson et al., 1996; Tseng et al., 1993; Wright et al., 2003) indicate additional cognitive deficits; however, these studies have not excluded language processing. Specific aim one will address this limitation. Further, studies of individuals with aphasia's self-ratings of task difficulty, and effort allocated indicate a mismatch between individuals with aphasia's perceptions and their behavioral performance. Specific aim two will replicate and extend these findings to determine if this relationship is different for verbal tasks than spatial tasks. In addition, there is a need for the application of an objective physiological measure of effort commonly used with neurologically intact participants to be applied to individuals with aphasia. Given HPA axis dysfunction in stroke patients (Fassbender, Schmidt, Mossner, Daffershofer, & Hennerici, 1994; Franceshini, et al., 2001; Johansson, et al., 2000; Olsson, 1990) and findings of participants with aphasia's lack of cortisol response to difficult tasks (Laures-Gore et al., 2007), cardiovascular measures such as HRV may prove to be more sensitive tools for advancing our understanding about the nature of the underlying deficit in aphasia. Specific aim three will provide a time-sensitive measure of the effort invested by individuals with aphasia, and will further extend previous work by including tasks that differ in linguistic processing demands (i.e. verbal working memory versus non-linguistic, spatial working memory task). Finally, specific aim 4 will combine all dependent measures to reveal how perceptions of task difficulty influence effort allocated to verbal and spatial tasks, and in turn, behavioral performance. Results of this research will inform our understanding of the nature of underlying deficit in aphasia and inform theories of cognitive processing in aphasia. Further, being able to quantify the physiological stress experienced during cognitively challenging tasks could have important health and treatment implications for individuals with aphasia.

Chapter 2

METHOD

We investigated performance differences between individuals with aphasia and control participants for verbal and spatial working memory tasks across various levels of mental workload (1-back, 2-back, 3-back). How individuals with aphasia performed on spatial working memory tasks was of primary interest. Additionally, HRV (.07-.14 Hz) was measured via an electrocardiogram (ECG) during resting baseline conditions and during the verbal and spatial working memory tasks to quantify effort allocated. Effort allocated is operationally defined as the difference in HRV measured during an n-back working memory task from HRV measured during a post-task resting state. A difference in change in HRV across verbal and spatial tasks was the variable of interest. Finally, ratings of task difficulty were obtained before and after each n-back in order to determine the relationship among perceived task difficulty, effort allocated, and behavioral performance for the verbal and spatial tasks.

Participants

Participants included 13 individuals with aphasia and 21 age- and education-matched control participants. Participants met the following criteria: (1) demonstrated hearing within functional limits by passing a hearing screening; (2) self reported that they are monolingual English speakers; (3) demonstrated aided or unaided visual acuity within normal limits, as indicated by passing a vision screening; and (4) demonstrated no depression at the time of the experiment as measured by a score of 0-4 on the Geriatric Depression Scale-Short Version (GDS; Van-Marwijk, Wallace, de-Bock, Hermans, Kaptein, & Mulder, 1995). Additional inclusionary criteria for adults with aphasia included the following: a history of left hemisphere stroke that occurred no less than six months prior to testing; the presence of aphasia determined by an aphasia quotient on the Western Aphasia Battery-Revised (WAB-R; Kertesz, 2006) of below 93.7, or if score on WAB-R was above cutoff, presence of aphasia was determined by clinical judgment based on discourse performance; and, no history of other neurological conditions. In addition, all participants with aphasia were screened for motor speech disorders using The Rating Scale Form for Deviant Speech Characteristics (Duffy, 1995). All control participants self-reported a negative history of neurological conditions and demonstrated normal cognitive functioning as evidenced by performance on the Mini-Mental State Examination (Folstein, Folstein, & McHugh, 2001). The Hand Usage Questionnaire (Chapman & Chapman, 1987) was also included as part of the screening protocol to asses hand dominance. Participants' demographic information is included in Table 1.

Experimental Tasks

Behavioral working memory task.

Baddeley's working memory model (2007) served as the basis for task selection. According to this model, verbal and visual-spatial information are stored separately in the phonological and spatial buffers and function to temporarily hold and manipulate information. Although verbal and spatial information are stored separately, these two components share an executive system that directs and monitors information storage and manipulation within the buffers. This executive component is limited in capacity and corresponds closely with the executive control system specified in attention models (e.g. Kahneman, 1973; Norman & Shallice, 1986), which have been readily applied to individuals with aphasia. In the current study, spatial working memory and verbal working memory were the cognitive processes of interest. The experimental tasks included verbal and spatial n-backs. Because the two working memory tasks share an executive component while isolating two different processing domains (Jonides, Lauber, Awh, Satoshi, & Koeppe, 1997), results of the study have the potential to provide an understanding of whether deficits in aphasia are domain-general, or solely dependent on language.

The n-back task is particularly ideal for assessing working memory in aphasia. It requires participants to decide whether each stimulus in a sequence matches the one that appeared *n* items ago. Therefore, it requires temporary storage and manipulation of information, while at the same time, constantly updating the contents in working memory (Jonides et al., 1997). The n-back task is ideal for individuals with aphasia because it requires only a button press for the response. In addition, the stimuli can be manipulated to investigate different domains (verbal and spatial) while keeping the working memory load constant.

To complete the n-back, participants must sustain attention to monitor a stream of stimuli; encode their identity or location; match the current stimulus against the internal representation of the previous stimuli; and, update that information while inhibiting previously relevant verbal or spatial information. Participants must also maintain the previous information through phonological (verbal n-back) or visual-spatial (spatial n-back) rehearsal. The memory load is increased with the number of items/locations to be remembered (i.e. *n*).

Prior to completing the experimental tasks, all participants completed a serial reaction time task in which they responded with a button press to the verbal and spatial stimuli presented on the computer screen. The experimental tasks included three verbal and three spatial n-back tasks that varied in processing load: 1-back, 2-back, and 3-back. The verbal stimuli included eight letters (B, F, H, L, M, R, Q, J) presented in 16 point Arial font one at a time in the center of the screen. In order to eliminate a visual coding strategy, letters varied in case. In the verbal task, participants were asked to respond as quickly as possible by pressing the spacebar when the letter was the same as the letter *n* back. The spatial stimuli included one inch in diameter black circles presented on a white background in eight different locations spaced in an octagon fashion around a central fixation point (See Figure 1). One dot appeared on the screen at a time. Participants were asked to respond to the spatial tasks by pressing the spacebar when the dot was in the same location as the one *n* back (See Figures 2-4 for examples of task presentation). Stimulus onset asynchronies (SOA) of 3500 ms, shown to be effective for use with individuals with aphasia (Wright, et al., 2007), were used in all n-back tasks. Each stimulus was presented for 750 ms with an interstimulus interval of 2750 ms. All participants responded using their non-dominant hand.

Physiological measure of effort: heart rate variability.

Heart rate variability (HRV) is the amount of heart rate fluctuation around the mean heart rate (Task Force, 1996). It is a physiological measure that is sensitive to cognitive processes such as memory (e.g. Hansen, Johnsen, Thayer, & Thayer, 2003), attentional capacity (Porges, 1992), and mental effort or workload (e.g. Althaus, et al., 1998; Bishop, 1994) all constructs, which have been difficult to assess in individuals with aphasia.

Although HRV in general is influenced by both sympathetic and parasympathetic activity, the rapid changes in heart rate variability that occur during short mental workload studies (e.g. of approximately five minute duration) have been suggested to be primarily due to changes in parasympathetic input (i.e. a decrease in vagal tone from baseline to task conditions [Axelrod, Gordon, Madwed, Snidman, Shannon, & Cohen, 1985]). The vagus nerve provides the parasympathetic input to the sinus node of the heart, which is the heart’s primary pacemaker. The cardiovascular role of the parasympathetic system is to modulate heart rate by inhibiting activity of the sinus node. The influence of the parasympathetic system on cardiovascular function is measured in experimental tasks by measuring the variation in heart rate (Duschek, Muckenthaler, Werner, & Reyes del Paso, 2009). When effort is allocated to cognitively challenging tasks there is increased sympathetic input and decreased parasympathetic input (vagal tone), which results in an accelerated heart rate and a decrease in HRV. HRV is particularly sensitive to differences from a resting baseline condition to tasks, which vary in their memory and attentional demands, particularly the .07 - .14 Hz spectral band (Backs & Seljos, 1994; Mulder & Mulder, 1981; Veltman & Gaillard, 1996).

The Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology (Task Force, 1996) established standard methods of measurement for heart rate variability. There are several ways to measure heart rate variability. The simplest measurements are obtained from time domain methods. Time domain measures are based on the heart rate at a point in time, or the difference between successive sinus node initiated R waves in the QRS complex. The QRS complex is the ECG output reflecting ventricular depolarization. It consists of several waves occurring in close proximity – a Q, R, and S-wave. The R-wave is the largest wave in the complex and is easily identified to calculate HRV. The distance in milliseconds between each R-spike forms the basis of an interbeat interval (IBI) series – the input data for programs that compute heart rate variability. The artifact free IBI series is called the normal-to-normal (NN) interval.

Statistical calculations can be derived from instantaneous heart rate, from direct measurement of NN intervals, or from differences between NN intervals. The simplest of these measures is the standard deviation of the NN intervals (SDNN). SDNN reflects all the components (i.e. sympathetic and parasympathetic activity) responsible for variability during the recording period. Another, more commonly used time domain statistical measure is the root mean square of successive differences between interbeat intervals (RMSSD). RMSSD is the recommended procedure for heart rate variability measurements taken in short, several-minute intervals (Task Force, 1996). The Task Force recommends five-minute recording times for experimental studies to facilitate comparisons among studies, and because some time domain measures can vary based on the length of recording (e.g. SDNN). This time period is particularly ideal for participants with aphasia who may fatigue easily and become frustrated with exceedingly long experimental procedures. Change in HRV in the .1 Hz frequency band (.07 - .14) from post condition baseline to HRV during each 5-minute experimental condition was the dependent measure of effort in this research study. However, Respiratory Sinus Arrhythmia (RSA) associated with the .12 - .40 spectral range was also of interest. This frequency range is vagally mediated and, thus, reflects primarily parasympathetic modulation of heart rate (Allen, Chambers, & Towers, 2006).

Although time domain measures of heart rate variability provide an adequate measure of overall variability, specific information about the extent to which sympathetic and parasympathetic systems influence heart rate variability can be determined through examining specific frequency domains via frequency-domain metrics. In short-term recordings three main spectral components are distinguished: very low frequency (VLF), low frequency (LF) and high frequency (HF) spectral components. VLF is thought to primarily reflect artifact and is not recommended for use in heart rate variability measurement (Task Force, 1996). The LF band includes the .04 - .15 Hz range and is thought to be related primarily to sympathetic modulation (e.g. the effect of epinephrine and norepinephrine on the sino-atrial (SA) and atrio-ventricular (AV) nodes increasing heart rate; Reed, Robertson, & Addision, 2005). The HF band includes frequencies between .15 - .40 Hz and is thought to reflect exclusively parasympathetic effects (e.g. the release of acetylcholine acting on SA and AV nodes to slow heart rate and conduction at the AV node; Akselrod, Gordon, Ubel, Shannon, Berger, & Cohen, 1981).

The ratio of LF to HF is often used as a metric of sympathetic-parasympathetic balance (see Berntson, Bigger, Eckberg, et al., 1997 for an alternative view). Although only one minute of recording is needed to assess HF spectral components of heart rate variability, and two minutes for LF components, five minutes of recording time are recommended for short duration studies to increase standardization among studies (Task Force, 1996). Although time domain methods are generally easier to perform, frequency domain methods are preferred over time domain methods because they provide more easily interpretable results about physiological regulations of HRV (Task Force, 1996). That is, by examining values of LF and HF, the relative changes in HRV resulting from sympathetic and parasympathetic input can be distinguished. For example, a decrease in the LF:HF ratio results from either a decrease in sympathetic input as reflected by a decrease in the LF band, and/or an increase in parasympathetic input as reflected by increases in the HF band. In contrast, a greater LF:HF ratio, indicates either an increase in sympathetic input (LF band) or a decrease in parasympathetic input (HF band). The relative contribution of sympathetic and parasympathetic systems cannot be as readily distinguished with time domain measures.

Because these measures have not been used with individuals with aphasia, both, time and frequency domain measures, were extracted and analyzed. It was expected that global measures of heart rate variability would be sensitive to differences between baseline and task conditions for individuals with aphasia. However, because of its response to mental workload, the mid frequency band between the range of .07 - .14 was of primary interest in this study.

ECG recording and HRV analysis.

ECG activity was continuously recorded using BIOPAC Student Labs (BSL) PRO MP35 recording unit with BSLPro software (500 samples/second, Filter .05 - .35 Hz). Start and end times of each task were coded during the task. Five minute segments were then extracted using AcqKnowledge software, with 12 seconds of pre-task padding and 12 seconds padding on the tail end of the five minute recording. This was to account for the filtering that excludes the first and last 12 seconds of data. The IBI series was extracted and visually inspected using QRSTool. Ectopic beats were interpolated using QRSTool. When ectopic beats could not be interpolated, the data was excluded from further analyses. CMetX was used to calculate measures of cardiac chronotropy.

Rating scale.

To assess the ability of individuals with aphasia to accurately perceive the difficulty of the verbal and spatial working memory tasks, participants rated the difficulty of each task immediately before and after each experimental condition. A vertically presented scale anchored with the words “easy” and “difficult” was used for this study (See Figure 5). In addition to the verbal descriptions, simple and complex math problems were included as further illustration of the concepts on the rating scale. The scale consisted of a 100-mm line in which participants indicate their rating by marking the point on the line that matches their perceptions. The line was presented vertically to eliminate the possible confound of hemispatial neglect which could be present in participants with aphasia. The current scale was developed because the linguistic demand is minimal and because it is similar to other scales that have been used with this population.

Prior to the first task, participants were asked to mark the middle of the line to ensure they were able to accurately perform the task. The value in millimeters corresponding to the point marked on the line was the dependent variable used in statistical analyses.

Experimental Procedures

Participants were asked to avoid smoking, caffeine, alcohol, and strenuous exercising for two hours prior to testing. They completed a brief questionnaire describing any deviations from that request as part of the screening protocol. Participants were also asked to either provide a list of current medications or to check off any medications being taken from a list of those known to affect heart rate. Upon arrival, participants completed informed consent followed by administration of screening measures. Participants with aphasia completed the screening measures and the WAB-R (Kertez, 1982) during the first session. They returned within two weeks to complete the experimental tasks. Control participants completed screening measures immediately prior to the experimental tasks.

To complete the experimental tasks, participants entered a sound booth where ECG leads were connected for the HRV recording, which was continuous throughout the duration of the session. Three surface electrodes were placed on the torso in a Lead II configuration. Participants sat in a high back chair for the duration of the session. Initial ECG output was reviewed to ensure a clear recording and the absence of noticeable arrhythmias.

Participants completed all the experimental tasks and an initial serial reaction time (SRT) task in one session. All tasks were followed by a five-minute rest period during which participants were instructed to rest quietly with their eyes open. The rest periods were signaled by a final slide in the experiments, which read, "Break. Relax for 5 minutes." HRV data was recorded continuously for the duration of the tasks and rest periods (See Figure 6 for timeline). The beginning and end of experimental tasks and rest periods were marked on the ECG recording using BSLPro software.

Prior to completing the tasks, participants viewed task instructions and sample stimuli in Microsoft PowerPoint while listening to oral instructions provided by the experimenter. Instructions and sample stimuli were repeated until the participant verbalized and demonstrated understanding of the practice items. After administration of task instructions, participants completed a pre-task difficulty rating scale to indicate how difficulty they thought the task would be. In the experimental task presented via E-Prime 2.0, an additional practice block was presented prior to each n-back. This practice block consisted of 10 items with two targets. After the practice block, participant began the experimental n-back task.

Each n-back included 33 targets presented in a single block containing 100 stimuli. Following completion of the task and five-minute rest period, participants completed the difficulty rating scale a second time to indicate the *actual* difficulty of the completed task.

Task difficulty order and presentation order for stimuli type was counterbalanced within the difficulty levels. For example, a participant who received the 2-backs first, completed both verbal and spatial stimuli for the 2-backs before moving on to a different difficulty level (i.e., 1-back or 3-back).

Data Analyses

Specific Aim 1: To assess differences in behavioral performance for individuals with aphasia and neurologically intact participants on spatial and verbal working memory tasks.

Response accuracy, in the form of hit rates and false recognition rates was recorded and converted to d prime values. Signal detection theory advocates for the use of d’ as a bias free measure of internal response or sensitivity (Lachman, Lachman, & Butterfield, 1979). D prime values were the behavioral performance measure used in statistical analyses. A 2 x 2 x 3 mixed between-within subjects ANOVA was performed to assess between and within group differences in performance on verbal and spatial n-backs. The between subjects factor was group, with levels control and aphasia. The first within subjects factor was task type. The levels were verbal and spatial. The second within subjects factor was difficulty with levels 1-back, 2-back, and 3-back. In addition, planned comparisons were performed to investigate between group differences in performance at each n-back level.

Specific Aim 2: To assess the ability of individuals with aphasia to accurately perceive the difficulty of the verbal and spatial working memory tasks.

Results of this aim extend previous research by comparing ratings of task difficulty with accuracy for verbal and spatial working memory tasks. Regression analyses were performed to test whether difficulty ratings predicted performance on n-back tasks (1-, 2-, and 3-back) for verbal and spatial working memory tasks. The value in millimeters corresponding to the point marked on the 100-mm difficulty rating scale was the predictor variable used in the regression analysis. The criterion was d prime scores.

Specific Aim 3: To assess differences in the relationship between task difficulty and level of effort (change in HRV from post-task baseline to task conditions) allocated by individuals with aphasia during verbal and spatial working memory tasks.

The dependent variable for effort allocated was the change in HRV from post-task baseline to task condition. The .07 - .14 frequency range extracted using CMetX software was the measure of HRV subjected to statistical analyses. This study addressed this aim by comparing the correlation between task difficulty and change in HRV for verbal compared with spatial working memory tasks.

<u>Specific Aim 4:</u> To determine if level of effort dedicated to the working memory tasks relates with accuracy or perceived level of difficulty for verbal and spatial tasks.

This aim was addressed by comparing the relationship among the dependent variables from the experimental tasks for individuals with aphasia and control participants. The correlation among effort (change in HRV from baseline to task), performance (d' scores), and difficulty ratings was compared across all difficulty levels (1-, 2-, 3-back) for verbal and spatial tasks. Relationships between effort, task difficulty, and performance for individuals with aphasia were compared with those for control participants to determine whether these relationships are different for individuals with aphasia for verbal and spatial tasks.

Chapter 3

RESULTS

Data were screened for outliers prior to analyses. Outliers greater than 3 standard deviations from the mean were excluded from all analyses. Histograms were reviewed to verify assumptions of normality. Maulchy's test was conducted to ensure the assumption of sphericity was upheld. When the sphericity assumption was violated, degrees of freedom were corrected using Huhnh-Feldt estimates of sphericity.

Specific Aim 1: Between Group Differences in N-Back Performance for Verbal and Spatial Tasks

A mixed analysis of variance (ANOVA) was conducted to assess group differences in performance on verbal and spatial working memory tasks across three levels of difficulty (1-back, 2-back, 3-back). Group means and standard deviations indicating performance on each task are reported in Table 2. The main effects of group, F (1, 30) = 11.53, $p < .01$, partial eta squared = .28, and task difficulty were significant, F (2, 30) = 188.54, $p < .01$, partial eta squared = .86. The control group had a significantly higher mean d prime score than the aphasia group; and, d prime scores decreased as n-back difficulty level increased. There was a significant task by group interaction, F (1, 30) = 9.78, $p < .01$, partial eta squared = .25, and a significant task by difficulty interaction, F (2, 10.19) = 4.05, $p < .05$, partial eta squared = .12. Of primary interest is the significant three-way interaction of task type by difficulty by group, *F* (2, 30) = 4.47, *p* < .05, partial eta squared = .13, which indicated the difference between groups at each level of difficulty differed for verbal and spatial tasks. See Figure 7 for the line graph depicting the three-way interaction. Model summary information is depicted in Table 3.

Follow-up tests were conducted to determine how performance between participants with aphasia and control participants differed for verbal and spatial stimuli. Three separate one way ANOVAs with the between group factor of task type (verbal, spatial) were conducted at each difficulty level using Holme's (1979) sequential Bonferroni to adjust for multiple comparisons. This procedure requires rank ordering the *p* values from smallest to largest and adjusting the alpha rate with each comparison. The smallest *p* value is tested at an alpha of .05 divided by the number of comparisons. The next smallest *p* value is tested at alpha equal to .05 divided by the number of remaining comparisons. The procedure stops with the first non-significant *p* value. Results indicated a significant difference between groups on all verbal n-backs with control participants performing significantly better than participants with aphasia: 1-back, *F* (1, 30) = 13.64, *p* < .01, partial eta squared = .31; 2-back, *F* (1, 30) = 14.85, *p* < .01, partial eta squared = .33; 3-back, *F* (1, 30) = 85.94, *p* < .01, partial eta squared = .21. In contrast, for the spatial n-back tasks, a significant group difference was only found on the 3-back, F (1, 30) = 11.18, *p* < .01, partial eta squared = .27. The groups did not differ on the spatial 1-back, F (1, 30) = 1.27, p = .27, partial eta squared = .04, or spatial 2-back, F (1, 30) = 1.77, p =.19, partial eta squared = .06.

To evaluate the significance of the difference between groups on verbal and spatial tasks, planned pairwise comparisons were performed using the difference between group means on each task type as the dependent variable. Three univariate one-way ANOVA’s were performed to test the significance of the between-group differences in verbal compared with spatial performance at each n-back level. The difference between groups on verbal compared to spatial tasks was statistically significant at the 1-back, F (1, 30) = 6.12, p <.05, partial eta squared = .17, and 2-back levels, F (1, 30) = 14. 35, p < .01, partial eta squared = .32. Differences between groups were larger for the verbal tasks at the 1- and 2-back levels and no difference was found for the 3-back tasks, F (1, 30) = .04, p = .84, partial eta squared = .001. These results indicate that the difference between individuals with aphasia and control participants for verbal stimuli compared with spatial stimuli was significantly different for both one and two-back tasks.

Within Group Comparisons for N-back

Two-way repeated measures ANOVAs were conducted to evaluate within group differences. For the control group, a significant effect of task type, F (1, 28.94) = 11.42, p < .01, partial eta squared = .36, indicated that the control participants performed better on verbal n-backs than spatial n-backs. There was also a significant effect of task difficulty, *F* (1.44, 40) = 106.23, *p* < .01, partial eta squared = .84. The interaction between task type and difficulty was not significant, *F* (2, 40) = 1.35, *p* = .271, partial eta squared = .06 indicating control participants performed better on verbal than spatial tasks across all levels of difficulty.

In contrast, results for the aphasia group revealed a significant interaction between task type and difficulty, *F* (2, 20) = 4.05, *p* < .05, partial eta squared = .29, but no significant effect of task type for participants with aphasia, *F* (1, 10) = 2.02, *p* = .19, partial eta squared = .17. The main effect of difficulty was significant, *F* (2, 20) =142.63, *p* < .01, partial eta squared = .93. Follow-up tests used Holm's (1979) sequential Bonferroni alpha adjustment for multiple comparisons. Three one-way repeated measures ANOVAs revealed no significant difference between verbal and spatial tasks at any level of difficulty: 1-back, *F* (1, 10) = .15, *p* = .71, partial eta squared = .01; 2-back, *F* (1, 10) = 7.22, *p* = .02, partial eta squared = .42; 3-back, *F* (1, 10) = .87, *p* = .37, partial eta squared = .08.

Specific Aims 2 – 4: Relationships among Performance, Ratings of Difficulty, and HRV

Descriptive statistics.

Correlation analyses were conducted to determine the relationship among performance, ratings of task difficulty, and HRV. Linear regression analyses were conducted to further investigate significant relationships. Visual inspection of scatterplots and plots of the standardized residuals indicated that assumptions of linearity and homoscedasticity were reasonably met. Outliers greater than 3 standard deviations from the mean were excluded from the analyses. Means and standard deviations for all dependent variables are included in Table 2. Means and standard deviations for the difference between baseline and task HRV at frequency ranges .07-.14 and .12 - .40 for each task are included in Tables 6 and 7. Correlation tables demonstrating the relationship among performance, perceived task difficulty, and HRV are reported by group in Tables 4 and 5.

Specific aim 2: Relationship between performance and difficulty ratings.

As preliminary analyses, one-way repeated measures ANOVAs were conducted for each group to determine whether the .07 - .14 frequency range was sensitive to differences between baseline and task conditions. The .07 - .14 Hz range was significant for both the control, F (1, 112) = 121.06, $p < .001$, partial eta squared = .52, and aphasia groups, F (1, 55) = 19.51, $p < .001$, partial eta squared = .26. HRV significantly decreased from post-task to task conditions indicating both groups allocated effort to the tasks.

To address specific aim two, correlations among n-back performance, pre-task difficulty ratings, and post task difficulty ratings were conducted. The correlations between ratings and n-back performance were negative for both groups with ratings of difficulty increasing with decreased n-back performance.

All correlations between ratings and performance were statistically significant. Means and standard deviations for all dependent variables are reported in Table 2. Correlations are reported in Tables 4 and 5.

Pre-task difficulty ratings

The correlations between pre-task difficulty ratings and performance were stronger for the control group than for the participants with aphasia. For the control group, pre-task expected difficulty ratings correlated strongly with verbal, $r = -.73$, $p < .01$, and spatial n-back performance, $r = -.60$, $p < .01$. For the aphasia group, pre-task difficulty ratings were moderately, but significantly correlated with verbal, $r = -.44$, $p < .01$, and spatial, $r = -.39$, $p < .05$ n-back performance.

Post-task difficulty ratings

For the control group, post-task ratings also significantly correlated with performance on verbal, $r = -.74$, $p < .01$ and spatial, -.68, $p < .01$ n-backs. Similarly, the aphasia group's post-task ratings were significantly correlated with performance on the verbal, $r = -.73$, $p < .01$, and spatial n-back tasks, $r = -.66$, $p < .01$. For both groups, post-task difficulty ratings were stronger for verbal than spatial tasks.

Linear Regression Analysis

Linear regression analyses were conducted to determine if pre-task ratings of expected task difficulty predicted performance on verbal and spatial n-backs. Linear regression analyses were also conducted to determine if n-back performance predicted post-task ratings of difficulty on the verbal and spatial n-back tasks. Analyses for each group were conducted separately.

Pre-task ratings and verbal performance

Linear regression analyses were performed to determine if pre-task ratings predicted n-back performance. For the control group, pre-task ratings accounted for 50% of the variance in verbal n-back performance, adjusted $R^2 = .50$, $F\ (1, 19) = 21.07$, $p < .001$. In contrast, for the participants with aphasia, pre-task ratings accounted for only 17% of the variance in verbal n-back performance, adjusted $R^2 = .17$, $F\ (1, 31) = 7.26$, $p < .05$.

Post-task ratings and verbal performance

A second linear regression was performed to determine the extent to which performance predicted post-task ratings. For the control group, performance accounted for 54% of the variance in post task ratings, adjusted $R^2 = .54$, $F\ (1, 61) = 73.68$, $p < .001$. Similarly, performance accounted for 52% of the variance in post task ratings made by the aphasia group, adjusted $R^2 = .52$, $F\ (1, 31) = 34.81$, $p < .001$.

Pre-task ratings and spatial performance

Linear regression analyses were performed to determine if pre-task ratings predicted n-back performance. For the control group, pre-task ratings accounted for 33% of the variance in spatial n-back performance, adjusted $R^2 = .33$, $F\ (1, 19) = 10.91$, $p < .01$. In contrast, for aphasia group, pre-task ratings accounted for only 12% of the variance in spatial n-back performance, adjusted $R^2 = .12$, F (1, 31) = 5.28, $p < .05$. Pre-task ratings accounted for more of the variance in performance for the control group, than for the aphasia group.

Post-task ratings and spatial performance

Linear regression analyses were performed to determine the extent to which performance predicted post-task ratings of the spatial n-backs. For the control group, performance accounted for 46% of the variance in post task ratings, adjusted $R^2 = .46$, F (1, 61) = 53.74, $p < .001$. Similarly, performance accounted for 41% of the variance in post- task ratings made by the aphasia group, adjusted $R^2 = .41$, F (1, 31) = 22.71, $p < .001$.

To summarize, the correlations between pre-task difficulty ratings and performance were stronger for the control group than for the participants with aphasia. For both groups, post-task difficulty ratings were stronger for verbal than spatial tasks. Pre-task ratings accounted for more of the variance in performance for the control group than for the aphasia group indicating that control participants are better at predicting task difficulty than individuals with aphasia. Control participants were better at rating task difficulty for verbal than spatial n-back tasks. This pattern was less pronounced for the aphasia group.

Specific Aim 3: Relationship between HRV and Task Difficulty

Correlation analyses were conducted to determine the relationship between task difficulty (n-back performance) and change in HRV in the .07-.14 frequency range. Correlations were non-significant for both groups for verbal and spatial tasks.

Specific Aim 4: Relationships among HRV, Perceived Difficulty, and Performance.

To determine if the physiological response during the n-back tasks related to accuracy or perceived level of difficulty for verbal and spatial tasks for the groups, correlations were examined. For both the control and aphasia group, correlations were non-significant.

Chapter 4

DISCUSSION

Researchers have suggested that the underlying deficit in aphasia may not be solely language related (McNeil et al., 1991; Erickson et al., 1996; Murray et al., 1997a; Murray et al., 1997b; Wright et.al., 2003). For example, individuals with aphasia have also shown impairments on attention and working memory tasks (Caspari et. al., 1998; Erickson et al., 1996; Murray, 2004; Tseng et al., 1993; Wright et al., 2003; Wright & Shisler, 2005). However, the tasks used to assess working memory and attention included verbal stimuli; or, verbal processing was required to complete the tasks (e.g. Caspari et al., 1998; McNeil, Doyle, Hula, & Rubinsky, 2004; Murray, 2000; Murray et al., 2997a; Murray et al., 1997b; Wright et al., 2003; Tompkins et al., 1994; Friedmann & Gvion, 2003; Sung, McNeil, Pratt, Dickey, Hula, Szuminsky, & Doyle, 2009)

This study followed Baddeley’s model (2000) of working memory as a means to explore the notion of whether working memory deficits in aphasia are domain specific or if domain general deficits account for the language deficits experienced by individuals with aphasia. According to Baddeley’s model (2000), verbal and spatial tasks share a common central executive component that directs attention to the tasks. In addition, two domain specific storage buffers are responsible for maintaining the phonological or visuospatial representations.

Specific Aim 1

The goal of Specific Aim 1 was to determine if participants with aphasia and control participants differ on verbal and spatial working memory tasks. If participants with aphasia were impaired on both verbal and spatial working memory tasks relative to control participants, this would suggest a domain-general impairment in working memory ability in individuals with aphasia that is not specific to verbal information and not driven by their primary language deficit.

In contrast, if working memory deficits observed in aphasia are driven by a primary language deficit and subsequently a deficit in the phonological loop, spatial working memory performance would be preserved for participants with aphasia relative to control participants. We hypothesized that participants with aphasia would perform worse than control participants on verbal, but not spatial n-back tasks. Results partially supported this hypothesis.

Group differences were found on all verbal n-back tasks; the control group performed significantly better than the aphasia group. In contrast, for the spatial working memory task, the aphasia group performed similarly to the control group at the 1-back and 2-back levels but not the 3-back. The mean score for the aphasia group on the 3-back spatial task was significantly lower than the control group's mean score. However, examination of the individual data indicated that many control participants performed similar to participants with aphasia on the task.

Possibly, the control participants with higher d prime scores on the 3-back spatial task employed a verbal strategy to complete the task. Anecdotally, several control participants reported trying to assign verbal labels to the dots on the 3-back task.

In a functional MRI study comparing verbal and spatial n-back performance on a 3-back task with a 0-back task, Nystrom (2000) found no difference in lateralization of cortical activation between tasks. The same cortical areas responded to the increase in memory load from the 0-back to 3-back task regardless of stimulus type. Nystrom suggested that participants may have used a verbal strategy on the complex spatial tasks which resulted in recruitment of similar cortical regions. Baldo (2010) has argued that language is necessary for higher level reasoning and problem solving performance and investigated this by having participants with aphasia complete the Wisconsin Card Sorting Test. Baldo (2005) found a relationship between severity of language impairment and performance on the Wisconsin Card Sorting Test (2005). Similarly, control participants were impaired on this task when asked to perform this task under articulatory suppression. Articulatory suppression requires minimal attentional demands but blocks the use of subvocalization. Baldo (2010) also found similar relationships between severity of language impairment in participants with aphasia and performance on items that involved higher level reasoning on the Raven’s Progressive Colored Matrices test (Baldo, 2010), but not on items in which a visual matching strategy could be used. Baldo’s work provides support for the notion that language is critical for higher level reasoning and problem solving. Baldo’s conclusions may partly account for why the aphasia group differed significantly from the control group on the spatial 3-back task but not on the other levels. Participants may have been able to use a spatial processing strategy on the 1- and 2-back levels, but a verbal strategy was necessary to perform the 3-back spatial working memory task. This hypothesis should be considered with caution and further investigations are warranted to systematically investigate strategy use.

Specific Aim 2

Researchers investigating self-ratings of task difficulty and effort allocated to lexical decision tasks in adults with aphasia indicated a mismatch between their perceptions and behavioral performance (e.g. Clark & Robin, 1995; Murray et al., 1997a; Murray et al., 1997b). That is, although participants with aphasia performed more poorly on the language tasks, as a group, they did not rate the tasks as more difficult (Murray et al., 1997a, 1997b) or as requiring more effort (Clark & Robin, 1995) than did neurologically intact control participants. Murray et al., (1997a) found this impaired relationship between performance and perceptions was only found for difficulty ratings and not for ratings of perceived accuracy, leading them to conclude that individuals with aphasia are impaired in their ability to perceive the demands of the tasks.

In the current study, we sought to extend these findings by including both pre- and post-task ratings of difficulty for verbal and spatial tasks. We hypothesized that if participants with aphasia are misperceiving the demands of the tasks, the relationship between performance and ratings of difficulty would be less for the pre-task ratings compared to the post-task ratings. This hypothesis was supported. The amount of variance in d prime scores accounted for by pre-task ratings was less for individuals with aphasia than for control participants. In contrast, the amount of variance in post task ratings accounted for by d prime scores was similar across groups. However, it is not clear the extent that pre-task difficulty ratings effect performance since the participants with aphasia performed like control participants on all but one of the spatial working memory tasks. Additional research is needed to investigate the reliability of perceived difficulty ratings as well as other constructs that can affect participants' ratings of difficulty.

We also hypothesized that the relationship between performance and ratings of difficulty would be stronger for spatial than verbal tasks in the aphasia group. This prediction was based on findings from previous studies demonstrating the mismatch between performance and ratings of effort or task difficulty in which only lexical stimuli had been used. The rationale was that if working memory deficits are specific to verbal stimuli, impaired perception of task demands may also be specific to verbal stimuli. The results do not support our hypothesis. For both the control and aphasia groups, the relationship among performance and perceived task difficulty was stronger for verbal tasks than the spatial tasks. This difference was less pronounced in the aphasia group than in the control group.

It is not clear why these results emerged. One potential explanation is that recalling the location of dots on the computer screen is a more novel task than recalling letters. Potentially the familiarity of the items could lead to differences in assessing the difficulty of the tasks. Additional research is necessary to investigate this hypothesis. Follow up questions about why they rated the tasks as they did, or comparison of ratings on other verbal and non-verbal tasks could provide further insight into this finding.

Specific Aims 3 and 4

Recently, researchers have reported that an inability to properly allocate cognitive resources to language tasks can account for language deficits in aphasia (e.g. Mcneil, Odell, & Tseng, 1991; Erickson, Goldinger, & LaPointe, 1996). Effort has been defined as the attentional resources or mental energy voluntarily allocated to a task (Kahneman, 1973). Cognitively challenging tasks provoke a physiological stress response which can be measured as a decrease in heart rate variability (HRV) from baseline to task. This decrease has been reported to reflect the mental workload demanded from the task (e.g. Veltman, & Gaillard, 1993) and has also been used as a measure of effort allocated to cognitively demanding tasks (e.g. Capa, Audiffren, & Ragot, 2008; Mulder et al., 1995).

The physiological stress response has been measured in participants with aphasia using salivary cortisol (Laures-Gore, 2007). However, the tasks used in Laures-Gore's study did not elicit a stress response from the participants with aphasia. The goal of Specific Aim 3 was to extend this research by using the mid frequency band of HRV as a measure of the effort allocated by individuals with aphasia to verbal and spatial tasks. Because it is a time sensitive measure and not dependent on the HPA axis that is reportedly impaired in individuals with aphasia, this measure had promise for measuring effort allocated to verbal and spatial tasks. We hypothesized that HRV would correlate with perceived level of difficulty for both verbal and spatial tasks for individuals with aphasia and neurologically intact participants. We expected that individuals with aphasia would allocate effort appropriately to the tasks based on their perceptions of task difficulty.

For the study participants with and without aphasia, HRV was not sensitive to changes in task difficulty. However, the .07-.14 Hz range was sensitive to differences between the baseline and task conditions indicating individuals with aphasia were allocating effort to the tasks. Both groups demonstrated an appropriate stress response from baseline to task as demonstrated by a significant drop in HRV during the tasks. However, a strong relationship between HRV and the other measures was not found.

The dynamic influences of the parasympathetic and sympathetic nervous systems result in heart rate variability (Allen, Chambers, & Towers, 2006). We know about these influences partly because of the use of medications that can block the effects of one system or the other on heart rate and heart rate variability. For example, pharmacologic blockade of vagal synapses at the sino-atrial node block the HRV associated with respiration – respiratory sinus arrhythmia (RSA) (McCabe, Youngue, Ackles, & Porges, 1985, as cited in Allen et al., 2006). In contrast, interruption of cardiac sympathetic inputs does not interfere with RSA, but affects the sympathetic modulation of heart rate. Because HRV is determined by the dynamic relationship among these disparate branches of the autonomic nervous system, it is important to consider factors not related to the experiment that can affect HRV. Medications with anticholinergic properties can affect RSA, and beta-blockers decrease the sympathetic input to the heart. Both types of medications are common in older adults and, particularly individuals who have had strokes. In this study, two participants with aphasia were excluded from the HRV analyses due to abnormal cardiac rhythms. Of the remaining participants, all of them were either taking anticholinergic medications that inhibit vagal input to the sino-atrial node, or were on beta-blockers. Further, approximately half of the control participants (i.e., 14 of 26) were taking medications with anticholinergic affects, or beta-blockers. It may be then; that the effects of the medications on HRV mask potential significant findings related to task difficulty.

Conclusions and Future Directions

Aphasiologists are interested in understanding the nature of working memory in aphasia because it may point to an underlying deficit that can be remediated to improve language skills and communication ability. A primary issue is related to the underlying cause of their performance deficits on cognitive and linguistic tasks. Working memory deficits have been reported to contribute to the language deficits seen in aphasia (e.g. Caspari, et al., 1998), but working memory tasks have been primarily isolated to the verbal domain. It has also been suggested that an inability to properly perceive task demands contributes to a misallocation of effort to verbal tasks (e.g. Murray, et al., 1997). Because tasks used to investigate these processes have primarily utilized verbal tasks, it has not been clear the extent to which a separate underlying deficit exists that is different from the language impairments germane to aphasia. The goals of this study were to extend previous research by 1) comparing performance of individuals with aphasia and control participants on verbal and spatial working memory tasks in a systematic way 2) evaluating task demand evaluation by having participants rate task difficulty both before and after completing verbal and spatial working memory tasks and 3) quantifying effort individuals with aphasia allocate through a physiological measure of workload. Results of the behavioral performance on the n-back tasks were interesting and informative. Group differences between individuals with aphasia and control participants were only found on the verbal tasks and with the most difficult spatial task - the 3-back. These results seem to indicate the central executive component of working memory is relatively intact in participants with aphasia. Future studies should systematically investigate the effect of strategy use to determine its impact on working memory performance.

Results further indicated that for participants with aphasia, ratings of task difficulty more closely reflect performance when probed after completion of the tasks, rather than prior to task completion. However, the extent to which pre-task ratings of difficulty reflect effort allocated to the tasks remains unclear. No relationship was found between HRV and perceptions of difficulty for either the aphasia or control group. However, baseline-task differences in HRV were found, with a decrease in HRV during the working memory tasks. This difference indicates participants with aphasia did demonstrate a physiological stress response to the verbal and spatial tasks. This baseline-task difference indicates that individuals with aphasia do allocate effort to both verbal and spatial working memory tasks. Additional research is needed to further quantify the amount of effort individuals with aphasia allocate to verbal and non-verbal tasks.

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Tables

Table 1.

Demographic information for the participant groups.

Subj.	Age	Level Educ.	Gender	Months s/p CVA	WAB-R AQ	WAB-R Profile
1	68	18	M	106	86.8	Conduction
2	41	15	F	82	56	Broca
3	54	13	M	62	57.1	Broca
4	69	16	F	336	62.4	Broca
5	64	12	F	8	67.1	Broca
6	61	16	M	18	34.1	Broca
7	53	14	M	20	78	Anomic
8	65	17	M	70	95.8	Anomic
9	31	15	M	68	92.76	Anomic
10	56	15	F	17	95.3	Anomic
11	65	18	M	64	59.8	Broca
Mean (SD)	57 (11.9)	15.5 (1.95)	M=7 F=4	77.36 (91.41)	71.37 (19.92)	Aphasia Group
Mean (SD)	58.9 (14.1)	15.42 (1.93)	M=10 F=11	N/A	N/A	Control Group

Table 2.

Mean (SD) scores on dependent variables by group (A = aphasia, C = control)

Task	Group	D’	Pre-Rating	Post-Rating	Change HRV
Verbal					
1-Back	A	3.27 (0.91)	37.00 (26.44)	34.27 (26.71)	0.67 (1.40)
	C	4.10 (0.36)	12.85 (11.35)	10.85 (13.34)	0.46 (0.63)
2-Back	A	1.26 (1.02)	68.63 (24.1)	79.90 (22.24)	0.42 (1.08)
	C	2.76 (1.06)	43.28 (24.51)	47.52 (22.18)	1.00 (0.60)
3-Back	A	0.78 (0.50)	70.54 (27.41)	92.00 (13.31)	0.11 (0.57)
	C	1.46 (0.72)	67.28 (19.08)	80.00 (16.62)	0.80 (0.93)
Spatial					
1-Back	A	3.35 (0.67)	26.09 (25.12)	10.54 (6.68)	0.92 (1.05)
	C	3.63 (.64)	23.85 (16.18)	12.57 (12.48)	0.43 (0.53)
2-Back	A	1.92 (1.08)	60.36 (28.15)	57.90 (25.59)	0.52 (0.84)
	C	2.46 (1.07)	50.14 (19.48)	44.14 (24.82)	0.92 (0.77)
3-Back	A	0.6 (0.54)	67.72 (30.13)	84.27 (18.48)	0.56 (0.71)
	C	1.23 (0.48)	69.57 (22.60)	77.00 (21.37)	0.77 (0.63)

Table 3.

Mixed ANOVA Results for N-Back Performance

Source	d*f*	*F*	*p*	ŋ^{2}
Between Subjects				
Group	1.00, 30.00	11.53	0.00	0.28
Within Subjects				
Type	1.00, 30.00	0.80	0.38	0.03
Type * Group	1.00, 30.00	9.78	0.00	0.25
Difficulty	1.68, 50.40	188.56	0.00	0.86
Difficulty * Group	1.68, 50.40	1.68	0.20	0.05
Type * Difficulty	2.00, 60.00	4.05	0.02	0.12
Type * Difficulty * Group	2.00, 60.00	4.47	0.02	0.13

Group = Control, Aphasia; Type= Verbal, Spatial; Difficulty = 1-back, 2-back, 3-back

Table 4.

Correlations among dependent variables for aphasia group, V= verbal, S=spatial

	D’		Post Rating		Pre Rating		Change HRV	
	1. V	2. S	3. V	4. S	5. V	6. S	7. V	8. S
2.	-.84**	-						
3.	-.73**	-.66**	-					
4.	-.54**	-.66**	.77**	-				
5.	-.44**	-.35*	.71**	.61**	-			
6.	-.28	-.39*	.65**	.75**	.63**	-		
7.	-.00	-.00	-.16	-.27	-.24	-.26	-	
8.	-.12	-.12	-.01	-.19	-.06	-.28	.54*	-

***Correlation is significant at p < .01(2-tailed), *p < .05(2-tailed)*

Table 5.

Correlations among dependent variables for control group, V= verbal, S=spatial

	D'		Post Rating		Pre Rating		Change HRV	
	1. V	2. S	3. V	4. S	5. V	6. S	7. V	8. S
2.	-.89**	-						
3.	-.74**	-.64**	-					
4.	-.72**	-.68**	.90**	-				
5.	-.73**	-.63**	.87**	.84**	-			
6.	-.67**	-.60**	.74**	.85**	.79**	-		
7.	- .18	-.13	.28*	.28*	.36	.39	-	
8.	-.18	-.16	.27*	.19	.27	.03	.31*	-

***Correlation is significant at p < .01(2-tailed), *p < .05(2-tailed)*

Table 6.

Aphasia Group Descriptive Statistics HRV Values by Task

Log RSA .07 - .14 Frequency Range				
	Min	Max	Mean	SD
1-back				
spatial	-.86	3.06	1.04	1.16
verbal	-.90	3.52	.69	1.32
2-back				
spatial	.08	1.62	.84	.58
verbal	-1.24	1.95	.64	1.27
3-back				
spatial	-.56	1.59	.56	.72
verbal	-.86	.81	.11	.57

Log RSA .12 - .40 Frequency Range				
	Min	Max	Mean	SD
1-back				
spatial	-1.01	.97	.16	.64
verbal	-.97	1.81	.03	.86
2-back				
spatial	-.70	1.03	.03	.59
verbal	-.45	1.16	.20	.48
3-back				
spatial	-.50	.91	.11	.47
verbal	-.50	.75	.24	.41

Table 7.

Control Group Descriptive Statistics HRV Values by Task

Log RSA .07 - .14 Frequency Range				
	Min	Max	Mean	SD
1-back				
spatial	-.71	1.20	.45	.55
verbal	-.83	2.24	1.04	.88
2-back				
spatial	.25	2.70	1.32	.58
verbal	.22	2.43	1.47	.59
3-back				
spatial	-.03	2.06	1.00	.61
verbal	-.23	1.67	.81	.63

Log RSA .12 - .40 Frequency Range				
	Min	Max	Mean	SD
1-back				
spatial	-2.44	3.43	.57	1.92
verbal	-1.67	2.75	.29	1.29
2-back				
spatial	-4.12	4.35	.73	2.17
verbal	-2.01	6.67	1.27	2.27
3-back				
spatial	-2.63	4.48	1.25	2.01
verbal	-3.74	4.24	1.30	2.14

FIGURES

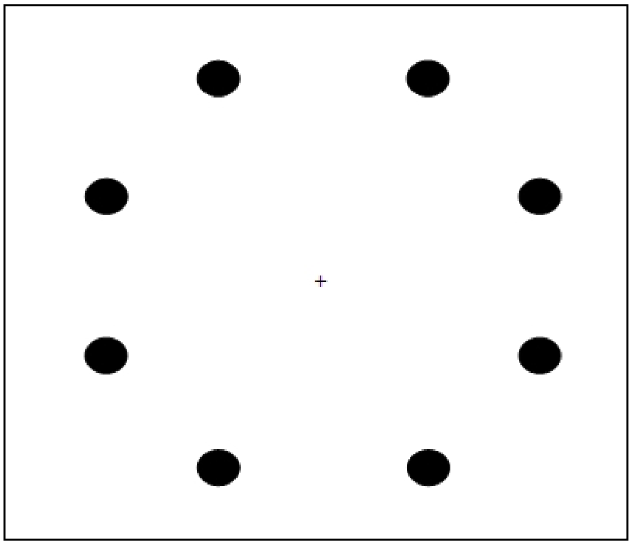


Figure 1. Eight possible locations of spatial stimuli.

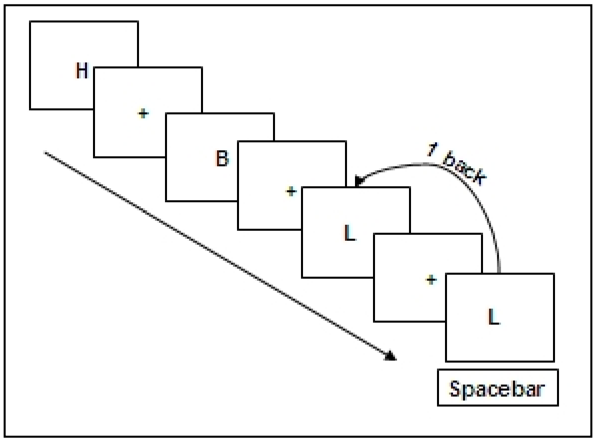


Figure 2. Illustration of 1-Back Verbal Task.

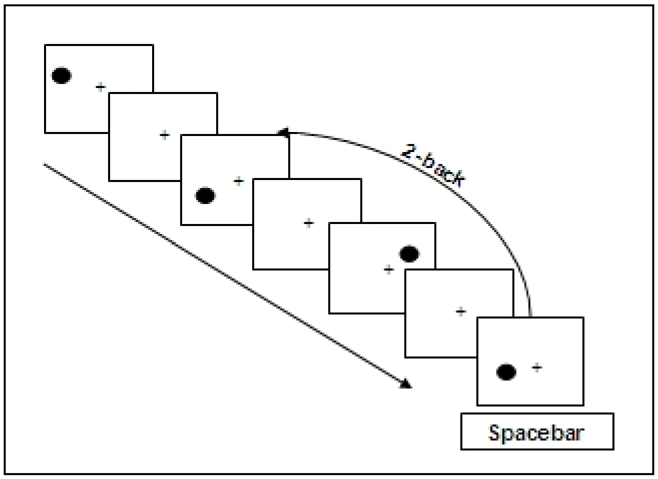


Figure 3. Illustration of 2-Back Spatial.

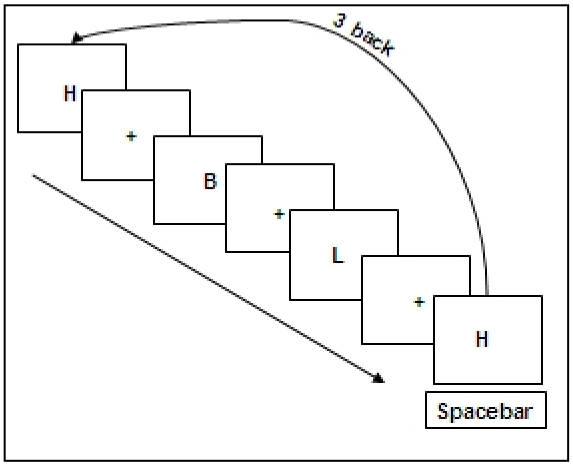
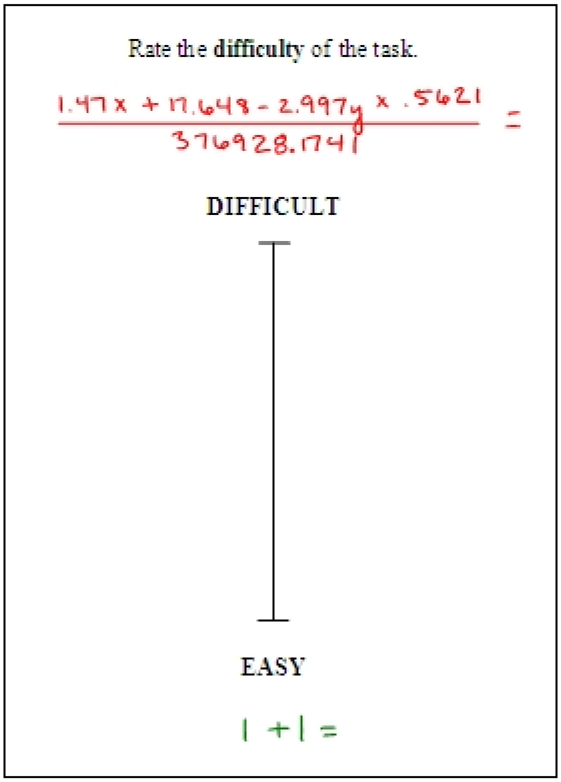


Figure 4. Illustration of 3-Back Verbal Task.



Rate the **difficulty** of the task.

$$\frac{1.47x + 17.648 - 2.997y \times .5621}{376928.1741} =$$

$$1 + 1 =$$

Figure 5. Difficulty Rating Scale.

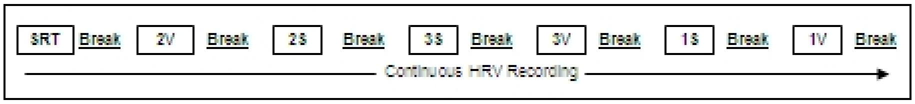


Figure 6. Sample Procedure Timeline. Breaks and tasks were approximately 5 minutes in duration. SRT: Serial Reaction Time task, 2V: 2back verbal, 2S: 2back spatial, 3S: 3back spatial, 3V: 3back verbal, 1S: 1back spatial, 1V: 1back verbal.

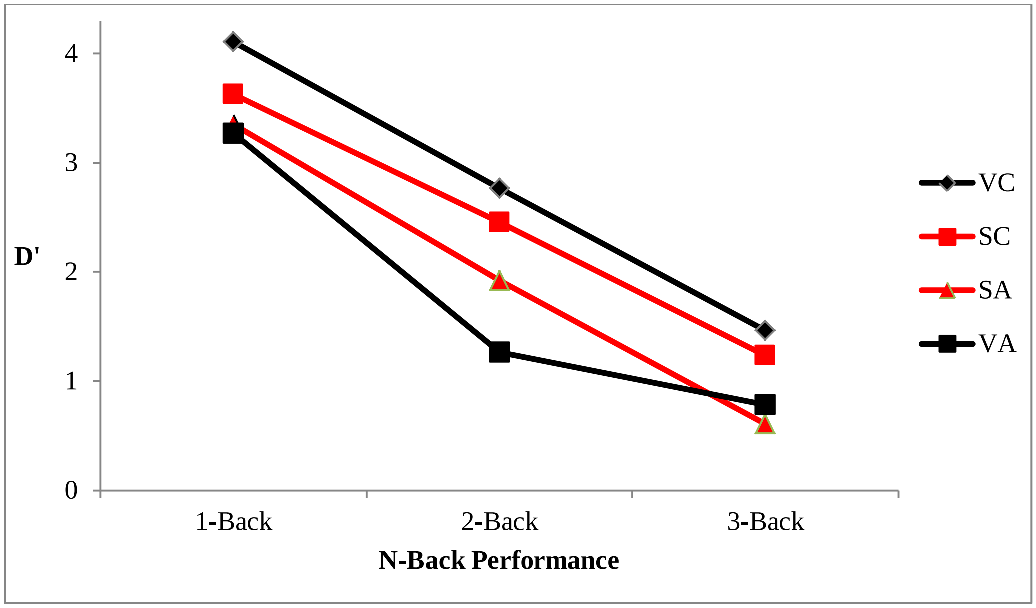
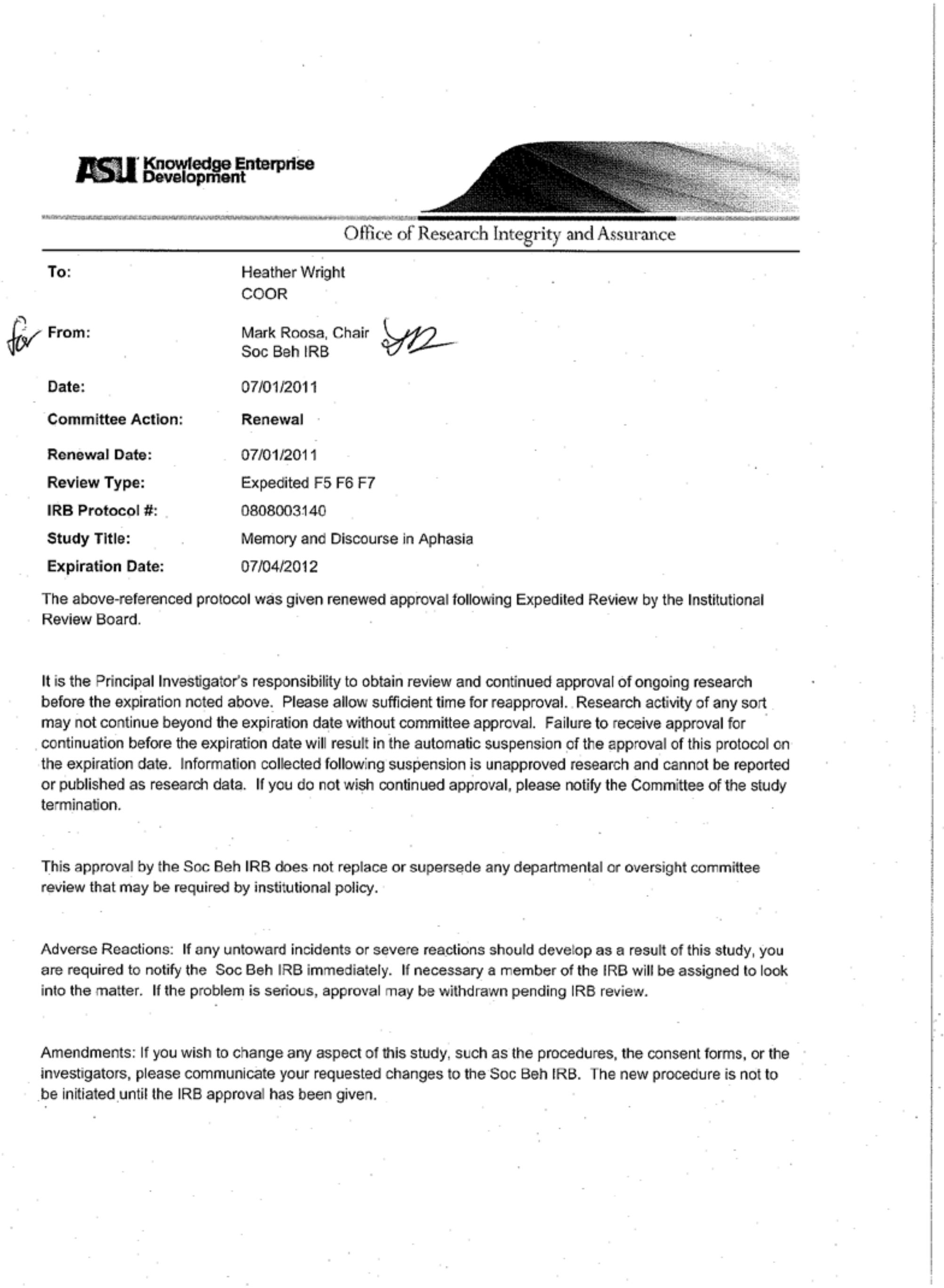


Figure 7. N-back performance across three levels of difficulty: 1-back, 2-back, 3-back. VC= Verbal Tasks Controls, SC = Spatial Tasks Controls, SA = Spatial Tasks Aphasia, VA = Verbal Tasks Aphasia.

APPENDIX A

IRB APPROVAL



ASU Knowledge Enterprise Development

Office of Research Integrity and Assurance

To:	Heather Wright COOR
for **From:**	Mark Roosa, Chair Soc Beh IRB
Date:	07/01/2011
Committee Action:	**Renewal**
Renewal Date:	07/01/2011
Review Type:	Expedited F5 F6 F7
IRB Protocol #:	0808003140
Study Title:	Memory and Discourse in Aphasia
Expiration Date:	07/04/2012

The above-referenced protocol was given renewed approval following Expedited Review by the Institutional Review Board.

It is the Principal Investigator's responsibility to obtain review and continued approval of ongoing research before the expiration noted above. Please allow sufficient time for reapproval. Research activity of any sort may not continue beyond the expiration date without committee approval. Failure to receive approval for continuation before the expiration date will result in the automatic suspension of the approval of this protocol on the expiration date. Information collected following suspension is unapproved research and cannot be reported or published as research data. If you do not wish continued approval, please notify the Committee of the study termination.

This approval by the Soc Beh IRB does not replace or supersede any departmental or oversight committee review that may be required by institutional policy.

Adverse Reactions: If any untoward incidents or severe reactions should develop as a result of this study, you are required to notify the Soc Beh IRB immediately. If necessary a member of the IRB will be assigned to look into the matter. If the problem is serious, approval may be withdrawn pending IRB review.

Amendments: If you wish to change any aspect of this study, such as the procedures, the consent forms, or the investigators, please communicate your requested changes to the Soc Beh IRB. The new procedure is not to be initiated until the IRB approval has been given.