Auditory Working Memory in Individuals with Traumatic Brain Injury

A THESIS SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF ARTS

Mary R. T. Kennedy

December 2009

Acknowledgements

Dedication

This thesis is dedicated to Mom, for her endless support and for always believing in me, and to Rick, for keeping me focused, but also encouraging me to relax.

Abstract

Thirteen adult survivors of traumatic brain injury (TBI) and 10 healthy controls completed three working memory (WM) tasks: an auditory verbal n-back task, a listening span task, and a digit span task. The n-back task required that participants manually respond to previously specified types of matches located within strings of letters. In the listening span task, participants listened to sets of sentences during which they made true/false judgments, while at the same time maintaining the final word from each sentence in their working memory. The digit span task involved the recall of increasingly longer strings of numbers in either forward or backward order.

Analysis of variance (ANOVA) was used when there were both between- and within-group comparisons, whereas simple group comparisons were made in the absence of within-group variables. In all tasks, participants demonstrated lower working memory scores as the tasks increased in length or difficulty. Participants with TBI made more errors on the listening span task, but did not perform worse on the n-back or digit span tasks compared to controls. Strong correlations were obtained between the n-back task scores and digit span backward scores within the TBI group whereas a moderate correlation was determined between the listening span task and digit span backward. Strong correlations were also found between predicted verbal IQ scores, verbal fluency scores, and errors on the listening span task, suggesting that pre-injury vocabulary and post-injury word retrieval are related to this WM task, which involves language. The clinical significance of these results is discussed.

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Introduction

Development of the Concept of Working Memory

The suggestion that memory consists of multiple components has been present for over a century. In 1890, William James referred to *primary memory* and *secondary memory*, distinguishing, respectively, between knowledge that a recalled object belongs to the immediate past, yet still exists within the present moment of consciousness, and recollection of a former state of mind after it has previously been dropped from consciousness. The possibility of a separate long-term memory (LTM) and short-term memory (STM) was first introduced by Hebb in 1949, who proposed two distinct neurophysiological systems located within the brain, one involving temporary circuits, the other representing a permanent physiological change. Though further development has continued on the neurophysiological aspects of these constructs, the majority of research has concentrated on LTM & STM within the realm of cognitive psychology.

By the late 1960s to early 1970s, the bimodal approach to memory was commonly supported among psychologists and researchers. However, early models focused on the structural nature of memory and considered the processing and encoding that have become an integral part of our current view of WM to be ancillary components (Atkinson & Shiffrin, 1968; Broadbent, 1958; Waugh & Norman, 1965). In the early 1970s, Craik and Lockhart (1972) began to develop their levels of processing approach to memory, which stressed the importance of function rather than structure, while Baddeley and Hitch (1974) were attempting to answer the question of whether STM acted as a WM. This gave rise to the suggestion of a new component to memory.

In 1974, Baddeley and Hitch proposed a working memory system that appeared to function as a control system for memory, with a limited capacity that could be divided between storage and processing demands. This model of memory suggested that working memory consists of a primary controlling mechanism, in addition to two subsidiary systems specialized for the processing and temporary maintenance of domain-specific (i.e., visual and auditory) material. Though this proposal did not come without its criticisms, it was one of the first models to suggest the significance of working memory.

Since the concept of WM began to develop, several distinct models have been proposed attempting to explain its nature, structure, and function. Miyake & Shah (1999) explored the ten most prominent models of WM in *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control*. The discussion and comparison of these ten models in detail would extend beyond the confines of this study. However, Shah & Miyake present six points of general theoretical consensus emerging among the models of working memory included. These points comprise the following:

1.   WM does not consist of a "box" or "place" in the brain that is structurally distinct from other memory or cognitive systems.

2.   WM is not simply for "memorizing," but is an active process directly linked to multiple cognitive processes.

3.   WM involves control and regulation of our cognitive procedures.

4.   Limits of WM capacity are attributed to multiple constraints, rather than a single, all-inclusive factor.

5.   WM does not consist of a unitary system.

6.   Long-term knowledge and skills play a role in WM performance.

Given these six themes, Shah & Miyake (1999) proposed the following, all-encompassing definition of WM:

> "WM is those mechanisms or processes that are involved in the control, regulation, and active maintenance of task-relevant information in the service of complex cognition, including novel as well as familiar, skilled tasks. It consists of a set of processes and mechanisms and is not a fixed "place" or "box" in the cognitive architecture. It is not a completely unitary system in the sense that it involves multiple representational codes and/or different subsystems. Its capacity limits reflect multiple factors and may even be an emergent property of the multiple processes and mechanisms involved. WM is closely linked to LTM, and its contents consist primarily of currently activated LTM representations, but can also extend to LTM memory representations that are closely linked to activated retrieval cues and, hence, can be quickly reactivated." (450)

Though the analysis of the aforementioned theories yielded a number of general agreements leading to this definition of WM, it serves only as a starting point for further exploration of WM and the development of more comprehensive, explicit models, as many disagreements and unresolved issues continue to exist between distinct models and theories.

Working Memory and Its Links to Cognitive and Linguistic Processes

Over the past few decades, a considerable body of research has accumulated examining the construct of WM and its links to various cognitive and lingusitic abilities. Of particular interest, has been the examination of the relationship between WM and language. Baddeley (2003) suggested that because WM is partially composed of a temporary storage system that supports the capacity for thinking, the construct has clear implications for language processing. A meta-analysis completed by Daneman and Merikle (1996) analyzed data from 6197 participants in 77 studies that investigated the association between working memory capacity and language comprehension ability. The results from this meta-analysis support the contention that WM plays a crucial part in language comprehension.

In a 1980 study of reading comprehension, Daneman and Carpenter determined that WM capacity is a critical source of individual differences in reading comprehension, supporting results from existing studies (Baddeley & Hitch, 1974; Waters et al., 1987). In a study of adolescents, Moran et al. (2006) showed support for the suggestion that figurative language and inference comprehension are influenced by WM. Similar results were found by Moran & Gillon in 2004.

Daneman and Green (1986) argued that an individual's ability to understand new words is based on the contextual cues available, and that the capacity to exploit those cues will depend on the availability of WM resources. Gathercole and Baddeley (1993) conducted a meta-analysis that suggested links between working memory and vocabulary acquisition. Other studies have linked WM to discourse memory (Light &

Anderson 1985), verbal reasoning (Baddley & Hitch 1974), and inference revision

(Daneman & Carpenter 1983, Tompkins et al. 1994).

Working Memory and Neurological Deficit

If the aforementioned language and cognitive processes are indeed regulated to

some extent by WM, then deficits within WM may seriously impair these abilities. A

considerable body of research exists examining WM capacity in individuals with

various deficits and disorders, in an attempt to determine what may account for the

various language and cognitive impairments typically associated with these conditions.

A number of studies have found that individuals with aphasia appear to exhibit

difficulty in processing distinct types of linguistic information (i.e., phonological,

semantic, and syntactic), which may contribute to their overall difficulties with

language (Angrilli et al., 2003; Martin et al., 2003; Vallar et al., 1992; Waters &

Caplan, 1996). Tompkins et al. (1994) investigated WM ability and auditory

comprehension, finding a correlation between word error in a WM task and severity of

auditory comprehension deficit. Caspari et al. (1998) showed similar findings for

deficits in reading comprehension. In addition to the neurological deficits previously

specified, a number of studies have also demonstrated deficits in WM among

individuals with dementia (Kashima, 2004; Kensinger et al., 2003) and multiple

sclerosis (Arnett et al., 1999; Thornton & Raz, 1997).

Some studies have found correlations between deficits in language production

and WM among individuals with schizophrenia (Harvey & Pedley 1989; Barch &

Berenbaum 1997; Cohen et al. 1999; Neuchterlein et al. 1986). Takahashi et al. (2005)

demonstrated that patients with schizophrenia showed a correlation between spatial WM and several aspects of social functioning, including speech disturbance, which indicates that social functioning at least partially requires spatial WM.

The study of WM in individuals with traumatic brain injury (TBI) has shown marked deficits as well. A study by McDowell et al. (1997) indicated that individuals with TBI exhibit specific cognitive deficits in WM. This study compared performance of 25 participants with TBI and 25 healthy control participants on various tasks designed to evaluate verbal and visuospatial WM. Evaluation of the two WM systems revealed a significant decrease of both immediate spatial and verbal WM after TBI.

Moran et al. (2006) examined WM and figurative langauge in 10 adolescents with TBI and 10 age-matched peers. Results indicated that the participants with TBI performed significantly worse on a measure of WM as compared to the control group. This supports similar results found in Moran and Gillon (2004), in which five of six adolescents with TBI scored below average on a measure of WM.

Azouvi et al. (2004) assessed dual-task performance in TBI patients, who showed a disproportionate increase in reaction time under the dual-task condition. These results were attributed to a reduction of available processing resources within working memory.

In addition to the adult population with TBI, more recent studies have begun to examine WM ability in children with TBI. In Roncadin et al. (2004), severity of head injury correlated strongly with verbal WM deficit in children, even several years beyond neurological insult. Levin et al. (2002) found similar results for visual WM in children with an average postinjury time of 5 years. Ewing-Cobbs et al. (2004)

demonstrated that TBI in young children was associated with difficulty on tasks with prominent demands on WM. In Mandalis et al. (2007), new learning in children with TBI was examined. The TBI group, shown to tax phonological loop (PL) and central executive (CE) resources to a greater extent than the control group when learning new verbally-based material, demonstrated lower PL and CE resources compared to their healthy peers, indicating that the TBI group's capacity for acquiring new verbal information may be at a significant deficit.

The information obtained in these studies shows the importance of the assessment of WM for individuals with TBI, as well as the implications that deficits in this construct may have regarding the effect on other areas of language and cognition. Deficits in WM may lead to or correlate with deficits in many other communicative abilities, making awareness of and insight into this ability crucial to any successful cognitive-linguistic evaluation and treatment program. Information obtained from the assessment of WM abilities may allow rehabilitation therapists to create a more appropriate and successful course of treatment for these individuals, with an emphasis on the importance of WM as a basic construct in other communicative tasks.

The Evaluation of Working Memory

Because WM abilities have been shown to correlate with such a vast array of cognitive abilities, the assessment of WM has become an essential part of comprehensive cognitive and language evaluations. This is especially true in the evaluation of individuals with TBI. Though these individuals may perform well on other standard cognitive and language tests, they often show distinct functional

difficulties in WM. Additionally, due to its imbedded nature, deficits in this construct

can also affect individual ability in other areas of language and cognition.

Many tasks have been developed to assess the construct of WM. This study

examines performance in three of these tasks: an auditory n-back task, a listening span

task, and a digit span task.

Auditory n-back task. One of the most recent experimental paradigms for

functional studies of WM is the *n*-back paradigm. The *n*-back model requires

individuals to monitor some feature of a series of stimuli and indicate when the feature

of the currently presented stimulus is identical to that of one presented *n* trials earlier.

Monitored features for the *n*-back task often consist of identity and/or location

matching in a visuospatial field. The stimuli are generally categorized as verbal (e.g.,

letters and words) or nonverbal (e.g., shapes and faces). Variations of the *n*-back task

have been used extensively in neuroimaging studies of WM.

For this study, rather than utilization of a visuospatial presentation, the *n*-back

task makes use of verbal stimuli in the form of letters, which are presented auditorily.

This task is modeled after a similar task used in McAllister et al. (1999), which in turn

was modeled after tasks used in a number of previous studies investigating WM in

healthy control participants.

Listening span task. In 1994, Tompkins et al. adapted a task from Daneman &

Carpenter (1980) designed to measure WM capacity in reading. Designed to tax the

processing and storage functions of WM, the original task was formatted somewhat

similarly to traditional digit span and word span tasks. In this task, participants read one

or more sentences grouped into increasingly larger sets and were asked to verbally

recall the final word of each sentence after reading the entire set. The task adapted by Tompkins et al. employs the use of a simultaneous truth value judgment in addition to word recall in order to further tax the processing and storage functions of WM.

This adapted task has been used in a number of studies, including those examining individuals with Dementia of the Alzheimer's type (Welland et al. 2002), aphasia (Friedmann & Gvion 2003), and brain damage associated with cerebrovascular accident (CVA) (Tompkins et al. 1994, Lehman & Tompkins 1998). Available literature documenting use of this task with individuals with TBI is limited. Moran et al (2006) utilized this same task among adolescents with TBI, finding significant differences in task performance when compared with a control group. To date, this is the only known study that has used this task to evaluate WM in adults with TBI, though modified versions of the task have been utilized in studies examining this population.

Digit span task. Numerous studies have evaluated WM post-TBI using a digit span task, which involves the storage and recall of a string of numbers. Most studies involving digit span frequently make use of two distinct tasks: digits forward and digits backward. The digits forward task involves the recall of a series of numbers in the order in which they are presented, while the digits backward task requires participants to recall a sequence of numbers in reverse order. These measures provide distinctive information regarding memory. Haut et al. (1990) proposed that digits forward reflects memory span, while digits backward requires manipulation of information in short-term memory (i.e., WM). Studies examining individuals who have sustained a TBI have reported that, while digit span forward may be intact, digit span backward is often impaired (Brooks 1976, Haut et al. 1990). This current study uses the Digit Span

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subtest from the Wechsler Memory Scale – 3rd Edition (WMS-III) (1997), which includes subsets of both digits forward and digits backward, and provides a standard score which represents overall performance on the task.

Comparison of performance in the three experimental tasks among a group of participants with TBI may help researchers to obtain more information about the WM abilities of this population, in addition to providing insight into the similarities and differences of the specific abilties assessed via the administration of each task. Knowledge of the relationship (or lack thereof) between performance on these tasks may furthermore offer insight into the necessity to include one or more of the tasks in an assessment of WM; if performance is found to strongly correlate between tasks, exclusion of one or more tasks may prove to be appropriate.

The Present Study

The primary purpose of this investigation is to examine how performance in an auditory-verbal *n*-back task and a listening span task compare within and between two groups: individuals who have sustained a TBI and a matched control group. A secondary purpose is to examine the association between performance in these tasks. Additionally, performance in these measures will be compared with that of the Digits Backward portion of the Digit Span subtest that can be found in the Wechsler Memory Scale-III (1997).

Research questions include the following:

1. Do adults with TBI perform more poorly than healthy controls on any or all WM tasks?

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2. Are the auditory-verbal *n*-back, listening span, and digit span tasks

correlated?

Two hypotheses were proposed: (a) Healthy controls are expected to yield

higher levels of performance in all WM measures when compared to those who have

sustained a TBI; and (b) WM tasks will be correlated with one another.

<center>**Methods**</center>

Participants

       Twenty-three adults participated in this study. Thirteen participants were recruited with a reported acquired TBI and ten were control participants without known neurological impairment. Participants with TBI were identified from lists of research participants who had taken part in previous studies; these individuals had given approval for contact for participation in future research studies. Additionally, experimental participants were recruited from local brain injury support groups. All participants with TBI met the following criteria: traumatic brain injury documented by medical records reports; age between 18 and 60 years; a minimum of 10 years of formal, full-time education; and English as a native/primary language. Exclusions were based on neurological illness or injury other than the primary documented TBI; known learning disabilities, visual/reading impairment, or giftedness; history of substance abuse; severe amnesia, aphasia, or apraxia of speech; less than six months post-injury; or current enrollment in rehabilitative therapy. When a potential participant indicated falling under one of these conditions, the person was excluded.

       Control participants were identified through responses to announcements posted at various community sites (e.g., dental clinics, fitness centers, coffee shops). Additionally, flyers were given to all participants with TBI at the end of their experimental session; participants were then encouraged to give them to interested friends without TBI as a method for recruitment of controls that would likely show similar age, IQ, and educational status as the participants with TBI themselves. Control participants met the same biographical inclusion criteria as the participants with TBI.

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Additionally, controls were questioned to rule out previous neurological illnesses or injury and chronic substance abuse.

Group demographic and clinical data are available in Table 1. Experimental and control groups were generally matched for age, years of formal education, gender ratio, and predicted premorbid verbal IQ[**]. No significant differences were found to exist between groups in age, education, or estimated verbal IQ.

Table 1. Demographic information for study participants.

Group	Gender (M/F)	Age (yrs.)	Education (yrs.)	Years Post-TBI	Estimated Verbal IQ**
TBI	6/7				
M		45.61	14.42	12.76	105.84
SD		11.87	2.13	12.44	7.44
Range		20-56	11-18	0.52-37.98	98-118
CONTROL	4/6				
M		45.7	14.8	-	108.1
SD		11.35	1.39	-	8.67
Range		21-52	12-16	-	94-116
Between-Group Comparison					
P		.97	.64	-	.51

Neurological information for participants with TBI is available in Table 2. TBI severity grouping included 9 severe, 2 moderate, and 1 mild TBI. Based upon medical records, 6 Glasgow Coma Scale (GCS) scores (mean = 6.17, SD = 2.04) and 8 losses of

Table 2. Neurological information for ABI participant injuries.

[**] Determined based upon scores obtained by administration of the National Adult Reading Test-2nd Edition (NART-2) (1991).

TBI Participant	Severity of injury	Neuropathological findings	LOC	GCS*	Years post-injury
1	Severe	L temporal subarachnoid hemorrhage, shear injury anterior peduncular fossa, small punctuate hyperintense focus L cerebral peduncle	@ accident site	7	5.56
2	Severe	Diffuse edema, increased ICP, possible subarachnoid hemorrhage, small punctuate hemorrhages L. posterior thalamus	4 days	6	19.01
3	-	No record or mention of dx TBI; R frontal tumor identified Aug 2001	-	-	6.44
4	Moderate	Small R temporal subdural hematoma	@ accident site	9	6.57
5	Severe	Reports refer to dx TBI Jul 1971; No records from injury available	**	**	35.11
6	Severe	Severe edema, diffuse subarachnoid hemorrhage, possible brainstem injury	2 days spontaneous, 4 induced	3t	1.56
7	Severe	Reports refer to TBI from Mar 1970 & document neurological deficits as sequelae of TBI; No imaging reports available	**	**	37.98
8	Moderate	Reports refer to TBI from Sept 1992; CT scan Mar 2006 documents old lacunar infarct R medial temporal lobe; No records from injury available	**	**	16.19
9	Mild	Reports from Neuropsych, SLP, & OT refer to TBI Nov 1990 & document neurological deficits as sequelae of TBI; No imaging reports available	**	**	16.23
10	Severe	Brain stem shear	17 days	**	6.04
11	Severe	R intraventricular hemorrhage with bilateral parenchymal hemorrhages	@ accident site	7	0.52
12	Severe	Frontal & temporal hemorrhages, small posterior subarachnoid hemorrhage	@ accident site	5	14.12
13	Severe	Diffuse L contusions, small R parietal-occipital subdural hematoma	2 days	**	0.63

* Teasdale, G. & Jennett, B. (1974). Assessment of coma and impaired consciousness. A practical scale. *Lancet*, 2:81-84.
** Information unavailable.

consciousness (ranging from at accident site only to 17 days) were reported. Loss of

consciousness (LOC) and GCS scores were unavailable for 3 participants, though

medical documentation of past brain injury was obtained. Mean years post-injury for

the TBI group was 12.77 (SD = 12.24).

Upon examination of the medical records, it was determined that one participant

in the experimental group had not in fact sustained a TBI; rather, this person's medical

records indicated identification and removal of a right frontal tumor around the time of

the reported TBI. Because no differences were found between this individual's

standardized and experimental task performance as compared to individuals from the

same group, the data was not deleted from the experimental set. Additionally, as the

TBI group includes an individual with a differing form of acquired brain injury (ABI),

the TBI group will be referred to as the ABI group from this point forward.

Procedures

All procedures in this study were approved by the University of Minnesota

Institutional Review Board (IRB) and all participants provided informed consent prior

to participation.

A series of standardized tests was administered prior to the experimental

session; these tests are detailed in Appendix A. Standardized tests were presented in a

similar order across participants to allow for planning of required delay times and in

order to minimize the length of the testing session. Participants were permitted to take

breaks as needed between tests or subtests provided that a break would not interfere

with the standardized test administration protocol, though no participant did request a

break at such a time. The digit span subtest from the Wechsler Memory Scale-III

(1997) was administered as part of the standardized testing protocol.

Means, standard deviations, and between-group significance for ABI and

control group standardized test performance is available in Table 3. Independent

sample t-tests were used with p ≥ .05. Analysis of this data yielded significant between-

group results in several measures. When compared to the control group, the ABI group

was found to display multiple significantly lower scores from the Verbal Fluency (VF)

subtest of the Delis-Kaplan Executive Function System (2001) (D-KEFS): category

fluency total correct (p = .03), category switching total correct responses (p = .00),

category switching total switching accuracy (p = .01), interval 2 total correct (p = .01),

and interval 4 total correct (p = .03). Significant differences were also seen in number

sequencing (p = .05) and motor speed (p = .04) tasks from the Trails subtest of this

same assessment battery.

Table 3. Means, *SD*s, and correlations of performance on neurocognitive standardized tests for adults with TBI (*n* = 13) and healthy controls (*n* = 10).

	TBI [mean(SD)]	Control [mean(SD)]	*p*
Aphasia quotient (WAB) (1982)	98.68(1.37)	99.40(1.36)	.22
Executive functions: alternating trails (D-KEFS)			
Number-letter switching	9.92(3.59)	11.70(1.95)	.17
Number-letter switching *vs.* combined number and letter sequencing	10.46(2.82)	9.50(2.76)	.42
Number-letter switching *vs.* motor speed	10.23(2.56)	10.40(2.27)	.87
Executive functions: verbal fluency (D-KEFS)			
Letter fluency total correct	9.00(2.61)	11.60(4.03)	.08
Category fluency total correct	10.69(3.17)	13.20(1.62)	.03*

	TBI [mean(SD)]	Control [mean(SD)]	p
Executive functions: verbal fluency (D-KEFS) (cont.)			
Category switching total correct	9.92(3.33)	14.70(2.98)	.00**
Category switching total switching accuracy	10.92(4.19)	15.30(2.21)	.01**
Interval 1 (0-15 sec.)	10.62(2.93)	12.40(2.95)	.16
Interval 2 (16-30 sec.)	9.23(2.86)	12.60(2.95)	.01**
Interval 3 (31-45 sec.)	8.85(3.31)	11.80(4.24)	.07
Interval 4 (46-60 sec.)	9.69(2.69)	12.50(3.24)	.03*
Immediate free recall (CVLT)	49.00(14.73)	55.60(10.36)	.24
Long-delay recall (CVLT)			
Free	-.27(.78)	.30(.98)	.14
Cued	-.31(.90)	.20(.79)	.17
Short-delay recall (CVLT)			
Free	-.19(1.03)	.25(.89)	.29
Cued	-.31(.99)	.10(1.10)	.36
Speed: simple trails (D-KEFS)			
Number sequencing	8.54(3.80)	11.20(1.48)	.05*
Letter sequencing	9.62(4.01)	11.90(1.60)	.11
Motor speed	9.69(2.29)	11.40(1.08)	.04*
Verbal IQ, predicted (NART-II) (1991)	105.85(7.45)	108.10(8.67)	.51

* = p ≤ .05 (2-tailed)

**= p ≤ 0.01 (2-tailed)

The primary experimental tasks consisted of two tasks designed to draw on auditory-verbal working memory: the listening span task introduced by Tompkins et al. (1994), and an auditory *n*-back task modeled after that found in McAllister et al. (1999). All experimental tasks were presented via computer, with the order of the tasks randomized across participants.

Listening Span Task. The first working memory task required participants to listen to a series of sentences, judging each as true or false while simultaneously retaining the final word of each sentence for spoken recall at the end of the series. Stimuli consisted of 42 simple, active declarative sentences based upon common knowledge (e.g., "The sky is blue.") Each sentence ended in a different, common lexical item consisting of a 1- to 2-syllable noun, verb, or adjective. These sentences were grouped into sets of increasing length, with three sets at each of four levels of difficulty. Level 2 sets were each comprised of two sentences, Level 3 sets contained three sentences each, and so on through Level 5. The number of words per sentence was approximately equivalent within and across sets (i.e., 3-5 words per sentence).

The number of true and false statements was balanced within each level. Sentences were constructed so the truth value was not obvious until the final word, maximizing the need for simultaneous information storage and stimulus processing. Additional details regarding construction of stimuli and administration protocol can be found in Tompkins et al. (1994).

All stimuli were pre-recorded and presented auditorily via speakers attached to the computer. Participants were asked to listen to each recorded sentence stimulus, immediately after which they were to verbally judge whether the sentence was true or false. Participants' responses were entered manually by the researcher into the computer program. This procedure continued until the end of a set had been reached. At this time, participants were directed to immediately verbally recall the final word of each sentence in any order. The words recalled were manually recorded by the researcher. The number of words to recall varied with each level; participants had two

words to recall for each set at Level 2, three words per set at Level 3, and so on. Data was gathered on both true/false (T/F) errors and word recall errors, though word recall errors provided the primary estimate of auditory WM.

This task was created and presented using ePrime. Researchers explained the task according to the instructions detailed in the original protocol created by Tompkins and her colleagues (1994). This procedure was completed independent of the computer, allowing for questions to be answered before the task began. Using two sample sentences, researchers led participants separately through each portion of the task (i.e., T/F judgment and final word recall) before instructing participants to complete both task demands using the same sample sentences. When understanding of the task demands was verified by the participants, researchers then led them through two practice sets of two sentences each before beginning the task to ensure complete understanding. These practice sets employed the use of prerecorded material presented via the computer program in order for the participants to become familiar with the task format.

Once the practice sets had been completed, particpants began the experimental task. Each set was preceded by a 5000 ms wait, followed by the set number and the alerting word, "Ready?" (e.g., "Set 1. Ready?"). A 1000 ms wait was inserted between the alerter and the first stimulus sentence of each set. Each sentence within a set was followed by a 1000 ms wait after participants gave the T/F response. Sets were presented by increasing set length (i.e., 2, 2, 2, 3, 3, 3, 4…), and researchers alerted participants before the next set level began. All instructions were presented auditorily by the researcher.

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Auditory N-back Task. The second working memory task required participants to listen to a string of consonant letters and decide whether the most current letter matched a single target letter appearing *n*-spaces back. This number *n* was specified prior to the onset of each section of the task. This task was modeled after the auditory *n*-back task detailed in McAllister et al. (1999).

In this task, three conditions were present: 0-back, 1-back, and 2-back. The 0-back control condition consisted of a minimal WM load in which individuals were asked to decide whether the current letter heard matched a single, previously-specified target letter specifed. In the 1-back condition, participants decided whether the current letter matched that shown immediately prior, or one place back. Similarly, the 2-back condition asked individuals to determine whether the current letter matched the letter presented two back in the sequence. The 0-back control condition was presented six times and alternated with the two experimental conditions to allow for a minimal WM load between 1- and 2-back sets. The experimental conditions appeared three times each. The order of presentation consisted of a 0-1-0-2 repeating pattern. Within each set, there were a total of 15 items comprising 5 matches and 10 foils. The placement of matches was counter-balanced within and across conditions.

Stimuli consisted of 12 sets of 15 randomly-selected consonant letters (omitting L, W, and Y). These stimuli were digitally recorded in a sound-treated booth using a female mid-register voice. Each letter was recorded three times to allow for later analyzing and selection of the best sample of that letter by the researchers. Using Goldwave software, this best sample was dissected from the original sound file into an individual file for later ease of compilation. Each individual sound file ranged in length

from 0.42-0.63 seconds. Goldwave was also used to compile individual sound files into 12 runs of 15 letters each, with a 3000 ms wait time after each letter to allow for participant response. This 3000 ms wait was consistent with the task detailed in McAllister et al. (1999). The order of letters in these runs was randomly selected and balanced across letter (i.e., number of total uses of each letter & placement of each letter within runs) and match (i.e., placement of matches in runs & letters used as matches). Two versions of this task were created to increase reliability.

The *n*-back task was created using ePrime software. The prototype program was composed of 1 session procedure containing one list of 12 samples, or runs. The program began with a written instruction and corresponding 5000 ms wait time. After the instruction was read, an inline code began each run of letters, with the 3000 ms wait time programmed between letters. Stimulus letters were presented auditorily only via speakers. A response from a participant, which consisted of pressing the space bar on the keyboard, was recorded as a response time within the specified run. The researcher was later able to compare response times with the positions of correct matches within each run to determine whether a hit, false positive, or omission had occured. After a run had been completed, a 2000 ms wait was programmed between its conclusion and the following instruction. However, as this program was initially run, it became clear that running procedures in a repeated list-type program would make a change in instruction with each sequence difficult. As a result, the original sequence of the procedure was maintained, with 12 individual procedures being created. This would allow each run to have its corresponding instruction without complicating the program procedure.

As stated, the second version of this program was composed of 1 large session procedure containing 12 individual procedures. Each individual procedure contained 1 list using 1 sample, or run. Each procedure began with a wait (first sample: infinite wait; remaining samples: 5000 ms), 5000 ms of instruction time, and a blank screen which continued throughout the run. An inline code began each sample. Again, a 3000 ms wait existed between letters to allow for recording of responses (depressing the space bar). Responses were recorded in the same manner as the prototype program. A wait time of 2000 ms was inserted between each run and the next sequence.

Using this original program, a series of trials was run with a number of sample participants both familiar and unfamiliar with the subject matter and/or field of study. During these trials, suggestions were made by these sample participants regarding ways to improve upon the original program. Suggestions included the following:

– In order to maintain the strictly auditory nature of the task, a blinder was created for the computer keyboard in which only the space bar was visible and accessible. This prevented participants from using the letters on the keyboard as visual aids for the task. It also reduced the potential for confusion regarding which key was to be used as the response key.

– Infinite time was suggested for each instruction in order to avoid hurrying, as well as to ensure for accurate comprehension of task expectations. This infinite time was factored in to make certain that errors completed during the experimental task were not due to lack of understanding of participant expectations. When a participant felt he or she had understood the

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instruction accurately, he/she was prompted to press the space bar to begin the subsequent run.

– Examples were added to each of the instructions presented for the 1-back and 2-back conditions, which also contributed to accurate understanding of the instructions.

– At the end of each run, an infinite wait time was added to permit participants to take a short break, if needed, during the experimental task. Participants were directed to press the space bar in order to prompt the next instruction.

At this point in the development of the *n*-back task, a separate practice program was created which would allow participants to become familiar with task expectations before beginning the true task. This program was structured similarly to the experimental program, though runs were shortened from 15 letters to 10 letters in order to allow for ease of learning each instruction. Once participants had read the general instructions provided at the beginning of the practice program, which included details regarding the sequences, desired response, and task procedures, participants had the opportunity to run through one trial of each condition (i.e., 0-back, 1-back, and 2-back). Participants completed this program in correspondence with the researcher. An infinite amount of time was programmed between trial conditions to allow for questions, and the researcher ensured participant comprehension of each condition by tracking participants' responses throughout the trial runs and interjecting when necessary.

Identification accuracy was recorded after each participant's responses from the experimental task were analyzed, and an adjusted accuracy score was calculated in order to account for false positive (FP) responding. The following formula was used for

this score: (Correct responses – [0.5 x FP]) x 100. Using this formula, the adjusted accuracy score would be 0 if an individual responded positively to every item.

Data Analysis

Analysis for this investigation involved group comparison of scores obtained for the listening span task, *n*-back task, and digit span. Within each task, level of difficulty was compared with group performance at each level (i.e., listening span set length, *n*-back level). The dependent variables considered in the group analyses consisted of listening span recall errors, listening span T/F errors, *n*-back adjusted accuracy, *n*-back omissions, and *n*-back false positives. Within-subject independent variables were *n*-back task level and listening span task set length. Additionally, standardized test scores, including digit span scores, were analyzed to determine whether correlations existed between these scores and the experimental tasks.

Results

Outcome Measures and Data Analysis

Outcome measures for the listening span task consisted of recall errors and true/false (T/F) errors. For the *n*-back task, outcome measures included adjusted accuracy, omissions, and false positives. Analysis of variance (ANOVA) was used when there were both between- and within-group comparisons, whereas simple group comparisons were made in the absence of within-group variables. Means and standard deviations from the three WM tasks are presented in Table 4.

Listening Span T/F Errors and Recall Errors

A simple between-groups comparison revealed no significant differences for T/F errors [$F(1,21) = .69$, $p = .42$, $d = .37$]. As T/F errors were rare in both groups, these scores could not be analyzed.

In a group (ABI, control) x set length (2, 3, 4, and 5 sentences) ANOVA, participants with ABI made significantly more recall errors than control participants indicated by a main effect for group [$F(1,21) = 6.52$, $p = .02$, $np^2 = .24$]. The mean total number of recall errors by participants with ABI was 12.61 (SD = 5.34), whereas the mean total recall errors by control participants was 7.40 (SD = 4.12). Both groups made more recall errors as length increased, indicated by a main effect for length [$F(1,21) = 106.31$, $p = .00$, $np^2 = .84$]. Thus, participants as a whole performed progressively worse on the listening span task as set length increased. This was expected, as increasing set length should place increasingly larger demands on working

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memory, thus making error responses more likely to occur. The group x length interaction was not found to be significant [F $(1,21) = 1.56$, p $= .23$, $np^2 = .07$].

N-Back Adjusted Accuracy, Omissions, and False Positives

A simple between-groups comparison showed no significant differences for adjusted accuracy (AA) scores [F $(1,21) = 1.06$, p $= .31$, d $= -.45$] obtained from the *n*-back task. Further analysis was completed on false positive error scores and omission error scores.

In a group (ABI, control) x level (0-, 1-, and 2-back) ANOVA, participants with ABI and control participants did not differ significantly in number of omissions or false positives, indicated by no main effects for group [$F_{Omission}$ $(1,21) = 1.11$, p $= .30$, $np^2 = .05$; $F_{FalsePositive}$ $(1,21) = .64$, p $= .43$, $np^2 = .03$]. The average number of omission and false positive errors by participants with ABI was 2.38, SD $= 2.72$, and .92, SD $= 1.04$, respectively, whereas the average number of omission and false positive errors by control participants was 1.4, SD $= 1.26$, and .60, SD $= .84$, respectively. These results are inconsistent with expected poorer task performance by the ABI group as compared with the control group. Both groups made more omission and false positive errors as level increased, indicated by a main effect for level [$F_{Omission}$ $(1,21) = 20.52$, p $= .00$, $np^2 = .49$; $F_{FalsePositive}$ $(1,21) = 5.84$, p $= .03$, $np^2 = .22$]. The group x level interaction was not significant for either score [$F_{Omission}$ $(1,21) = .24$, p $= .63$, $np^2 = .01$; $F_{FalsePositive}$ $(1,21) = .27$, p $= .77$, $np^2 = .01$].

Table 4. Means and *SD*s for listening span, *n*-back, and digit span tasks.

	TBI Mean(SD)	Control Mean(SD)
Listening Span		
Recall Errors		
2 sentences	.31(.48)	.00(.00)
3 sentences	1.69(1.55)	.40(.70)
4 sentences	4.15(1.95)	2.10(1.60)
5 sentences	6.46(2.40)	4.90(2.73)
Total	12.61(5.34)	7.40(4.12)
T/F Errors		
2 sentences	.00(.00)	.00(.00)
3 sentences	.17(.39)	.00(.00)
4 sentences	.25(.45)	.10(.32)
5 sentences	.27(.47)	.20(.42)
Total	.62(1.12)	.30(.48)
N-Back		
Omissions		
0-back	.31(.63)	.00(.00)
1-back	.15(.55)	.10(.32)
2-back	1.92(1.98)	1.30(1.16)
Total	2.38(2.72)	1.40(1.26)
False Positives		
0-back	.23(.44)	.00(.00)
1-back	.15(.38)	.10(.31)
2-back	.54(.78)	.50(.71)
Total	.92(1.04)	.60(.84)
Adjusted Accuracy	57.31(3.04)	58.40(1.58)
Digit Span		
Total (standard score)	9.92(2.99)	9.70(1.95)
Digits forward	10.31(2.39)	10.10(2.38)
Digits backward	6.15(2.27)	6.30(1.77)

Digit Span Total, Digits Forward, and Digits Backward

A simple between-groups comparison showed no significant differences for digit span total [F (1,21) = .04, p = .84, d = .09]. The average digit span total standard score was 9.92 (SD = 2.99) for ABI participants and 9.70 (SD = 1.95) for controls. Average ABI & control scores for digits backward, which is proposed to reflect WM, were 6.15 (SD = 2.27) and 6.30 (SD = 1.77), respectively. No significant difference was found between ABI and control participants in digit forward or digit backward scores, indicated by no main effect for group [F (1,21) = .00, p = .97, np^2 = .00]. Both groups made more errors in the digits backward portion of the task than digits forward [F (1,21) = 62.95, p = .00, np^2 = .75]. Additionally, the group x level (digits forward and digits backward) interaction was not significant [F (1,21) = .13, p = .73, np^2 = .01].

Relationships Between Working Memory Measures

Pearson correlations were calculated between the following scores: *n*-back adjusted accuracy (AA), omissions (O), and false positives (FP); listening span recall errors (RE); and Wechsler Memory Scale-III (1997) Digit Span (DS) Forward and Digit Span Backward.

Correlational data for ABI and control groups may be found in Tables 5 and 6, respectively. Both ABI & control groups were found to have strong (0.70-0.90) to very strong (0.90-1.00) correlations between *n*-back AA and O (r_{ABI} = -0.99; $r_{Control}$ = -0.98), as well as *n*-back AA and FP (r_{ABI} = -0.73; $r_{Control}$ = -0.87). This would be expected, as AA scores are determined based on a formula using O and FP scores. The control group

Table 5. ABI parametric correlational data.

		N-Back AA	N-Back O	N-Back FP	List. Span RE	DS Forward	DS Backward	PVIQ
N-Back AA	r	1	-.99**	-.73**	-.51	.71**	.72**	.28
	Sig. (2-tailed)	-	0	.00	.08	.01	.01	.36
N-Back O	r	-	1	.66*	.52	-.68**	-.73**	-.31
	Sig. (2-tailed)	-	-	.01	.07	.01	.01	.29
N-Back FP	r	-	-	1	.19	-.49	-.38	.09
	Sig. (2-tailed)	-	-	-	.54	.09	.20	.78
List. Span RE	r	-	-	-	1	-.49	-.67*	-.71**
	Sig. (2-tailed)	-	-	-	-	.09	.01	.01
DS Forward	r	-	-	-	-	1	.77**	.46
	Sig. (2-tailed)	-	-	-	-	-	.00	.11
DS Backward	r	-	-	-	-	-	1	.52
	Sig. (2-tailed)	-	-	-	-	-	-	.07
PVIQ	r	-	-	-	-	-	-	1
	Sig. (2-tailed)	-	-	-	-	-	-	-

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2.tailed).

Table 7. Control parametric correlational data.

		N-Back AA	N-Back O	N-Back FP	List. Span RE	DS Forward	DS Backward	PVIQ
N-Back AA	r	1	-0.980**	-0.869**	0.007	0.462	0.311	0.102
	Sig. (2-tailed)	-	0	0.001	0.985	0.179	0.382	0.778
N-Back O	r	-	1	0.792**	-0.034	-0.495	-0.308	-0.075
	Sig. (2-tailed)	-	-	0.006	0.925	0.146	0.386	0.837
N-Back FP	r	-	-	1	-0.045	-0.31	-0.432	-0.404
	Sig. (2-tailed)	-	-	-	0.902	0.383	0.212	0.247
List. Span RE	r	-	-	-	1	-0.209	-0.141	0.089
	Sig. (2-tailed)	-	-	-	-	0.562	0.698	0.807
DS Forward	r	-	-	-	-	1	-0.14	0.032
	Sig. (2-tailed)	-	-	-	-	-	0.699	0.931
DS Backward	r	-	-	-	-	-	1	0.114
	Sig. (2-tailed)	-	-	-	-	-	-	0.754
PVIQ	r	-	-	-	-	-	-	1
	Sig. (2-tailed)	-	-	-	-	-	-	-

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2.tailed).

was found to have no further significant correlations between scores in any of the tasks included in correlational analysis.

Within the ABI group, strong correlations were obtained between *n*-back AA and digit span forward (r = 0.708), *n*-back AA and digit span backward (r = 0.718), *n*-back O & digit span backward (r = -0.725), listening span recall errors & NART-II (1991) predicted verbal IQ (r = -0.707), and digit span forward and backward (r = 0.774). Moderate correlations (0.5-0.7) were found to exist between *n*-back O and digit span forward (r = -0.684) and listening span recall errors and digit span backward (r = -0.668).

Because of the verbal nature of the listening span tasks, relationships between the error measure, Verbal fluency (VF) measures of the D-KEFS (2001), and Predicted Verbal IQ (PVIQ) of the NART-II (1991) were of interest as well. Pearson correlations are available in Table 7. Significant correlations were found between PVIQ and VF category fluency – total correct (r = .62), as well as predicted verbal IQ and listening span recall errors (r = -.71); the correlation between listening span recall errors and category fluency – total correct did not reach statistical significance (r = -.52). A significant correlation was also seen between VF category switching – correct responses and VF category switching – switching accuracy (r = .91), though this would be expected, as both scores are determined based upon performance within the same task (VF category switching).

Table 7. Correlational data between verbal fluency, listening span, and predicted verbal IQ.

	TC	CR	SA	PVIQ	RE
Verbal fluency (D-KEFS) (2001)					
Category fluency: total correct (TC)	1	.28	.21	.62*	-.52
	-	.35	.50	.02	.07
Category switching: correct responses (CR)	-	1	.91**	.12	-.27
	-	-	.00	.70	.37
Category switching: switching accuracy (SA)	-	-	1	.04	-.15
	-	-	-	.91	.63
NART-II (1991) predicted verbal IQ (PVIQ)	-	-	-	1	-.71**
	-	-	-	-	.01
Listening span total recall errors (RE)	-	-	-	-	1
	-	-	-	-	-

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Discussion

The intent of this study was to compare performance in an auditory-verbal *n*-back task and a listening span task in two groups, adults with and without brain injury. First, investigators were interested in determining how performance in the *n*-back task compared with performance in the listening span task within and between groups of adults with and without brain injury. A secondary intent was to examine the association between performance in these tasks. Additionally, performance in these measures was compared with that of the Digit Span subtest in the Wechsler Memory Scale-III (1997). The research questions established in the introduction are revisited here, along with probable explanations, clinical implications, limitations of this study, and directions for future research.

Do adults with ABI perform more poorly than healthy adults on any or all WM tasks?

In this study, those without brain injury made less recall errors than the ABI group in the listening span task; this finding supports the researchers' hypothesis that adults without brain injury would yield higher levels of performance in measures of WM when compared to those with ABI. Decreased performance on this task was also seen in adolescents with TBI, as reported by Moran et al (2006). In this study, participants ages 12-21 who had sustained a TBI prior to age 10 performed significantly worse on the listening span task than age-matched controls. To the researchers' knowledge, this is the only other known study to have used the Tompkins et al. (1994) listening span task with

individuals with TBI in comparison to a control group. A modified version of the

listening span task, the Competing Language Processing Test (Gaulin & Campbell, 1994)

was employed with a group of individuals with TBI in Turkstra (2008). In a study of 19

adults with moderate to severe TBI and 19 matched controls, the TBI group performed

significantly worse on the word recall portion of the task than did the control group.

Friedmann & Gvion (2003) used a similar task among individuals with aphasia as a result

of TBI; however, as one of the exclusion criteria in the present study included a score on

the Western Aphasia Battery (1982) indicating no aphasia, results for these two studies

cannot be appropriately compared.

On the *n*-back task adults with brain injury performed similiarly to those without

brain injury. Similar to the findings by McAllister et al. (2001), in which 17 participants

with mild TBI and 12 without brain injury performed similarly on a similar task, the

pattern of performance was similiar across the two groups. This may partially be

attributed to lower level of impairment notable in the lack of group differences in some of

the standardized test results in the current study, and the mild impairment level in the

McAllister et al. study. At the generally high level of functioning seen among the ABI

participants in this study, the *n*-back task does not appear to tax the cognitive-linguistic

abilities of these participants to the extent that a significant difference is seen when

compared with healthy adults without brain injury. It is possible that this task may only

be sensitive to the more severe working memory impairments among individuals who

have not made as good recovery as the individuals in this current study. No studies have

been found to date that have used this task with more severely impaired individuals with ABI.

Are the auditory-verbal n-back, listening span, and digit span tasks correlated?

Several strong correlations were found to exist between scores within the ABI group. A strong positive correlation existed between *n*-back adjusted accuracy and digit span backward (i.e., as adjusted accuracy scores increased, performance on the digit span backward task increased as well, and vice versa), while a strong negative correlation was found between *n*-back omissions and digit span backward (i.e., as number of omission errors increased, digit span backward scores decreased). The direction of these correlations is expected; as errors on one task increase, it would be expected that performance in a related task would decrease as well. Because the digit span backward task is proposed as a measure of WM ability, the correlations found between these tasks suggest that the *n*-back task taxes WM as well. The correlation between these tasks may also indicate that working memory for numbers (utilized in the digit span task) and letters (in the *n*-back task) is stored and utilized in a similar manner in individuals with brain injury. No additional studies have been found to compare scores on a verbal auditory *n*-back task with scores on a backward digit span task in any population.

A moderate negative correlation was observed between listening span recall errors and digit span backward among ABI participants (i.e., as number of recall errors increased, digit span backward performance decreased), which indicates that listening span to some extent calls upon the same WM abilities as those utilized in the digit span

backward task, though to a lesser extent than the *n*-back task. This was the only

correlation noted between listening span and either of the other working memory tasks

(*n*-back and digit span backward). There are no other known studies that have compared

performance in the listening span task with that of a backward digit span task in adults

with ABI. In Lehman & Tompkins (1998), performance on a listening span task and a

digits backward task was compared among individuals with right hemisphere damage due

to cerebrovascular accident and a group of normally ageing adults. A moderate

correlation was found between listening span and digit span backward in non-brain

damaged participants (r = 0.68), but this relationship was not found in the RHD group.

Lehman and Tompkins partially attribute this to both a low internal consistency of the

digits backward task and a small sample size.

Inclusion of the standardized test results in correlational analysis yielded a strong

negative correlation between NART-II (1991) predicted verbal IQ and listening span total

recall errors among ABI participants, indicating higher predicted verbal IQ associated

with fewer recall errors on the experimental task. This implies that completion of the

listening span task requires individuals with brain injury to call upon vocabulary

knowledge. Additionally, a moderate positive correlation was observed between

predicted verbal IQ and category fluency total correct on the verbal fluency subtest of the

D-KEFS (2001), suggesting a relationship between vocabulary knowledge and verbal

fluency. The direction of this correlation was expected, as those individuals with a higher

predicted verbal IQ should perform better on a test of verbal fluency.

The correlations identified here help to support the researchers' hypothesis that

working memory tasks would be correlated with one another, although, not all measures

within each task correlated with each other to a level worthy of note. Additionally, no

strong correlations were found within the adults without brain injury other than those

among the various scores on the *n*-back task, which are expected to correlate based on the

nature of the scores. This can potentially be explained based upon the cognitive and

linguistic deficits that commonly exist within the ABI population. Because ABI

participants are likely to have deficits in one of more areas of language and/or cognition,

it may become necessary to call on atypical cerebral pathways or regions to complete

certain tasks. In McAllister et al. (1999), 11 adults without brain injury and 12 with mild

TBI who were 1 month post-injury, performed an *n*-back task similar to the task used in

the present study, while participating in a functional magnetic resonance imaging (fMRI)

procedure. Though task performance did not differ significantly between groups, the TBI

group showed differences in brain activation patterns as WM processing load increased

as compared to the control group. Differences were also seen in a group of 6 controls and

11 mild TBI participants 11 months post-injury (McAllister et al., 2002). Other

neuroimaging studies have found similar results, though the exact activation patterns vary

(Chistoudoulou et al., 2007; McAllister et al., 2001). Because the differences seen in

brain activation among individuals with TBI are likely due to damage inflicted on the

regions or pathways that are typically utilized for WM, this forces these individuals to

adapt to the utilization of other areas of the brain in order to compensate for the damage.

In individuals with TBI, this would make similarities in brain activation more likely

across cognitive and linguistic tasks that might otherwise show more diverse activation in healthy, non-brain-damaged individuals.

Limitations

The inclusion of an individual with a brain tumor presents one limitation in this study. However, as this person's data was not found to be significantly different from the participants with TBI, the inclusion of these scores does not significantly affect the outcome of the study.

Another limitation lies in the study's relatively small sample size. With only 13 participants with ABI and 10 control participants, the statistical power of this study was small. However, a small sample was also used in many of the aforementioned studies of working memory and individuals with brain injury; this information is provided in Table 8.

Table 8. Sample sizes of related studies.

	TBI	Control
Lehman & Tompkins (1998)	11	28
McAllister et al. (2001)	17	12
Moran et al. (2006)	10	10
Turkstra (2008)	19	19

That all standardized testing was completed prior to completion of the

experimental tasks may have threatened the validity of the results if participants

experienced fatigue. Many studies have reported significantly greater fatigue in

individuals with TBI when compared with non-injured controls. In Cantor et al. (2008),

223 individuals with mild to severe TBI were compared with 85 non-injured controls on

data collected through interview and administration of self-report measures. Fatigue was

found to be more severe and prevalent in individuals with TBI. Similar results have been

found in other studies (Ponsford & Ziino, 2003; Borgaro et al., 2005; Ashman et al.,

2008). The standardized session in this study, excluding breaks, took an average of

116.46 minutes (SD = 23.20) for ABI participants and 99.60 minutes (SD = 12.85) for

control participants. The experimental tasks were then completed following the

standardized testing. Though breaks were provided and participants were encouraged to

request additional breaks as often as desired, by completing the standardized testing first,

fatigue may have influenced performance on the later experimental tasks. As no data was

gathered evaluating participant fatigue during the study session, the researchers are

unable to assess the impact this factor may have had on task performance.

Future Research

Future research should be directed toward evaluating individuals with TBI who

present with more severe cognitive and memory impairment. The ABI group evaluated in

this study presented with a somewhat low level of impairment, which may explain the

lack of differences found between groups in the *n*-back task, as well as the lack of

correlation between the *n*-back and listening span tasks. Examining individuals with higher levels of deficit could provide further insight into the working memory abilities of this population, in addition to assisting researchers in determining whether one task is more appropriate or better evaluates working memory.

Other options for future research could include error analysis within the listening span task. In Tompkins et al. (1994), word recall errors were categorized according to error type (i.e.; related to target word, repetition, intrusion from a previous set, non-target word from same set). Because the purpose of the present study was to compare performance on the listening span task to performance on the *n*-back and digit span tasks, analysis of recall error types was not completed. The inclusion of this analysis would be merited in a study more closely examining the listening span task in a group of individuals with TBI in comparison to a group of adults without brain injury, and may provide further insight into the working memory abilities of this population.

As results of the *n*-back task showed correlations with the digit span backward task, further research into the exact relationship between these tasks may prove to be useful as well. Additional research into this correlation may assist clinicians in determining whether one of these tasks may be utilized in place of the other in a comprehensive examination of cognitive abilities in individuals with TBI.

Summary and Clinical Significance

The findings of this study support prior evidence that the working memory abilities of adults with ABI are different from those of healthy adults. Although the

manifestation of these differences was somewhat unexpected when compared with the original research hypotheses, the information obtained offers valuable insight into the advantages and disadvantages of each of the experimental tasks as they are utilized in the evaluation of working memory in individuals with ABI.

Because the results of the *n*-back task did not reach statistical significance for any measure (adjusted accuracy, omissions, or false positives) and similar results have been produced in other studies (McAllister et al., 2001), this task may not be sufficiently sensitive to assess working memory in individuals with a low level of impairment and who have made good cognitive recovery. As there is little research examining performance of individuals with more severe levels of impairment on a comparable task, care should be taken when utilizing this task to assess a more impaired ABI population.

Group differences on the listening span task suggest that this task may be effective in evaluating subtle working memory impairments with individuals with ABI who have made a good recovery. The relationship between the listening span task and verbal fluency subtest suggests that the listening span task calls to some extent upon the use verbal fluency abilities. However, care should be taken in assuming relationships between tests of verbal fluency that have not been evaluated in this study.

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Appendix A. Standardized Tests Administered.

	Subtests Administered	Cognitive/Linguistic Component Evaluated	Author(s)	Year of Publication
California Verbal Learning Test, 2nd Edition (CVLT-II)	N/A	Word list immediate & delayed recall & recognition	Delis, Kramer, Kaplan, Omer	2000
Delis-Kaplan Executive Function System (D-KEFS)	Trails, Verbal Fluency, Design Fluency	Divided attention; verbal fluency; nonverbal fluency	Delis, Kaplen, Kramer	2001
National Adult Reading Test, 2nd Edition (NART-II)	N/A	Predicted premorbid verbal intelligence	Nelson & Willison	1991
Wechsler Memory Scale, 3rd Edition (WMS-III)	Digit Span	Immediate & working memory	Wechsler	1997
Western Aphasia Battery (WAB)	Aphasia Quotient & Reading	Language function: content, fluency, auditory comprehension, repetition, naming, reading	Kertesz	1982

Appendix B. Experimental Task Instructions.

N-Back Practice Task Instructions as Appearing on Computer Screen

In this task, you will listen to several sequences of letters. Each sequence will be about 45 seconds long. There will be a break after each sequence. Press any key to continue.

Before each sequence of letters begins, you will be given 1 of 3 different types of instructions. The instruction to follow will change with each sequence. Press any key to continue.

In each type of instruction, you will be asked to respond to certain letters in the sequence. You will be given 2 seconds to respond after each letter in the sequence. Press any key to continue.

The following are practice sequences to allow you to become familiar with the 3 different types of instructions. Press any key to continue.

One instruction will ask you to press the space bar when you hear a certain letter. This letter will be different for each sequence and will be given to you in the instruction before the sequence begins. Press any key to practice.

Press the space bar when you hear "*n*". Press any key to start.

[*Practice stimulus sequence presented auditorily*.]

Do you have any questions? If not, press any key to continue.

Another instruction will ask you to press the space bar when a letter is the same as the letter that was one place back in the sequence. For example, if you heard the following sequence: L P M M Q you would press the space bar after the 2nd "M", because it is the same as the letter one place before it. Press any key to practice.

Press the space bar when the letter matches the letter one place back. Press any key to start.

[*Practice stimulus sequence presented auditorily*.]

Do you have any questions? If not, press any key to continue.

The last instruction will ask you to press the space bar when a letter is the same as the letter that was two places back in the sequence. For example, if you heard the following sequence: J D P D X you would press the space bar after the 2nd "D", because it is the same as the letter two places before it. Press any key to practice.

Press the space bar when a letter matches the letter two places back. Press any key to start.

[*Practice stimulus sequence presented auditorily*.]

Do you have any questions? If not, press any key to finish the practice session.

Practice session complete.

N-Back Experimental Task Instructions as Appearing on Computer Screen

Press any key to start.

0-back Instructions:

Press the space bar when you hear "*n*". Press any key to start.

[*Practice stimulus sequence presented auditorily*.]

You may take a break now if you wish. Press any key to continue.

1-back Instructions:

Press the space bar when a letter matches the letter one place back. For example, if you heard: L P M M Q you would press the space bar after the 2nd "M". Press any key to start.

[*Practice stimulus sequence presented auditorily*.]

You may take a break now if you wish. Press any key to continue.

2-back Instructions:

Press the space bar when a letter matches the letter two places back. For example, if you heard: J D P D X you would press the space bar after the 2nd "D". Press any key to start.

[*Practice stimulus sequence presented auditorily*.]

You may take a break now if you wish. Press any key to continue.

After Final Stimulus Sequence:

Session complete.

Listening Span Practice and Experimental Task Instructions

Computer Instructions:

The experimenter will read the instructions now. Press any key to continue.

Verbal Instructions:

In this task, you're going to hear some short statements. I will ask you to do 2 different things. First, I want you to show me or tell me whether each statement you hear is true or false. Let's try that part:

Snow is cold.
You eat a mountain.

That part's easy. But now I'm going to make it a little harder. After you decide whether the statement is true or false, I want you to remember the last word of each statement. Then, when I point to you, tell me the last words that you remembered for those statements. It doesn't matter what order you remember the words. Let's try it with the two statements you just heard:

Snow is cold.
You eat a mountain.

Yeah, you've got it. So there are 2 things to do. Point to or say true or false, and remember the last word of each statement. Let's practice a few more. Are you ready?

Computer Instructions:

[*Practice stimulus sentence presented auditorily.*]

1 is True
2 is False

[*Procedure repeats until end of practice set is reached.*]

Now have them repeat the final words. When they are done, press 1 to begin practice set B.

[*Procedure repeats until end of practice set is reached.*]

When they are done, press 1 to begin the experiment.

Verbal Instructions:

Now we'll go on to the real thing. We'll start with sets of 2 sentences, and increase to sets of 5 sentences. Most people can't remember all of the words when we get to 5 sentences, so don't worry about that. Just remember as much as you can. And, if there are any that you miss or don't quite hear, just go on to the next one. We can't repeat any once we get started. Any questions?

Computer Instructions:

[*Stimulus sentences presented auditorily.*]

1 is True
2 is False

[*Procedure repeats until end of set is reached.*]

Now have them repeat the final words. When they are done, press 1 to begin set [*n*].

When they are done, press 1 to go to the next block.

Verbal Instructions Between Levels:

Now, we'll move up to [*3, 4, 5*] sentences, so there will be [*3, 4, 5*] words to remember.

After Final Stimulus Set:

The experiment is finished. Press any key to end E-prime.