2008-08-07

fMRI Evidence of Group Differences on the Word Memory Test in a Sample of Traumatic Brain Injury Patients

James Douglas Larsen
Brigham Young University - Provo

fMRI EVIDENCE OF GROUP DIFFERENCES ON THE WORD MEMORY TEST IN A SAMPLE OF TRAUMATIC BRAIN INJURY PATIENTS

by

James D. Larsen

A thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Master of Science

Department of Psychology

Brigham Young University

December 2008

BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

James D. Larsen

This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

Date	Mark D. Allen, Chair
Date	Erin D. Bigler
Date	Ramona O. Hopkins

BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the thesis of James D. Larsen in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

Date	Mark D. Allen Chair, Graduate Committee

Accepted for the Department

Date	Ramona O. Hopkins Department Chair

Accepted for the College

Date	David B. Magleby Dean, College of Family, Home, and Social Sciences

ABSTRACT

fMRI EVIDENCE OF GROUP DIFFERENCES ON THE WORD MEMORY TEST IN A SAMPLE OF TRAUMATIC BRAIN INJURY PATIENTS

James D. Larsen

Department of Psychology

Master of Science

The Word Memory Test (WMT) is a popular effort test that requires participants to memorize lists of paired words and repeat them back in a variety of different memory tasks. Four brain injured patients participated in two trials of the delayed recall (DR) portion of the WMT while undergoing fMRI scanning. In the first trial subjects put forth full effort, and during the second trial subjects were instructed to simulate increased memory impairment in order to represent poor effort. fMRI activation from both trials were compared in order to contrast full and simulated poor effort activation patterns during the WMT. Raw scores from full effort and simulated poor effort trials were compared to a control group to test the hypothesis that a brain injured population will score lower than a healthy population on the WMT while putting forth full effort. Raw score results showed lower WMT scores for TBI group. fMRI results showed larger

between-group differences than between-condition differences, suggesting that the WMT is sensitive to TBI.

ACKNOWLEDGEMENTS

Thank you to Drs. Mark D. Allen, Erin D. Bigler, and Ramona O. Hopkins for their many corrections, suggestions, and revisions, as well as countless hours of mentoring. A special thanks to Dr. Jim Snyder of the Utah Valley Regional Medical Center for his cooperation and assistance. I would also like to thank all of those who sacrificed their time to act as research participants. My most sincere thanks go to my wife Cassidy who faithfully supported me through countless late nights and busy weekends.

fMRI Evidence of Group Differences on the Word Memory Test in a Sample of Traumatic Brain Injury Patients

Symptom Validity Tests

Traumatic Brain Injury (TBI) is the leading cause of disability in adolescents and is prominent among people of all ages. The sequelae of TBI vary widely and can include impairments ranging from speech to memory impairments (Vakil, 2005). Often individuals with TBI have disabilities that inhibit their ability to function and maintain employment, Impairments following TBI may lead to an application for disability pay or government aide, a personal injury lawsuit, or the evaluation of a soldier claiming disability in order to avoid being sent to a war zone (Richman et al., 2006). Because of its prevalence and its wide variety of side effects, TBI cases are often included in litigation (Anderson, 2008; Hall, Thompson, & Pairier, 2007).

Insurance companies and government agencies responsible for distributing monies to individuals who are not able to work have become increasingly concerned that TBI patients might be feigning or exaggerating their impairment, more commonly referred to as malingering. If malingering goes unidentified, monies that should be used to help individuals with real deficits may be given to people who have no residual problems and who are able to support themselves. Such an improper distribution of monies may result in unnecessary financial costs that could otherwise help genuinely impaired individuals(Anderson, 2008).

In order to prevent financial payments to individuals who are malingering, insurance companies and agencies must rely on trained clinicians to evaluate the cognitive function of brain injured individuals. However, opinions of clinicians may be

subject to bias, and some clinicians may be more inclined to identify patients as malingering than others (Larrabee, 1990).

In recent years, tests known as symptom validity tests (SVTs) or effort tests have become increasingly popular as a more objective way of identifying individuals who may be malingering. SVTs are tests that assess normal cognitive function, but which are supposed to be so easy that almost anyone, including patients with severe cognitive impairments, should be able to perform near perfectly. Since even populations of severely cognitively impaired individuals supposedly can perform well on these tests, individuals who scores low on the test are said to be putting forth "poor effort" (Green, Iverson, & Allen, 1999) and are identified as malingering. The SVTs are meant to provide a more objective way of detecting malingering, using a cutoff score to determine which patients are malingering and which are truly impaired. The cutoff scores are in large part designed to eliminate clinician biases in diagnosis.

The WMT

An SVT that has gained increasing attention in the past few years is Dr. Paul Green's Word Memory Test (Green, 2003). The Word Memory Test (WMT) is an SVT that focuses on a patient's ability to remember simple word lists. In the WMT, patients are first asked to memorize 20 pairs of related words (i.e. SHOE and LACE[1]) displayed on a computer screen one at a time. Immediately after presentation of the words, patients are asked to complete an immediate recall (IR) task in which 40 new word pairs are presented on the computer screen one at a time. In each of the 40 new word pairs, one word is taken from the original list, and the other is a new foil word that has not yet been seen (i.e. SHOE and SOCK). For each word pair the patient is asked to identify which of

the words was seen in the original word list. A 30 minute delayed recall (DR) task is then administered. The DR task is exactly the same as the IR task, but for each of the 40 word pairs the foil word is different than it was in the IR task (i.e. SHOE and FOOT). After the IR and DR tasks have been completed, the patient is given three more measures of memory. In the Multiple Choice subtest, the patient is presented with the first word from each of the original word pairs and is asked to identify the second word of the pair from eight choices. In the Paired Associates subtest, the patient is given the first word from each of the original word pairs and is asked to state the second word in the pair. Finally, in the Free Recall subtest, the patient is asked to recall as many words from the original list as they can, in any order (Flaro, Green, & Robertson, 2007).

Two recent articles investigating performance on the WMT in brain injured individuals (Flaro et al., 2007; Richman et al., 2006) found that performing well on the WMT requires little or no effort, and that the only patient population that appeared to do poorly on the WMT were patients with severe dementia. In addition, Flaro et al. state that individuals with motivation to perform poorly, specifically those involved in litigation, score significantly lower on the WMT compared to individuals not involved in litigation. Richman et al. found that individuals with soft tissue head injuries will perform well on the WMT even when administered in a language in which they are not fluent. Both articles further state that if an individual scores poorly on the WMT, their low score is therefore due to a lack of effort rather than cognitive impairment.

Thus, the WMT is proposed to provide an objective way to detect malingering that will eliminate variability and biases that are inherent in other forms of malingering

assessment. Deeper analysis of the WMT shows that these claims encounter serious difficulties regarding the theoretical basis of the test.

Error in Effort Tests

The topic of error in SVTs was addressed by Merten, Bossink, & Schamand (2007). They suggest that effort tests such as the WMT have placed too much emphasis on sensitivity and not enough on specificity. Sensitivity is an important component to an effort test, since effort tests are concerned with making sure that they effectively identify patients who are genuinely malingering. However, with high sensitivity comes lower specificity. An effort test with low specificity is bound to result in false positives. In the case of individuals who might honestly need assistance, the SVT should be more concerned with avoiding false positives than false negatives. Stressing the avoidance of false positives could shift the focus of research and clinical work from identifying malingerers to identifying patients with genuine impairment. Tests such as the WMT which have high sensitivity are likely to result in a high number of patients being classified as malingering when in fact their poor performance is due to true cognitive impairment. The theoretical flaws of the WMT and other SVTs extend beyond the issue of sensitivity and specificity. The very nature of the observed cognitive impairments, including impaired memory, in individuals with TBI cast doubt on the ability of the test to correctly identify poor effort.

Variability in the Effects of TBI

A test that is meant to assess cognitive impairment in any population needs to recognize that cognitive impairment is not one general impairment, but rather a spectrum of selective impairments in a variety of cognitive domains. Vakil (2005) stated that there

are a number of different variables that will contribute heavily to the individual impairment of any TBI patient. The variables include the nature of the TBI (location of the lesion), etiology of the TBI, the severity of the injury, the patient's age at the onset of the injury, the patient's premorbid intelligence, and current participation in a rehabilitation program.

Some specific types of cognitive impairment, such as aphasia, are illustrative of how selective some cognitive impairment can be. Aphasic subjects often function very highly in most areas of cognition but have very specific impairments in language. Some forms of aphasia can affect even very specific parts of language, such as syntax in the case of Broca's aphasics or semantics in the case of Wernicke's aphasics (Schoenbrodt & Coll, 2001).

Selective cognitive impairment due to TBI may have a profound effect on memory. In a recent review of TBI, Vakil (2005) found impaired memory is one of the most significant deficits following TBI, and is also among the most frequent complaints of TBI patients and their family members. Of the various cognitive impairments from which TBI patients suffer, memory is often the slowest to improve and may never recover (Vakil, 2005). It is for this reason that memory tests, even simple memory tests, may not be the best foundation for an SVT designed for use in a brain injured population. Below is a review of studies that have shown memory impairments in a brain injured population that may increase the likelihood of scoring poorly on a memory-based SVT.

Memory Impairment in TBI

Vakil (2005) divides memory impairment into two groups, impairment of explicit memory and of implicit memory. He further subdivides these categories into impairments

of working memory, immediate memory, verbal memory, visual memory, skill learning, priming, and other groups. In fact, TBI patients can have a severe impairment in one type of memory while all other forms of memory remain in tact. The existence of such selective memory impairments may be problematic for the WMT's claim that all brain injured subjects can score well on the test, as the WMT is a measure of explicit memory.

Zec et al. (2001) measured the memory performance in 32 individuals with severe TBI 10 years following the injury. The TBI group was compared to a group of normal controls as well as a group of controls who had suffered from Spinal Cord Injuries 10 years previously. All subjects were tested using the Wechsler Memory Scale-Revised (WMS-R), the Rey Auditory Verbal Learning Test (RAVLT), and the Buschke Selective Reminding Test (SRT). Lower scores were found in TBI subjects compared to the normal and spinal cord injury control groups on all variables of the SRT and WMS-R, and on 9 of the 12 measures of the RAVLT. These findings demonstrate that memory impairments from TBI can remain up to 10 years after the injury occurs (Zec et al., 2001). More interesting is that Zec's (2001) study showed the TBI group was significantly impaired on delayed recall tasks. Given that a major component of the WMT involves delayed recall, these findings raise questions as to how individuals with TBI and impaired memory would perform on the delayed recall portion of the WMT. In fact, the Zec et al. results suggest that some individuals with memory impairment due to TBI may be impaired on a delayed recall task 10 years post injury.

Other studies have shown that patients with TBI are less able to use relationships between words to facilitate memorization. Carlesimo et al. (1998) showed that TBI patients scored significantly lower than controls on tests of memory when words were

presented for memorization in related pairs. During the memorization phase of the WMT, words are presented in pairs that are semantically related to each other (i.e. SHOE and LACE). In both IR and DR trials, the memorized words are presented alongside semantically related foil words (i.e. SHOE and SOCK). This use of related words may act as an advantage for normal subjects in the recall tasks, but may not facilitate memorization for individuals with TBI.

Schmitter-Edgecombe and Anderson (2007) performed a study in which healthy control subjects and individuals who had suffered from a closed head injury (CHI) participated in a word memorization task. Each individual was asked to memorize 36 words. Each word was presented for memorization alongside a cue word that was meant to facilitate recall. During the recall phase, each of the cue words was presented one at a time along with a list of possible partner words. For each cue word, the participant was asked to identify from the list which of the partner words had originally been paired with the cue word. The results showed that the CHI participants scored significantly lower than controls both in the number of questions answered and in the number of correct responses given.

Attentional Impairments in TBI

Other studies have shown that TBI patients may have a variety of deficits in attention, which is an integral component of all memory processes and therefore may affect performance on memory tests. Cremona-Meteyard, Clark, Wright, & Geffen (1992) examined the ability of TBI patients to direct attention in a visual cueing paradigm. Subjects were asked to focus their attention on a target at the center of a screen. A visual cue was then presented, after which a light appeared on either the left or right side of the

target on which the participant had been focusing. The visual cues appeared as either an arrow or a plus sign. An arrow indicated that there was an 80% chance that the light would appear on the side to which the arrow was pointed, and a plus sign indicated that the odds were equally likely that the light would appear on either side. Arrows which correctly identified the side that the light would appear on were called valid cues. Arrows which incorrectly indicated the side that the light would appear on were called invalid cues. Trials that used a plus sign were used as a baseline. The control subjects' reaction times were much faster on trials in which they had received a valid cue. However, TBI patients benefited significantly less from valid cues than control subjects did. The TBI patients had difficulty moving their attention from the initial target to the location indicated by the cue, suggesting that TBI affects a person's ability to direct and maintain attention.

Another study done by Leclercq et al. (2000) investigated attention deficits in TBI patients. Participants were asked to generate a list of 100 numbers ranging in value from 1 to 10. Participants were instructed to make their list as random as possible, and to avoid any obvious patterns in the way the numbers were selected. Next, they were told to focus their attention on a computer screen in front of them and to press a response button as soon as they had noticed a white box appear in the center of the screen. In a third trial, patients were asked to perform both tasks at the same time. The TBI patients did not differ from controls when performing either task, but they were significantly impaired when asked to perform both tasks at simultaneously. Thus, patients with TBI have difficulty multitasking, even when both tasks are simple, which may be due to deficit in divided attention.

These studies and others (Axelrod, Fichtenberg, Liethen, Czarnota, & Stucky, 2001; Bublak, Schubert, Matthes-von Cramon, & von Cramon, 2000; Christodoulou et al., 2001; Demery, Pedraza, & Hanlon, 2002; Groot, Wilson, Evans, & Watson, 2002; Mangels, Craik, Levine, Schwartz, & Stuss, 2002) demonstrate that a memory task becomes difficult for people suffering from TBI due to multiple reasons. First, attentional deficits make it more difficult to concentrate on remembering the original word list. Second, memory deficits may make it difficult to retrieve words presented in the initial phase of the task. The fact that TBI patients frequently have impaired memory leads to the prediction of low scores when completing an SVT that relies on memory.

Evidence of High Cognitive Effort on the WMT

One of the boldest claims made by the authors of the WMT is that anyone, besides individuals suffering from dementia, can perform well with very little cognitive effort (Flaro et al., 2007). A recent study by Allen, Bigler, Larsen, Goodrich-Hunsaker, & Hopkins (2007) administered the WMT to healthy, unimpaired subjects. The original word list memorization phase of the test, as well as the IR trial were administered on a laptop computer. The DR trial was given while subjects were inside a GE 1.5T MRI machine to assess brain activation patters during recall. The performance of all subjects on the WMT was nearly 100%. The observed activation patterns during the DR trial of the WMT were similar to activation patterns shown to be associated with high cognitive effort on a variety of tasks (Braver et al., 1997; Buckner, Koutstaal, Schacter, Wagner, & Rosen, 1998; Ranganath, Johnson, & D'Esposito, 2000), including activation in the dorsolateral prefrontal cortex, anterior insula, superior parietal cortex, and dorsal anterior cingulate. During a post-test debriefing session, each subject also reported that while they

were able to score well on the test, the task still required a fair amount of attention and effort. These findings suggest that while the subjects scored well on the WMT, it is not effortless, and requires a fair amount of cognitive processing even in normal subjects. This finding suggests that normal individuals require a significant amount of effort to successfully complete the WMT. The above fMRI findings raise questions regarding how TBI subjects with known memory impairments would perform on the WMT.

Donders & Boonstra (2007) showed that difficulty in WMT performance for TBI patients increased with age, number of days post injury, female gender, prior psychiatric history, prior personal abuse, and a coma lasting longer than one day. The authors state that a failing score on the WMT should only be taken to indicate the possibility of malingering or poor effort rather than as proof that a patient is exaggerating their impairments.

Functional Imaging as a Measure of Effort

The evidence indicates that there may be cases in which individuals with brain injury and resulting memory impairment might have poor performance on the WMT, even when putting forth substantial effort. The question now becomes one of determining whether or not the WMT is actually measuring effort. A possible answer to this question is described in a study by Sarter, Gehring, & Kozak (2006), who found that the highest levels of attentional performance take place in the prefrontal regions. Other studies have shown that neural activation involving effort takes place in the dorsolateral prefrontal cortex (particularly the middle frontal gyrus), anterior insula/frontal operculum, superior parietal cortex (including medial portions), and the dorsal anterior cingulate (Braver et al., 1997; Buckner et al., 1998; Ranganath et al., 2000). Given that these areas of the brain

are active during tasks that require high effort, they could be used as a marker of high effort during the WMT.

Further, effort may be required not only in performing well on the WMT, but in malingering as well. Since patients who are malingering must first identify the correct answer in order to purposefully choose an incorrect answer, malingering utilizes the cognitive processes involved with truthful performance as well as processes involved in the suppression of the correct answer. In this case, malingering may be an even more cognitively demanding task than simply doing one's best to perform well. It is therefore important to identify a pattern of activation that not only shows effort, but which can distinguish between effort as a result of malingering and effort as a result of genuine task performance.

Although no studies have assessed brain activation specifically tied to malingering on effort tests, functional imaging studies have been done to identify the cognitive processes involved in deception. Spence et al. (2004) performed a study investigating the cognitive processes involved with answering questions dishonestly. In their study, participants first filled out a questionnaire which consisted of simple 'yes' and 'no' questions about activities they had participated in that day. Next, subjects underwent fMRI scanning while asked to answer the same questions that they had answered on the questionnaire. Before the session started, participants were told that when the questions were presented, they would either be written in red or green ink. One of the colors was to indicate that they should respond truthfully while the other color meant that they should answer dishonestly. In order to give the study a more genuine feel, an investigator acting as a 'stooge' was introduced to the room. Subjects were told that

the ‘stooge’ did not know which color prompted the truth and which prompted a lie, but that they would be trying to guess based on the answers that the subjects gave. Participants were told that they were hoping to be able to fool the stooge as to the color coding. Experimenters used the original questionnaire as a check to make sure that participants were correctly answering each question according to its color coding. The data showed an increase in activation in bilateral ventrolateral prefrontal and anterior cingulate cortices and greater activation in the ventrolateral prefrontal cortices, associated with the inhibition of the truthful response.

While Spence et al. were unable to find a system of brain activation that accompanied the creation of a lie, they were able to identify activation patterns that accompany the suppression of a correct answer and the delivery of an incorrect answer. Subjects who were exaggerating impairment on the WMT would have to suppress the correct answer and choose the other word that is presented to them. By using functional imaging it is possible to identify patterns of brain activity that are specifically correlated with malingering on the WMT. This activation pattern could be assessed by asking healthy subjects with no motivation to perform poorly on the WMT to complete both a “full effort” and a “simulated poor effort” trial on DR portion of the test. Activation patterns from the two trials could be compared in order to discover which activation patterns are involved with malingering rather than full effort on the WMT.

Predictions and Hypotheses

The current study seeks to use functional neuroimaging to test three hypotheses about the WMT. First, both control subjects and brain injured subjects will have increased activation in the ventrolateral prefrontal cortices while feigning impairment

during the DR trial of the WMT. Second, given that TBI patients have been shown to suffer from a wide variety of attentional and memory impairments, patients with TBI will score significantly lower than healthy controls during the DR portion of the WMT. Third, even though TBI patients will score significantly lower on the WMT, the activation recorded during their DR trial will be similar to that of the healthy controls on a "full effort" DR trial.

Contributions of This Study

This study will make two significant contributions to the research on SVTs. First, no study has compared performance on the WMT with functional imaging evidence of truthful responses and high effort. Functional imaging may provide us with an objective measure of malingering to which we can compare performance on the WMT. Second, much of the research that has been done up to this point to test the validity of the WMT has been done by the test's authors and affiliates (Green & Flaro, 2003; Green et al., 1999; Green, Rohling, Lees-Haley, & Allen, 2001) It would be beneficial for studies of the validity of the WMT to be carried out by researchers with no personal interest in the test's acceptance in the professional community.

Methods

Ten individuals (5 males and 5 females) between the ages of 18 and 30 with no history of brain injury served as the healthy control group. Four of these individuals were the same who participated in Allen et al.'s (2007) study. Due to the fact that financial compensation has been linked to altered performance on the WMT (Flaro et al., 2007), these subjects received no compensation for participation in the study in order to ensure they had no "extra motivation" to do well or poorly on the test. Subjects were recruited

from undergraduate classes at Brigham Young University through graduate level psychology students who were teaching undergraduate courses. This first group participated in the computerized version of Green's WMT as outlined by (Green, 2003). Differences in the test's administration were altered during the delayed recognition phase of the test in order to facilitate MRI scanning, as outlined below. During participation, subjects first memorized a set of 20 semantically associated word pairs (e.g., SHOE-BELT). During memorization words appeared on the screen of a laptop computer placed on a desk approximately 24" from the subject in a quiet room. Words appeared on the screen in two second intervals. During memorization, the subject was alone in the room in order to facilitate concentration.

Next, participants were given an immediate recognition (IR) test in which each word from the study list was paired with a new semantically related word (e.g., BELT-BUCKLE) and presented to the participant in one second intervals. Participants were required to indicate which of the two words had appeared on the study list via a button press on the laptop keyboard. The IR test took place in the same room and under the same conditions as the memorization phase.

After a 30 minute interval, participants were given two trials of a second, delayed recognition (DR) test in which each word from the study list was paired with a new associate word (e.g., BOOT-SHOE) and presented at one second intervals. Participants were once again asked to identify which of the two words appeared on the original study list via a button press. For full details, see Green, 2003. Before administration of the DR trial, participants were told to do their best to remember the words from the study list. This trial represented a full effort on the WMT. After the first trial, subjects were told that

they were going to take the exact same test that they had just taken, but using a different set of instructions. The full instructions that they were given are provided in the Appendix. The subjects were asked if the instructions were clear, and the DR test was administered in exactly the same manner as in trial one, but using the new instructions. This trial represented simulated poor effort on the WMT, and will be referred to as the simulated poor effort (SPE) trial.

Participants underwent fMRI imaging during both DR and SPE trials. Word pairs were projected on to a screen which was visible to the subject through a series of mirrors placed on the head coil of the fMRI machine. Word-pair stimuli were presented at one second intervals in blocks of eight sequential test trials. Each test block was followed by a control block in which two rectangle boxes appeared side-by-side in the same positions as the word stimuli, where one of the boxes was randomly filled in, and participants simply identified the filled box with a button press. This control task was chosen both because it matches the motor activity of the test task and because it clearly requires minimal cognitive effort compared with the DR test. Five block cycles resulted in 40 total trials for each condition.

At the conclusion of each assessment a debriefing was performed on each subject to obtain a qualitative perspective on cognitive effort in performing the WMT.

A TBI group consisted of 4 individuals (2 male and 2 females) between the ages of 18 and 30 who had suffered a mild to moderate TBI and who had memory impairment documented by independent neuropsychological assessment as part of a hospital based out-patient rehabilitation program. For the purpose of this study, TBI was considered mild or moderate if the patient's initial Glasgow Coma Scale score was 8 or below.

Patients with severe TBI were not included in the study in order to avoid large lesions that could interfere with the neural networks involved in task completion and signal characteristics from lesions or atrophic brain regions. These individuals were recruited from the UVRMC Hospital in Provo, UT with the help of Dr. Jim Snyder. The TBI subjects received no compensation for their participation, and none were currently involved in litigation. Green's WMT was administered to the TBI group in exactly the same way that has been described for the normal controls. The only change in the instructions for the TBI group occurred during the instructions for the SPE trial of the WMT. Rather than being told to imagine that they had been involved in a car accident, as presented in the Appendix, they were told to imagine that their memory impairments were worse than what their symptoms currently were. This was meant to avoid confusion for TBI subjects whose injuries were caused by a car accident.

fMRI

During all DR and SPE tests, functional images were acquired at 23 contiguous axial locations using an EPIBOLD sequence with the critical parameters TR = 2000; TE = 40ms in a 64 X 64 matrix. Conventional pre-processing and statistical analyses were performed using MRIcro and SPM2 (http://www.fil.ion.ucl.ac.uk) software packages, respectively. SPM2 analysis used a standard procedure of ANCOVA analysis at the subject level followed by a group level t-test on the between-condition contrast weights from each participant. All data was displayed with a critical $p < .001$, FWE corrected, voxel extent threshold = 9. TBI group data were also displayed with a critical $p < .05$ in order to show more diffuse activation patterns.

Data Analysis

All image pre-processing and statistical analysis was performed using MRIcro software (Rorden and Brett, 2000, http://www.sph.sc.edu/comd/rorden/mricro.html) and the SPM2 statistical parametric mapping software package (http://www.fil.ion.ucl.ac.uk).

Image Pre-processing. The functional volumes from each participant were submitted to a slice acquisition-time adjustment procedure, using sinc interpolation, followed by a motion correction procedure using a six parameter (in three translation and three rotation directions) rigid-body affine transform and additional unwarping corrections for EPI distortions. Any head movement exceeding 1mm translation or 1° rotation displacement disqualified the data from use. After motion/distortion correction, all functional volumes were spatially normalized and resampled to an isotropic $3mm^3$ voxel size, using the Montreal Neurological Institute (MNI) templates implemented in SPM2, placing all participants' functional images into a common stereotactic space. Following normalization, functional images were spatially smoothed with an 8mm FWHM Gaussian kernel, in order to increase signal-to-noise ratio and to reduce the effects of moderate intersubject variability in brain anatomy.

Subject-Level Analysis. A time-series ANCOVA implemented in SPM2 was used to test each voxel, for each subject, against the null-hypothesis that changes in BOLD signal in that voxel, over the duration of the experiment, did not significantly correlate with stimulus epochs of interest. A boxcar waveform convolved with a synthetic hemodynamic response function with a 4 sec lag-to-peak was used to model task-related activation. The data was high-passed-filtered in time, using a set of discrete cosine basis functions with a cut-off period of 128 seconds, and conditioned for temporal autocorrelations using AR1 correction. For each participant, *t*-values for condition

contrasts *test* (word choice) and *control* (filled box choice) were computed for each voxel, using the parameter estimates of the ANCOVA. The resulting three-dimensional contrast map from each subject was saved for further group-level.

Group-Level Analysis. Group-level effects were assessed using a modification of the RFX approach recommended by Penny et al. (2003) in order to deal with small sample sizes (specifically, less than 12), in which the value of the sum of each of the between-condition contrast weights for each voxel from each subject's ANCOVA is entered into a *second-level t*-statistic computation, with the mean value for each voxel across subjects modeled as the effect term and the variance between subjects modeled as the error term. Between-conditions effects were assessed using two-sample *t*-tests (test vs. control). All activation peaks were reported with a critical FWE corrected *p*-value of <.001, and a voxel cluster extent threshold of 9 contiguous voxels. TBI group data were also displayed with a critical p <.05 in order to show more diffuse activation patterns.

Behavioral Performance Data. Independent-groups t-tests were run to compare the WMT score differences between groups on the IR, DR and SPE trials. All t-test analyses on WMT scores were performed using the SPSS 16.0 statistical software package.

Results

Control Group

Behavioral Performance Data. All but one of the participants in the control group were 100% accurate on the IR phase of the WMT. One subject missed a single item, receiving a score of 97.5%. On the DR phase, nine of the ten control subjects scored 100%, and one of the control subjects scored 97.5% (see Table 1). The subject scoring

below 100% on the IR phase and the subject scoring below 100% on the DR phase were not the same individual. Scores on the SPE trial were more varied, with scores ranging from 50% to 70% correct.

After their participation in the WMT was complete, all but two of the control participants reported that although they were able to score well on the WMT, the test seemed moderately difficult and required concentration and deliberation. One of the participants reported that the test had been extremely difficult, and apologized for a poor performance, assuming that numerous errors had been made when in fact they scored 100% correct on the IR trial and 97.5% correct on the DR trial. The individual who reported the test to be extremely difficult was the same subject who missed an item during the DR phase. Only the control subject who missed an item during the IR phase reported that the test had been easy.

Table 1

WMT Raw Scores for Control and TBI Groups

Control Group												
Trial	S01	S02	S03	S04	S05	S06	S07	S08	S09	S10	Range	Mean
IR	40	40	40	40	40	39	40	40	40	40	39-40	39.9
DR	40	40	40	40	39	40	40	40	40	40	39-40	39.9
SPE	24	24	26	27	28	24	21	20	23	27	20-28	24.4

TBI Group						
Trial	S01	S02	S03	S04	Range	Mean
IR	23	39	38	38	23-39	34.5
DR	19	39	37	40	19-40	33.75
SPE	30	28	8	21	8-30	21.75

Note. Scores shown are raw scores out of a possible 40 questions.

fMRI Data. The observed pattern of activation in the control group during the DR trial of the WMT was consistent with the pattern observed by Allen et al. (2007). The strongest peaks in activation were found in the left occipital area and in the dorsal anterior cingulate/supplementary motor area, with other suprathreshold foci at the right and left middle frontal gyri, bilateral anterior insula, bilateral superior parietal lobe, and right occipital area (see Figure 1).

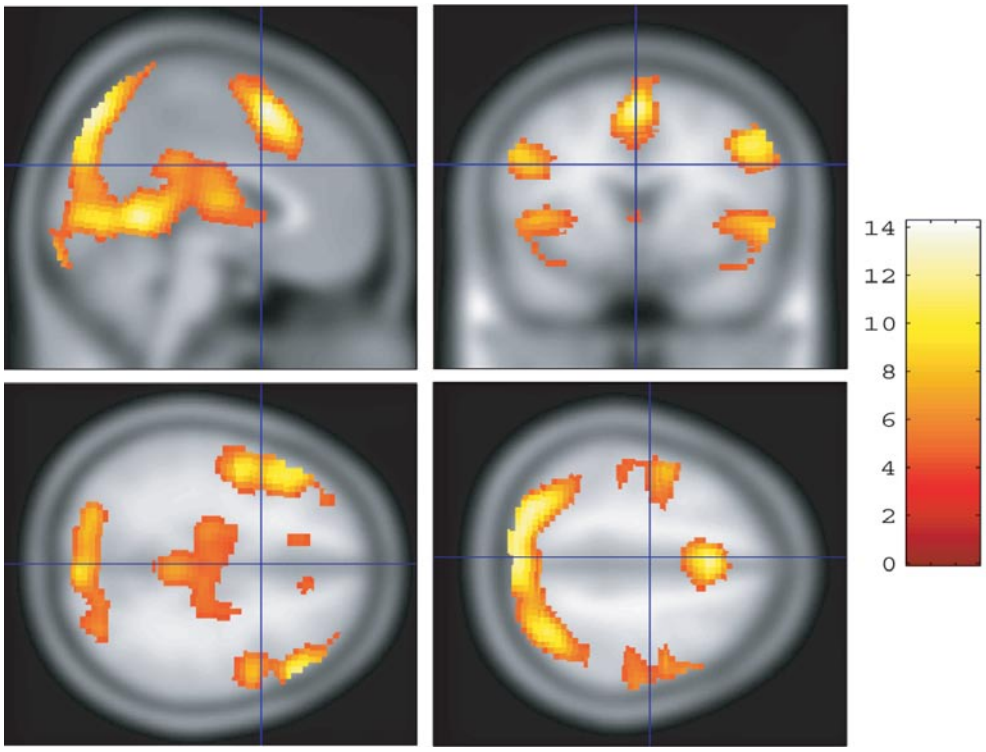

Figure 1. Group level comparisons testing condition test-control during the control group's DR trial (left = right). The numbers in the key represent t-score values.

The observed pattern of activation in the control group for the SPE trial of the WMT was similar to that found during the DR portion of the test. The strongest peaks in activation were found in the right occipital area and the dorsal anterior cingulate/supplementary motor area, with other suprathreshold foci at the right and left

middle frontal gyri, bilateral anterior insula, bilateral superior parietal lobes, and left occipital area. While the t-scores at these peaks closely resemble those observed during the DR phase, the t-scores of surrounding areas are much lower (see Figure 2).

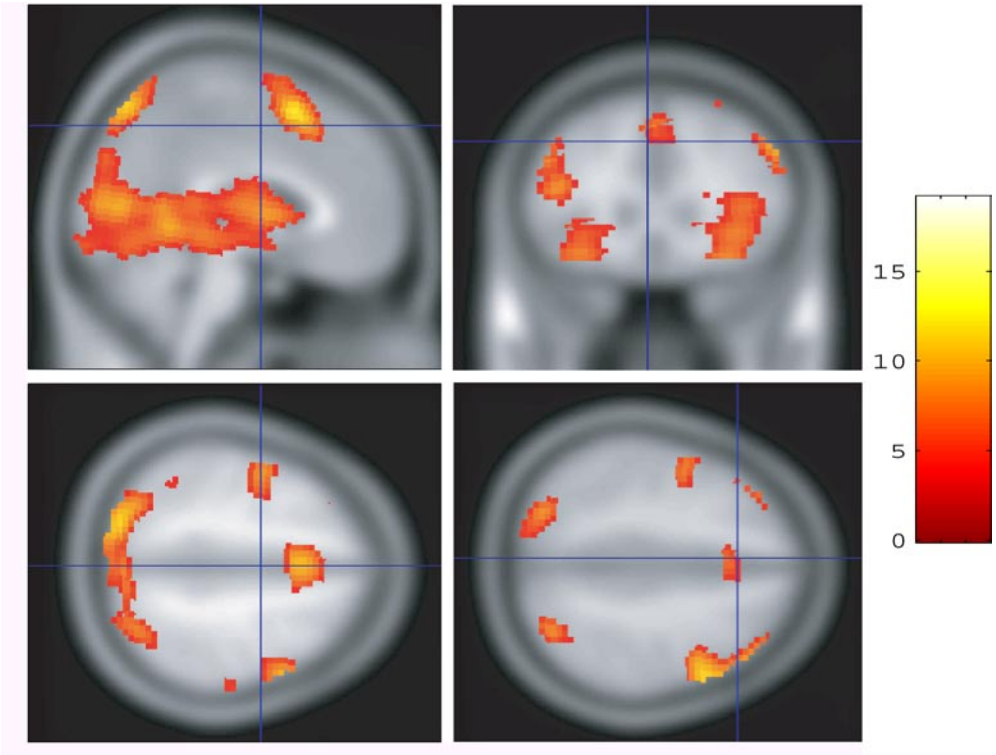

Figure 2. Group level comparisons testing condition test-control during the control group's SPE trial (left=right). The numbers in the key represent t-score values.

Since the final t-scores are derived from a compilation of individual activation patterns, these lower t-scores during the SPE trial are most likely due to individual differences in the strategies employed to simulate malingering.

Table 2

Control Group Regions of Significant Activation for Contrast Test-Control

	DR Trial		SPE Trial	
Region of Interest	MNI Coordinates (x,y,z)	t-score	MNI Coordinates (x,y,z)	t-score
R. Middle Frontal Gyrus	44, 29, 32	9.91	47, 26, 32	8.26
L. Middle Frontal Gyrus	-52, 27, 33	11.83	-47, 36, 32	9.04
Dorsal Ant. Cingulate/Supp. Motor Area	1, 12, 56	13.57	1, 12, 56	12.63
Right Anterior Insula	38, 15, 1	8.20	51, 5, -7	11.82
Left Anterior Insula	-49, 15, -2	9.49	-43, 13, -1	9.01
R. Superior Parietal Area	27, -73, 46	12.58	21, -82, 51	11.51
L. Superior Parietal Area	-34, -67, 49	10.84	-31, -69, 52	7.49
R. Occipital Area	27, -96, -17	12.20	27, -96, -17	19.08
L. Occipital Area	-31, -96, -17	14.20	-34, -96, -14	18.55

Note. Data displayed at a critical value of $p<0.001$, FWE corrected.

TBI Group

Behavioral Performance Data. None of the individuals comprising the TBI group scored 100% on the IR phase of the WMT, and only one individual scored 100% on the DR phase (see Table 1). Individual scores on the IR phase ranged from 57.5% to 97.5%, while individual scores on the DR phase ranged from 47.5% to 100%. SPE scores were also more varied in the TBI group, with a range from 20% to 75% correct.

All TBI subjects reported difficulty in completing the test, and all but one of the TBI subjects expressed a lack of confidence in their memory at some time during the test. Independent groups t-tests showed no significant differences between control and TBI groups on the IR, DR, or SPE trials (IR trial $t = 1.406$, DR trial $t = 1.241$, SPE trial $t=.533$).

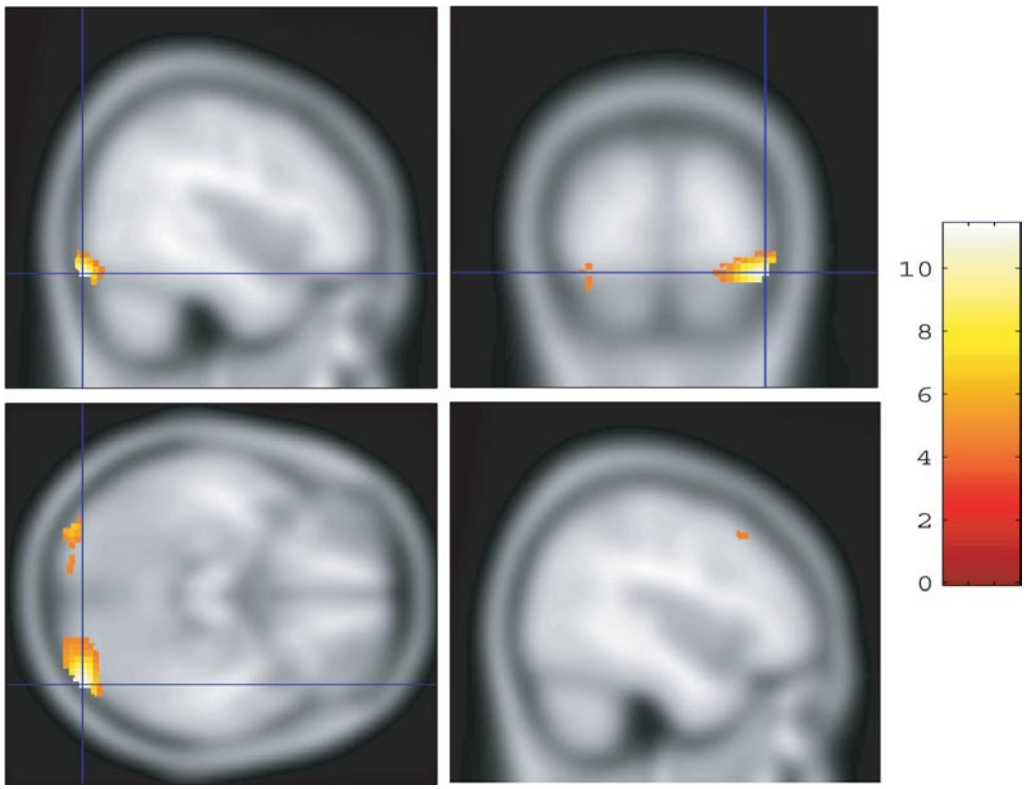

Figure 3. Group level comparisons testing condition test-control during the TBI group's DR trial (left = right). The numbers in the key represent t-score values.

fMRI Data. The observed pattern of activation in the TBI group during the DR portion of the WMT showed the strongest peak of activation in the left occipital area, with other suprathreshold foci at the right middle frontal gyrus and left occipital area (see Figure 3).

The observed pattern of activation in the TBI group during the SPE trial of the WMT was similar to the activation patterns observed during the DR portion, but with larger suprathreshold activation t-scores in occipital areas and lower suprathreshold activation t-scores in the Right middle frontal gyrus (see Table 3). The strongest peak of

activation was found in the left occipital area, with other suprathreshold foci at the right middle frontal gyrus and the left occipital area (see Figure 4).

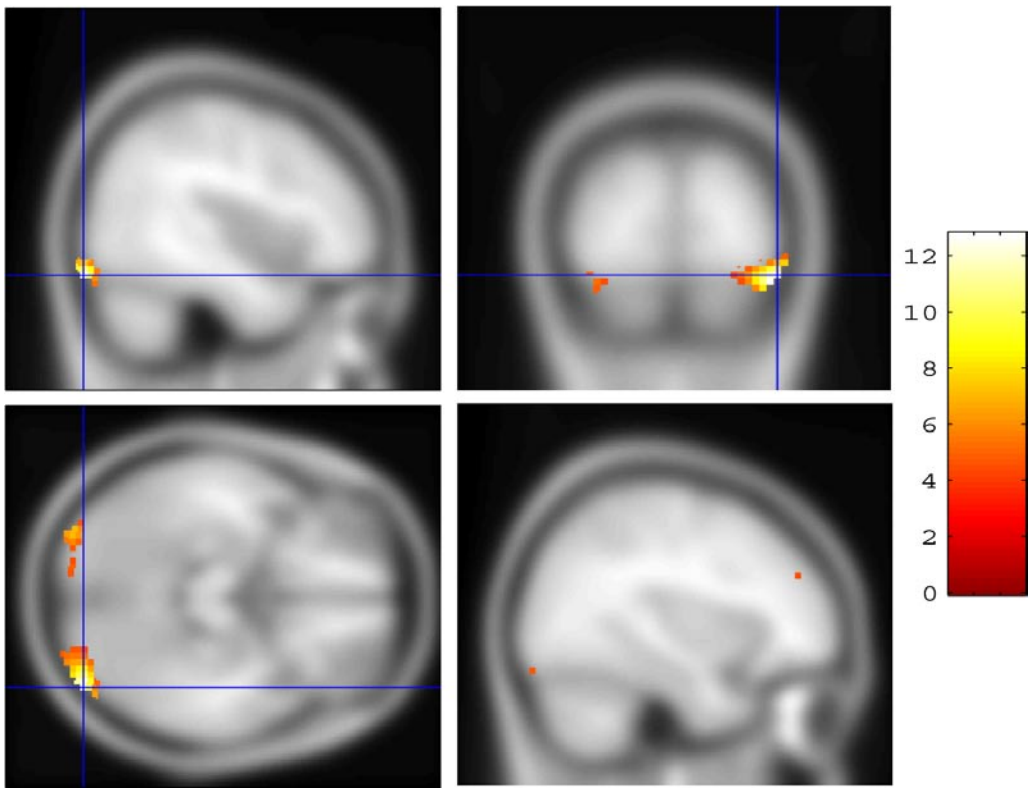

Figure 4. Group level comparisons testing condition test-control during the TBI group's SPE trial (left = right). The numbers in the key represent t-score values.

Table 3

TBI Group Regions of Significant Activation for Contrast Test-Control

	DR Trial		SPE Trial	
Region of Interest	MNI Coordinates (x,y,z)	t-score	MNI Coordinates (x,y,z)	t-score
R. Middle Frontal Gyrus	42, 19, 50	4.48	34, 43, 27	4.46
R. Occipital Area	29, -93, -20	7.03	29, -93, -20	9.14
L. Occipital Area	-43, -88, -18	11.37	-43, -88, -17	12.76

Note. Data displayed at a critical value of $p<0.001$, FWE corrected.

Lowering the critical threshold of activation to p <.05, FWE corrected, in the TBI group showed suprathreshold foci of activation in areas similar to those seen in the control group, including left and right occipital areas, anterior cingulate/supplementary motor area, left and right middle frontal gyri, and left superior parietal areas during DR and SPE trials. However, activation in these areas was much more diffuse, showing lower overall t-scores (see Figures 5 and 6).

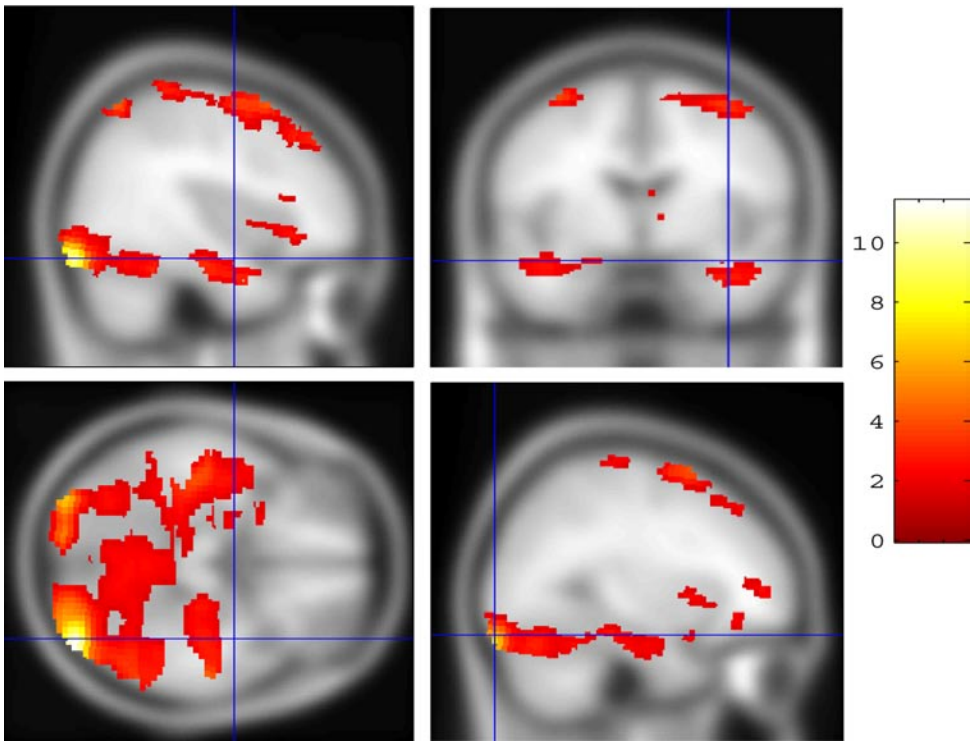

Figure 5. Group level comparisons testing condition test-control during the TBI group's DR trial (left = right) with a critical cutoff value of p <.05, FWE corrected. The numbers in the key represent t-score values.

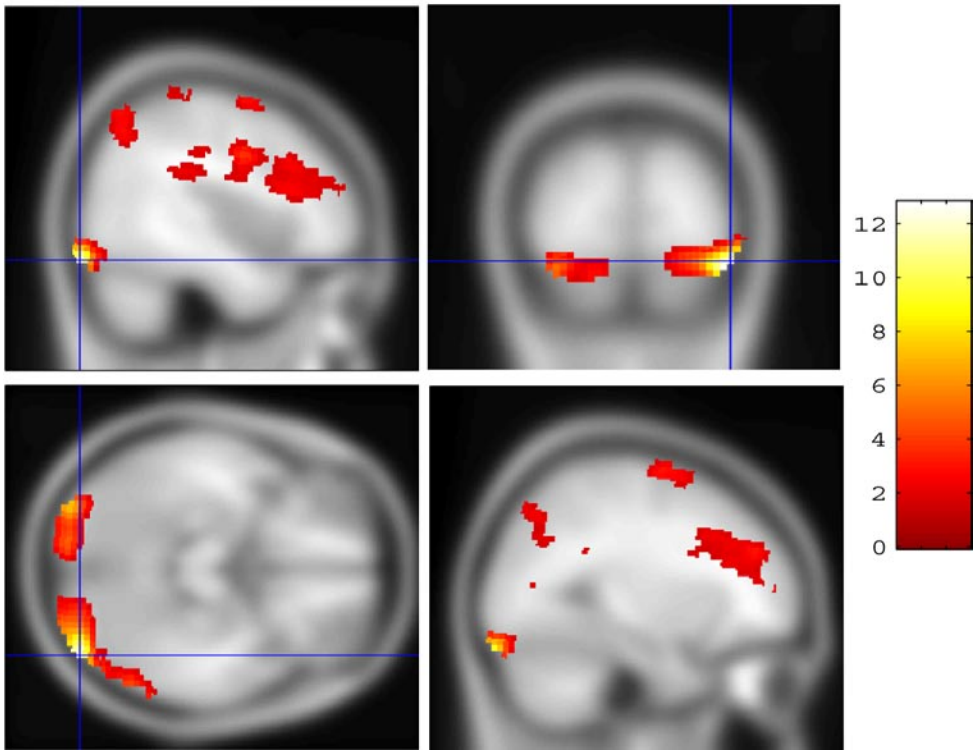

Figure 6. Group level comparisons testing condition test-control during the TBI group's SPE trial (left = right) with a critical cutoff value of $p < .05$. The numbers in the key represent t-score values.

Discussion

The first hypothesis of this study was that both healthy controls and TBI subjects would show strong foci of activation along neural networks that have been shown to be associated with high cognitive effort (Braver et al., 1997; Buckner et al., 1998; Ranganath et al., 2000), and that these foci of activation would see higher levels of activation during malingering trials. The control group showed strong activation along the predicted neural networks during the DR phase of the WMT. During the SPE trial the control group showed strong peaks of activation in the same areas, but the surrounding activation signals were significantly weaker than during the DR trial. The TBI group also

showed less activation along these neural networks during both the DR and SPE trials of the test.

Although these findings do not follow the initial predictions, they do provide interesting insight into the nature of the cognitive processes involved in successful completion of the WMT. The strong pattern of activation found in the control group during the DR portion of the test supports the conclusion of Allen et al. (2007) that the WMT is a cognitively demanding task that employs a wide network of neural systems.

Because the group level analyses were averages of multiple participants, the weaker foci of activation found in the control group during the SPE trial of the test and in the TBI group during both phases are more likely due to a higher level of individual variability than to a lower level of cognitive demand. This claim is supported by the more varied scores observed during the SPE trials. The observation of more diffuse activation in the TBI group is also consistent with the findings of McAllister, Flashman, McDonald, & Saykin (2006) The fact that score variability increased during SPE trials suggests that each participant had a different idea of what constituted partial effort, and thus each individual employed a different strategy or set of strategies in order to simulate poor effort.

These results suggest two possible explanations. First, that individual strategies are more diverse in individuals who are malingering than those who are putting forth full effort on the WMT, and that brain-injured individuals use a wider variety of strategies while completing the WMT than healthy controls, regardless of the amount of effort that they are putting forth. Second, that variability in patient pathology is responsible for the observed variation in fMRI activation patterns during participation in the WMT.

It was originally hypothesized that SPE activation would be stronger and more concentrated than DR activation due to the increased cognitive effort involved in suppressing a correct answer and choosing an incorrect answer, especially in the dorsal anterior cingulate due to its known role in performance/error monitoring. However, the less concentrated activation that was observed may be due to the reduced cognitive effort involved in taking the DR phase of the test for the second time. This would signify that the reduced cognitive demand from taking the test twice is greater than the increased cognitive demand involved in the simulation of malingering.

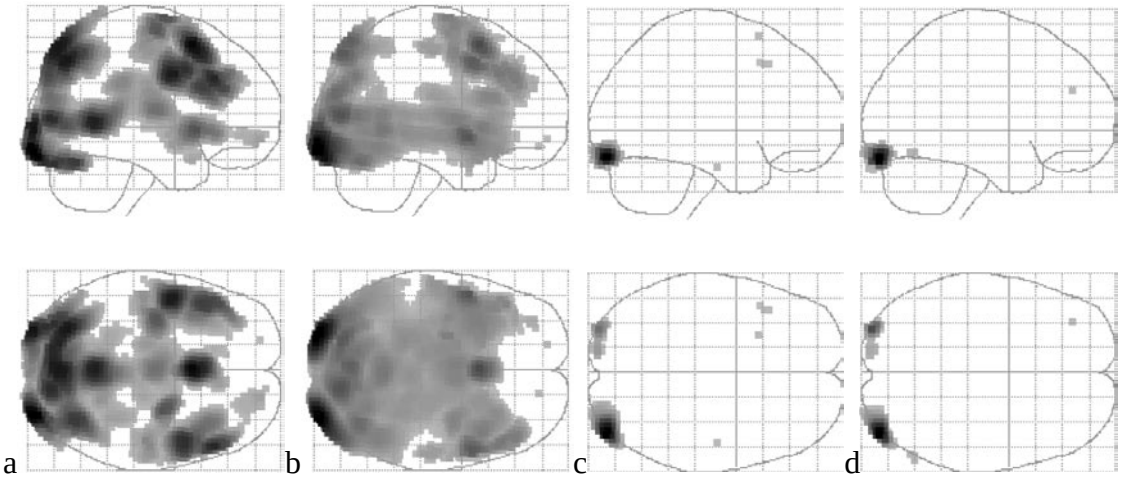

Figure 7. fMRI activation results for (a) control group DR trial, (b) control group SPE trial, (c) TBI group DR trial, and (d) TBI group SPE trial. Axial images correspond to the sagittal images above them.

fMRI results also show greater between-group differences than between-condition differences (see Figure 7). The WMT is designed to distinguish between good and poor effort while remaining insensitive to any neurological or psychological conditions, including TBI (Flaro et al., 2007; Green, 2003). The success of the test rests on its ability

to identify the amount of effort being put forth regardless of participant pathology. These results show that the WMT was more sensitive to TBI than it was to the amount of effort being put forth by participants, and raises questions as to how well the test can distinguish between the two. If the WMT identifies cognitive deficits due to TBI as poor effort, the chances are high that TBI patients who put forth a full effort on the test will be incorrectly identified as malingerers.

The second hypothesis of this study was that TBI subjects would score significantly lower than control subjects on the DR trial of the WMT. Although t-test results showed no significant differences between groups on either the IR or DR portion of the test, the lack of significance is most likely due to the small sample size in the TBI group. Even though no significant differences were found, it is interesting to note that while only one subject in the control group scored below 100% on both the IR and DR portions of the test, no member of the TBI group scored 100% on the IR trial, and only one scored 100% on the DR trial. One subject in the TBI group scored 57.5% on the IR trial and 47.5% on the DR trial, both well below WMT cutoff scores (Green, 2003). The same individual scored 75% during the SPE trial, suggesting that performance during the IR and DR trials was genuine, and that an attempt to chose incorrect answers during the SPE trial resulted in a higher score.

The third hypothesis of this study was that the observed patterns of activation in the TBI group during the DR trial would match those of the control group during the DR trial. The purpose of this prediction was to show that the TBI group was putting forth a full effort on the WMT even when their scores were low. Rather than observing matching patterns of activation between the TBI and control groups, results showed that TBI

subjects employed a wider variety of neural networks while participating in the WMT. Even though sample size in the TBI group was very low, Allen et al. (2007) showed a very consistent pattern of activation during the DR trial of the WMT with only 4 control subjects. As stated above, this discrepancy between groups suggests that at some level the WMT may be sensitive to TBI, and that some aspect of the WMT may be measuring memory performance rather than effort.

These results bring into question the claim that almost all individuals, including brain-injured individuals, should be able to perform well on the WMT (Flaro et al., 2007; Richman et al., 2006). As stated in the beginning of this study, the memory impairments that commonly accompany TBI should cast doubt on the ability of a brain-injured population to perform well on a word memory task. The fMRI evidence presented here support the claim that the WMT is sensitive to TBI, and that effort is not the only predictor that can affect an individual's performance. The WMT scoring data presented in this study also leave room for investigation into the claim that brain-injured individuals will score significantly lower than healthy controls on the WMT.

The evidence presented in this study demonstrates that there is more involved in successful performance on the WMT than effort. The complexity and severity of the memory problems encountered by brain-injured individuals make it difficult for the WMT to remain insensitive to neurological impairment. When assessing effort, clinicians should be aware of the difficulty involved in identifying malingering, and would be wise to employ a wide variety of assessment methods and all available patient information rather than relying on the results from a single test.

While this study provided insights into the neural networks involved in successful completion of the WMT, more research is necessary in this area. Continued research in this area is needed which employs larger sample sizes for both the control and TBI groups. More attention could also be paid to WMT scores, and the remaining WMT post-tests could be included in the research protocol. Research studies in the future could also be expanded to include individuals with severe TBI to see how severe head injuries affect performance on the WMT.

References

Allen, M. D., Bigler, E. D., Larsen, J., Goodrich-Hunsaker, N. J., & Hopkins, R. O. (2007). Functional neuroimaging evidence for high cognitive effort on the Word Memory Test in the absence of external incentives. *Brain Injury, 21*(13), 1425-1428.

Anderson, J. M. (2008). Malingering: A Constant Challenge in Disability Arenas. *Journal of Controversial Medical Claims, 15*(2), 1-9.

Axelrod, B. N., Fichtenberg, N. L., Liethen, P. C., Czarnota, M. A., & Stucky, K. (2001). Performance characteristics of postacute traumatic brain injury patients on the WAIS-III and WMS-III. *Clinical Neuropsychologist, 15*(4), 516-520.

Braver, T. S., Cohen, J. D., Nystrom, L. E., Jonides, J., Smith, E. E., & Noll, D. C. (1997). A parametric study of prefrontal cortex involvement in human working memory. *Neuroimage, 5*(1), 49-62.

Bublak, P., Schubert, T., Matthes-von Cramon, G., & von Cramon, Y. (2000). Differential demands on working memory for guiding a simple action sequence: evidence from closed-head-injured subjects. *Journal of Clinical and Experimental Neuropsychology, 22*(2), 176-190.

Buckner, R. L., Koutstaal, W., Schacter, D. L., Wagner, A. D., & Rosen, B. R. (1998). Functional-anatomic study of episodic retrieval using fMRI. I. Retrieval effort versus retrieval success. *Neuroimage, 7*(3), 151-162.

Carlesimo, G. A., Sabbadini, M., Bombardi, P., Di Porto, E., Loasses, A., & Caltagirone, C. (1998). Retrograde memory deficits in severe closed-head injury patients. *Cortex, 34*(1), 1-23.

Christodoulou, C., DeLuca, J., Ricker, J. H., Madigan, N. K., Bly, B. M., Lange, G., et al. (2001). Functional magnetic resonance imaging of working memory impairment after traumatic brain injury. *Journal of Neurology, Neurosurgery, and Psychiatry, 71*(2), 161-168.

Cremona-Meteyard, S. L., Clark, C. R., Wright, M. J., & Geffen, G. M. (1992). Covert orientation of visual attention after closed head injury. *Neuropsychologia, 30*(2), 123-132.

Demery, J. A., Pedraza, O., & Hanlon, R. E. (2002). Differential profiles of verbal learning in traumatic brain injury. *Journal of Clinical and Experimental Neuropsychology, 24*(6), 818-827.

Donders, J., & Boonstra, T. (2007). Correlates of invalid neuropsychological test performance after traumatic brain injury. *Brain Injury, 21*(3), 319-326.

Flaro, L., Green, P., & Robertson, E. (2007). Word Memory Test failure 23 times higher in mild brain injury than in parents seeking custody: the power of external incentives. *Brain Injury, 21*(4), 373-383.

Green, P. (2003). *Word Memory Test for Windows: User's manual and program.* Edmonton: Green's Publishing.

Green, P., & Flaro, L. (2003). Word memory test performance in children. *Child Neuropsychology, 9*(3), 189-207.

Green, P., Iverson, G. L., & Allen, L. (1999). Detecting malingering in head injury litigation with the Word Memory Test. *Brain Injury, 13*(10), 813-819.

Green, P., Rohling, M. L., Lees-Haley, P. R., & Allen, L. M., III. (2001). Effort has a greater effect on test scores than severe brain injury in compensation claimants. *Brain Injury, 15*(12), 1045-1060.

Groot, Y. C., Wilson, B. A., Evans, J., & Watson, P. (2002). Prospective memory functioning in people with and without brain injury. *Journal of the International Neuropsychological Society, 8*(5), 645-654.

Hall, H. V., Thompson, J. S., & Pairier, J. G. (2007). Detecting Deception in Neuropsychological Cases. *The Forensic Examiner, 16*(3), 7-14.

Larrabee, G. J. (1990). Cautions in the use of neuropsychological evaluation in legal settings. *Neuropsychology, 4*(4), 239-247.

Leclercq, M., Couillet, J., Azouvi, P., Marlier, N., Martin, Y., Strypstein, E., et al. (2000). Dual task performance after severe diffuse traumatic brain injury or vascular prefrontal damage. *Journal of Clinical and Experimental Neuropsychology, 22*(3), 339-350.

Mangels, J. A., Craik, F. I., Levine, B., Schwartz, M. L., & Stuss, D. T. (2002). Effects of divided attention on episodic memory in chronic traumatic brain injury: a function of severity and strategy. *Neuropsychologia, 40*(13), 2369-2385.

McAllister, T., Flashman, L., McDonald, B., & Saykin, A. (2006). Mechanisms of working memory dysfunction after mild and moderate TBI: evidence from functional MRI and neurogenetics. *Journal of Neurotrauma, 23*(10), 1450-1467.

Merten, T., Bossink, L., & Schmand, B. (2007). On the limits of effort testing: symptom validity tests and severity of neurocognitive symptoms in nonlitigant patients. *Journal of Clinical and Experimental Neuropsychology, 29*(3), 308-318.

Penny, W., Holmes, A., & Friston, K. (2003). Hierarchical Models. In R. Frackowiak, K. Friston, C. Frith, R. Dolan, K. Friston, C. Price, S. Zeki, J. Ashburner & W. Penny (Eds.), *Human Brain Function, 2nd ed.* (pp. 851-866). San Diego, CA: Academic Press.

Ranganath, C., Johnson, M. K., & D'Esposito, M. (2000). Left anterior prefrontal activation increases with demands to recall specific perceptual information. *Journal of Neuroscience, 20*(22), RC108.

Richman, J., Green, P., Gervais, R., Flaro, L., Merten, T., Brockhaus, R., et al. (2006). Objective tests of symptom exaggeration in independent medical examinations. *Journal of Occupational and Environmental Medicine, 48*(3), 303-311.

Sarter, M., Gehring, W. J., & Kozak, R. (2006). More attention must be paid: the neurobiology of attentional effort. *Brain Research Reviews, 51*(2), 145-160.

Schmitter-Edgecombe, M., & Anderson, J. W. (2007). Feeling of Knowing in Episodic Memory Following Moderate to Severe Closed-Head Injury. *Neuropsychology, 21*(2), 224-234.

Schoenbrodt, L., & Coll, L. (2001). *How TBI affects speech and language*. Bethesda, MD: Woodbine House.

Spence, S. A., Hunter, M. D., Farrow, T. F., Green, R. D., Leung, D. H., Hughes, C. J., et al. (2004). A cognitive neurobiological account of deception: evidence from functional neuroimaging. *Philosophical Transactions Of The Royal Society Of London. Series B, Biological Sciences, 359*(1451), 1755-1762.

Vakil, E. (2005). The effect of moderate to severe traumatic brain injury (TBI) on different aspects of memory: a selective review. *Journal of Clinical and Experimental Neuropsychology, 27*(8), 977-1021.

Zec, R. F., Zellers, D., Belman, J., Miller, J., Matthews, J., Femeau-Belman, D., et al. (2001). Long-term consequences of severe closed head injury on episodic memory. *Journal of Clinical and Experimental Neuropsychology, 23*(5), 671-691.

Appendix

Complete Instructions Given to the Control Group Before the Beginning of the SPE Trial

You are now going to repeat the exact same test that you just took. This time I would like you to imagine that you have been involved in a car accident, and that the insurance company has told you that you will be rewarded a large amount of money if this test shows that you have memory problems because of the accident. You will not want to do so poorly that it is obvious that you are faking, but you will want to do poorly enough that someone might believe that you have memory problems. Also, it is important to remember that you should not do poorly by slowing down, since response times are not recorded. You should simply do poorly by occasionally picking an incorrect answer.

Footnotes

1. To avoid copyright infringement, the example WMT word pairs presented in this paper are conceptually similar to, but not the same as, the actual words appearing in the test.