Working memory impairments in traumatic brain injury: evidence from a dual-task paradigm

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Abstract—Although many individuals with traumatic brain injury (TBI) perform well on standard neuropsychological tests, they often exhibit marked functional difficulties. The functions which are impaired seem to be analogous to the role of the central executive system (CES) in Baddeley’s [Working Memory, 1986. Oxford University Press, New York] widely accepted model of working memory. The purpose of this study was to investigate CES function in individuals with TBI with a dual-task paradigm. We studied 25 non-demented persons who were at various stages in their recovery from severe TBI and compared their performance on a dual-task paradigm to a group of age-matched controls. Our dual-task paradigm measured performance on a simple visual reaction time task both alone (baseline) and during concurrent tasks of articulation or digit span. Subjects were also assessed with other neuropsychological tests of executive function. TBI patients had slower reaction times on the primary task when performed alone (P<0.05) and greater decrements in performance during dual-task conditions (P<0.01). They also exhibited significantly greater deficits than control subjects on other measures of executive function. Although correlations between dual-task performance and other executive measures were quite low, principle components analysis suggested that a common factor does exist between these measures. These findings support the conclusion that TBI patients have a working memory impairment that is due to dysfunction of the CES and which may be related to executive function deficits as measured by standard neuropsychological testing. © 1997 Elsevier Science Ltd.

Key Words: executive function; frontal lobes; traumatic brain injury; working memory.

Introduction

Individuals with frontal lobe pathology, such as anterior cerebral artery infarction or traumatic brain injury (TBI), often exhibit marked functional difficulties in performance of complex tasks, even when functioning well in basic cognitive domains such as arousal, language, memory and perception [2–4]. The practical difficulties these people experience in everyday life seem to arise from gross oversights of important information, poor planning and time management, and a lack of judgment and spontaneous organizational skills which have been described as ‘executive functions’ [5]. These cognitive impairments and their functional sequelae have a devastating impact on individuals with frontal lobe lesions and their families, due to the difficulty these persons have

recovering normal function in activities of daily living and their requirement for supervision and cueing. Most often, these cognitive impairments have been defined empirically using performance on neuropsychological tasks, but a theoretical model could suggest which cognitive processes are involved and define ways to measure the deficits, thus offering significant advantages.

Baddeley and Hitch’s working memory model [6–8], may help to explain the functional difficulties experienced by individuals with frontal lobe injury. They define working memory as a process for holding information on-line during the performance of other cognitive functions such as language comprehension or problem-solving. This model has three major components: two slave systems and a central executive system (CES). Separate slave systems are responsible for temporarily storing verbal and non-verbal information, and the CES regulates the distribution of limited attentional resources. The CES, analogous to the Supervisory Attentional System (SAS) [7, 9] also coordinates information processing and controls cognitive functioning when novel tasks are performed or

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when existing habits have to be overridden. Complex tasks tax the CES, which must allocate its attentional capacity such that working memory can hold onto multiple pieces of information at once. Since the CES is thought to have limited capacity, simultaneous performance of two tasks which use the same processing systems places increased demands on this system.

There is extensive evidence from both primate and human studies that working memory is subserved by the dorsolateral prefrontal cortex (PFC). Single-unit recording and lesion studies performed on primates [10–12] have identified the PFC as critical for maintaining representations over time. Many investigations of the anatomy, metabolism and electrophysiology support the role of the PFC in spatial working memory [13–16]. Working memory in neurologically intact human subjects has been investigated using functional neuroimaging studies. A large number of studies show that memory slave systems for verbal and visuospatial information activate the PFC [17–19]. Furthermore, active manipulation of verbal and non-verbal information held in working memory during a dual-task paradigm, a function of the CES, has also been shown to activate the PFC [20].

Evidence that the CES specifically is impaired after frontal damage is indirect since there has been only a single study of dual-task paradigms in such patients with focal frontal lesions. However, studies using other paradigms are suggestive of such an impairment. In one study, Shallice used the Tower of London task thought to tap SAS function [21]. Other executive problems found after frontal damage may be explained by a CES deficit. For example, CES impairment would not be evident during performance of well-learned or automatic tasks, but would make switching to a different set of responses difficult which could result in ‘stuck-in-set’ type of perseverations [22]. Several studies show that patients with frontal lesions do exhibit this behavior [2, 23, 24]. With complex or novel tasks, performance is more dependent on the overextended CES since associations between stimulus and response are weak and uncertain. This absence of strong associations and memory for ultimate task goals increases susceptibility to capture errors and inappropriate control of behavior by irrelevant aspects of the environment or tasks which elicit stronger, more automatic responses. Similarly, impaired concentration on tasks [25–28] and utilization behavior [29, 30] found in these patients may reflect this CES impairment. In this study, we use a dual-task paradigm to directly test the hypothesis that the CES is impaired after frontal damage.

As we have reviewed, performance on many apparently different tasks is reported to be impaired in individuals with frontal pathology (see Table 1). There are two approaches to accounting for the varied manifestations of frontal dysfunction: differentiated versus unified accounts. The differentiated accounts theorize the existence of many different subfunctions of the PFC which affect performance on many different tasks. This approach, therefore, defines the cognitive impairments with reference to performance on specific neuropsychological tests and has used extensive testing of patients with frontal lobe damage to identify numerous behavioral functions of the frontal cortex. Use of this approach has also been successful in identifying and localizing many functional domains of the frontal lobe. There is now some evidence of anatomic specificity within the prefrontal cortex and this predicts dissociability of different executive deficits in patients [31].

Unified theories of executive function, on the other hand, propose that the heterogeneous tasks all require use of a similar process subserved by the PFC. Thus, a single impairment can cause performance problems on disparate tasks, not by affecting the individual cognitive operations, but by controlling their integration. For example, Kimberg and Farah [32] offered some confirmation that a unified theory may be applicable to patients with prefrontal damage; a single disruption in their computational model led to impairments on a variety of apparently different tasks analogous to the impairments seen in patients with frontal lobe injury. Baddeley, as well as other researchers [33, 9] have also developed a unified account for prefrontal function by proposing an executive or controller which spans various cognitive domains and asserts a controlling influence over many cognitive networks. Impairment of this executive could, therefore, explain the failure in completion of complex tasks with success at the individual task components that is typically seen in patients with frontal damage. This account requires that either no dissociability of the disparate performance deficits be found or that dissociations be attributed to varying damage to the different modules being supervised.

One population of patients with frontal lobe damage is those individuals with TBI. TBI frequently causes local contusions and other lesions of prefrontal cortical areas [34, 35]. The diffuse axonal injury seen in this patient population disrupts dopaminergic inputs to the PFC [36]. It also disrupts neural connections between PFC and
other areas of the brain such as the posterior parietal cortex and subcortical regions which are activated during working memory tasks. Importantly, these individuals frequently also have executive function deficits. We chose, therefore, to use subjects with TBI to study the effects of frontal lobe injury on working memory and its relationship to performance on other measures of executive function.

In the present study, we used Baddeley’s model of working memory as a framework to explore the nature of the executive function deficits in individuals with TBI. This study examined the cognitive performance of individuals who have had TBI on tests of the two slave systems, a direct measure of CES, and other commonly used clinical measures of executive function. Our hypothesis was two-fold. First, we expected that TBI would result in working memory deficits secondary to an underlying CES impairment. Secondly, we hypothesized that the CES impairment might account for their executive function deficits. Performance on tests of CES capacity would therefore be related to performance on more standard clinical measures of executive function.

Methods

Subjects

Two groups of subjects were tested in this study: patients with TBI and controls. TBI was defined as concussion with loss of consciousness (Glasgow Coma Scale <8) for more than 6 hours. All patients went through a medical hospitalization and inpatient rehabilitation. Testing was performed at least 6 weeks post-injury, and as long as 10 years. Only right-handed subjects with at least a high school education and English as a primary language were included. Subjects were excluded for penetrating head injury, dementia (Mini-Mental Status Exam score <26), oculomotor, uncorrected acuity or visual field deficits as noted on medical records or by brief bedside exam, or a major mental illness. Subjects were also excluded for uncontrolled high blood pressure, pregnancy, and current use of centrally acting medications since these patients were chosen for later involvement in a drug study. Control subjects were age-matched to the brain injury patients with the same exclusion criteria as were used for patients with the additional requirement that they had never suffered loss of consciousness from a traumatic brain injury.

Subjects with TBI were referred primarily from inpatient and outpatient rehabilitation programs at a rehabilitation hospital with a specialized TBI program. Since the patients in this study were drawn from a referral hospital, we did not have access to the acute CT or MRI scans. However, we did have radiology reports for 22 of our 25 TBI patients for scans performed from 1 day to 8 months post-injury. In these reports, frontal injury was noted in 18/22 subjects (6 left hemisphere injury, 5 right, 6 bilateral, 1 unknown). Two patients for which we did not have reports suffered facial fractures, one including a orbital fracture and the other requiring jaw reconstruction, suggesting frontal lobe injury may have occurred. Subjects were paid $10 per hour for their participation in the study. Not all subjects completed all tests, due to time constraints and the desire of one patient to discontinue the testing for social reasons. In addition, one of the TBI subjects was unable to perform the dual task with digit span at all.

Experimental design and tasks

Each subject was given seven neuropsychological tests in each of two sessions. The first session was used only to familiarize the subject with the tasks and the data were discarded. This was done to make sure that the subject understood the tasks and to reduce the effects of practice during the actual testing session. Experimental sessions were brief (<60 min) in order to reduce mental and physical fatigue. Below are the actual test measures that were used. Subjects completed the tests in the order described.

Measures

Neuropsychological testing, except for the Trail-making test and FAS test, was performed on an Apple Macintosh Powerbook, using an active matrix color monitor set to 256 colors. The software for these tasks was custom written for this experiment using Think C 5.0.4. Measures were chosen to directly test verbal (digit span) and visuospatial (spatial delayed response task) slave systems of working memory and the CES (dual-task paradigm). In addition, four more commonly used measures of executive function were chosen (Stroop Interference Test, Trail-making Test, Wisconsin Card Sort Test, and Controlled Oral Word Association Test). Each of these is described in detail below.

Dual-task Paradigm

We chose simple reaction time to a visual target as our primary task. While simple reaction time is a relatively undemanding task, there is evidence that it reflects the attentional capacity available to a subject [37], hence allowing the concurrent measurement of performance on more than one task. Subjects were told that a dot would appear on the computer screen at random intervals, at random positions on the screen. They were instructed to simply press the spacebar with a finger of their dominant hand as soon as possible after each dot appeared. Each of sixty-four trials represented the visual target appearance following one of four possible interval delays after subject response, each used 25% of the time: 0.5 sec, 1.0 sec, 1.5 sec, and 2.0 sec. The target was a sharply demarcated black dot which appeared in one of sixteen dot positions in random order, with location counterbalanced. The dot remained on the screen until the subject responded. Performance was measured as the mean reaction time across trials.

The reaction time task was performed three times. The first task performance was alone and was considered a baseline condition. For the second administration, the task was performed simultaneously with the subject counting aloud from one to ten repeatedly, at a rate of the subjects’ own choice. This was selected to make minimal extra demands on the CES. However, although the infor-
ination load is minimal, combining it with reaction time requires concurrent performance of two activities.

During the third administration, subjects simultaneously performed the reaction time task and an oral digit span task. The difficulty of this task was calibrated across subjects by performing the test using the subject’s own digit span, determined to be the largest digit span which the subject was able to perform correctly three times consecutively, without failing three times consecutively. This task was expected to place much greater demands on the CES. For each administration, it was stressed to the subjects that they should try to perform the primary reaction time task as quickly as possible.

Digit span task

In this task, subjects were asked to immediately repeat back random sequences of numbers of different spans. The test began with two-digit numbers and progressed one digit at a time. Subjects were advanced by one digit after three consecutively correct responses. The test was stopped after three consecutive incorrect responses, and the subject’s digit span was then specified as the previous level.

Stroop Color Interference Test

Two conditions of the Stroop task [38] were used: the color-naming control condition, in which subjects had to name the colors of rectangles, and the conflict condition, in which subjects had to name the ‘ink colors’ in which different color names were printed. The color names and the ink colors were always in conflict. The Stroop stimuli were presented in five columns of sixteen against a black background, using the default Macintosh red, blue, green, and yellow colors. Subjects were asked to go as quickly as possible without making errors. The examiner timed the subjects, using a programmed timer in the computer which was activated with display of the task and stopped by pressing a computer key. Performance was defined as the time required for each subject to complete each form of the Stroop test. The numbers of errors was also recorded for each subject.

Trail-making test

The Trail-making Test [39] consists of two parts. In the first part, (Trails A), a subject is timed while drawing a line joining consecutively numbered circles randomly arranged on a page. In the second section of the test, (Trails B), the subject is timed again while connecting letters and numbers in an alternating sequential manner (1-a-2-b...13). The rapid alternation between numbers and letters creates some interference which tests executive function. This was scored using Reitan’s method [40] which is the most commonly used method today. In this method the examiner points out errors as they occur so that the patient can always complete the test. In this method, scoring is based on time alone. This method penalizes for errors indirectly through increased time requirement, and any bias based on speed of the examiner in pointing out errors or speed of the patient in comprehending and correcting these errors is eliminated by having all subjects tested by the same examiner and using the difference score for this study.

Controlled Oral Word Association

In this test of verbal associative fluency, [41, 42], the examiner asks subjects to say as many words as they can think of, excluding proper nouns, that begin with a given letter of the alphabet. The score is the sum of all acceptable words produced in three one-minute trials, using the letters F, A, and S.

Spatial Delayed-response Task (Visual Slave System Test)

Subjects were administered a dot location task similar to that developed by Funahashi, Bruce, and Goldman-Rakic [10], in which the subject must recall the location of a black dot stimulus after a brief delay. The subject was seated in front of a computer monitor and asked to observe a central fixation point. The visual stimulus appeared for 0.2 sec in the periphery at any location on the screen within 10 deg of the fixation point (to avoid the subject’s blind spot) excluding locations of 0, 90, 180, and 270 deg (to avoid referencing to the exact vertical and horizontal). After the stimulus, the screen was blank for 8 sec and then an auditory tone signaled the subject to touch a point on the screen where the stimulus appeared and this location was marked by movement of the cursor. This was repeated 40 times. Performance was defined as the mean distance between the stimulus and the response over all the trials.

Card Sorting Test

This was an adapted version of the Wisconsin Card Sorting Test [2, 23] presented on the computer. Subjects were asked to place cards from a stack onto one of four reference cards. The computer screen showed them their card below the reference card, with the word ‘right’ or ‘wrong’ as feedback. Subjects were told the computer would be checking to see if their card belonged with the reference card they chose. Subjects continued until they had either achieved six categories or placed 48 cards. The sequence of categories was always the same: color, then shape, then number. The category was shifted after six correct consecutive trials. The cards used were only those
24 (repeated continuously) that shared no more than one attribute with any given card, following Nelson's variation, so that each card placement could be interpreted unambiguously. Performance measures were the number of categories achieved, the number of cards placed correctly, the number of cards placed incorrectly, and the number of perseverations (cards placed in the same wrong category as an immediately preceding incorrect response).

Data analysis

Demographic comparisons between patients and controls were made with the Chi Square statistic for gender and the Mann–Whitney U statistic for age and education. Overall comparisons of patients and controls were done with a repeated measure ANOVA for dual-task performance and a MANOVA for executive test performance. Both statistical tests were performed with ranked data since raw data violated the assumptions of univariate and multivariate homogeneity of variance [43, 44]. We used the Mann–Whitney U statistic for post-hoc testing of individual performance differences between TBI patients and age-matched control subjects, because the data were not normally distributed. Spearman correlations were performed to assess the relationships between continuous variables.

Performance

Experimental data were obtained to test working memory function using oral digit span and a delayed spatial response task to evaluate the working memory slave systems and the dual-task paradigm to measure CES function. More standard clinical measures of executive function used were the Stroop Color Interference Test, the Trail-making Test, the Wisconsin Card Sorting Test, and the Controlled Oral Word Association Test.

Several measures had more than one condition (Dual-task, Stroop, Trail-making). Performance on these tasks was therefore characterized with respect to two broad dimensions: baseline task performance and decrement on a second condition compared to baseline. Performance on each of these tasks was measured by response time; therefore performance decrement was calculated as the difference between speeds on the secondary and the corresponding baseline tasks. Finally an exploratory principal components analysis was performed to assess possible relationships between CES capacity, as measured by performance decrements as above on the dual-task paradigm, and the more standard tests of executive function.

Calculation of Performance decrement

Patients and controls had significantly different speeds for baseline tasks in the Trail-making Test, Stroop Test, and Dual-task Paradigm. Therefore, in order to compare performance decrements, it was important to know whether performance decrement was related to baseline speed in normal subjects. In order to evaluate this issue, we examined correlations between the baseline and the decrement among the control subjects in each of these tests. The decrement scores during secondary task performance were not significantly correlated with baseline speed (Spearman Correlation rho's -0.022 to -0.352, P's 921 to 086). The only relationship that approached significance was dual-task counting performance. In this task, however, the correlation was in the opposite direction from that predicted if slower motor and cognitive processing in simpler tasks leads to greater slowing in more difficult tasks; here, slower reaction time was associated with reduced decrements. Based on these results, a simple difference score was selected as an appropriate measure of performance decrement.

Results

Subject demographics

Gender distribution was comparable in patient and control groups (see Table 2) [Pearson Chi Square (1, N = 50) = 1.049, P = 0.306]. The two groups did not differ significantly with respect to age [Mann–Whitney U (25,25) = 325.5, P = 0.801]. However, since the groups were not perfectly balanced and the sample size was small, the effects of age and gender on performance were assessed. Neither gender nor age had any significant relationship to performance measures in controls. Age and gender, then, are unlikely sources of bias.

Unfortunately, our group of TBI patients and controls were not well matched for education level [medians of 14 vs. 16 years: Mann–Whitney U (25,25) = 465, P = 0.003]. However, individual Spearman Correlation tests revealed no significant correlation between baseline performance

<table>
<thead>
<tr>
<th>Table 2. Subject demographics</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBI subjects</td>
</tr>
<tr>
<td>Gender</td>
</tr>
<tr>
<td>Age median; range</td>
</tr>
<tr>
<td>Education median; range</td>
</tr>
</tbody>
</table>
and education level among controls, and between only one executive function measure (verbal fluency Spearman rho = 0.439, \( P = 0.041 \)). Nevertheless, performance differences found between patients and controls were verified on a subsample which was well-matched for education level (see ‘Education as a confound’ section).

**Group analyses**

**Baseline speed.** Patients and controls had significantly different speeds for baseline tasks in the Stroop Test, Trail-making Test, and Dual-task Paradigm [MANOVA \( F = 24.3 \) (3.43) \( P < 0.001 \)]. Median reaction time for TBI patients was 390 msec compared to 303 msec for controls \( (P < 0.001) \). Similarly, performance on the Stroop Color Control Test and Trail-making A Test was significantly slower in patients than controls (median of 67 sec vs. 45 sec, \( P < 0.001 \) and 48 vs. 25, \( P < 0.001 \)) respectively.

**Dual-task measure.** Both patients and controls showed consistent performance decrements on visual reaction time tasks during dual-task performance (See Table 3) (Wilcoxon signed ranks tests on control subjects: \( Z = 3.73, 4.29; P < 0.001 \), < 0.001 and Wilcoxon signed ranks tests on TBI patients: \( Z = 4.29, 4.20; P < 0.001 \), < 0.001) for dual task with counting and dual task with digit span respectively. Digit span performance was also consistently worse for both subject groups during dual-task performance than when performed alone (Wilcoxon signed rank tests on controls subjects: \( Z = -2.668, P = 0.008 \) and TBI subjects: \( Z = 3.945, P < 0.001 \), demonstrating that subjects did attempt to perform both tasks simultaneously, rather than engaging in a speed-accuracy trade-off.

The impact of TBI on CES function was examined statistically with a repeated-measures ANOVA with simple reaction time, reaction time while counting and reaction time during digit span performance as the within subject factor and TBI patients vs. control subjects as the between subject factor. The effects of subject group \( [F(1,45)] = 30.7, \ P < 0.001 \) and test condition \( [F(2,90)] = 260.1, \ P < 0.001 \) were significant for this comparison with a strong interaction effect \( [F(2,90)] = 6.4, \ P = 0.002 \), demonstrating a larger impairment of dual-task performance in patients (see Fig. 1 A).

**Baseline as a confounding variable**

Although the performance baselines did not correlate with performance decrements in control subjects, the large baseline differences between groups were still a concern as a possible source of confounding for these variables. In order to address this concern, a separate analysis was performed for dual-task performance, by pairing a subsample of TBI patients with control subjects matched to within 6 ms for baseline reaction time performance [MWU (12,12) = 72, \( P = 1.00 \), rather than for age. Paired subject performance was then assessed using the Mann-Whitney-U Test. Evaluation of the dual-task paradigm in this way revealed that reaction time performance decrement while performing dual-tasks remained significantly higher for TBI patients than controls [MWU (12,12) = 33, 24; \( P = 0.024 \), 0.01 for dual task with counting and digit span, respectively], see Fig. 1 (B).

**Education as a confounding variable**

Demographic differences represent another source of potential bias. As discussed earlier, we were unsuccessful

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**Table 3. Effect of TBI on performance of CES tests**

<table>
<thead>
<tr>
<th>Set of subjects</th>
<th>Test</th>
<th>TBI subjects</th>
<th>Control subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( n )</td>
<td>Mean</td>
</tr>
<tr>
<td>All TBI and control subjects</td>
<td>Reaction time alone</td>
<td>24</td>
<td>390</td>
</tr>
<tr>
<td></td>
<td>Reaction time with counting</td>
<td>24</td>
<td>532</td>
</tr>
<tr>
<td></td>
<td>Reaction time with digit span</td>
<td>23</td>
<td>890</td>
</tr>
<tr>
<td></td>
<td>Dual-task reaction time with counting decr.</td>
<td>24</td>
<td>142</td>
</tr>
<tr>
<td></td>
<td>Dual-task reaction time with digit span decr.</td>
<td>23</td>
<td>500</td>
</tr>
<tr>
<td>RT-matched subset of subjects</td>
<td>Reaction time alone</td>
<td>12</td>
<td>318</td>
</tr>
<tr>
<td></td>
<td>Reaction time with counting</td>
<td>12</td>
<td>437</td>
</tr>
<tr>
<td></td>
<td>Reaction time with digit span</td>
<td>12</td>
<td>804</td>
</tr>
<tr>
<td></td>
<td>Dual-task reaction time with counting decr.</td>
<td>12</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>Dual-task reaction time with digit span decr.</td>
<td>12</td>
<td>489</td>
</tr>
</tbody>
</table>
and education level as covariates, and our result did not change (subject group effect \( F(2,42) = 4.567, P = 0.016 \)).

**Working memory slave systems.** Evaluation of the two working memory slave systems with individual Mann–Whitney U comparisons revealed a significant diminishment of immediate spatial memory after TBI (MWU = 216, \( P = 0.013 \)) and a similar trend for verbal memory (MWU = 320.5, \( P = 0.058 \)).

**Executive function measures.** Executive function of the two groups was compared using a MANOVA with each of these measures as dependent variables and subject group as the independent variable. The effect of subject group was significant (\( P < 0.001 \)) for this comparison with an effect size of 0.632. Post-hoc comparisons of individual tests showed that individuals with TBI had impaired executive function as measured by all tests but the Wisconsin Card Sort (see Table 4).

Two of the executive function tests (Stroop Interference and Trail-making Tests) are similar to the dual-task paradigm, in that they consist of a simple task which is primarily dependent on speed and a more complex task which requires executive function. When these are evaluated and displayed in the manner of the dual-task paradigm, the performance profiles are strikingly similar to the dual-task results as shown in Fig. 2 (A) and (B).

**Baseline function as a confounding variable**

Similarly, when new paired data sets were constructed pairing patients and controls for the baselines (Stroop Color Control Times within 3 sec (MWU = 31.5, \( P = 0.958 \)) and Trail-making A Times within 2 sec (MWU = 34, \( P = 0.833 \))) the differences remained significant (MWU = 12 and 6, \( P = 0.036, 0.006, \) respectively). Other individual tests revealed that verbal fluency was also significantly reduced after TBI.

**Education as a confounding variable**

Using the comparable education subset of TBI and control subjects as discussed above and significance between the two groups remained the same for all executive tests in this smaller subset of patients. Verbal fluency, the only executive function test which correlated with education level in our larger subject group, remained significantly worse in patients with TBI than controls. Although education level did not correlate strongly with baseline performance on the Trail-making or Stroop Interference tests (Spearman \( \rho = -0.141 \) and 0.109, \( P = 0.522 \) and 0.612, respectively), we also performed an ANCOVA on the executive measures using both education and the baseline measures as covariates to check for any possible confounding of the results. Once again, the effect of subject group remained highly significant \( F(5, 33) = 4.226, P = 0.004 \).
Table 4. Effect of TBI on performance of clinical executive function tests

<table>
<thead>
<tr>
<th>Test</th>
<th>TBI</th>
<th>Control</th>
<th>MWU</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Mean</td>
<td>n</td>
<td>Mean</td>
</tr>
<tr>
<td>Stroop color control time</td>
<td>25</td>
<td>67</td>
<td>24</td>
<td>45</td>
</tr>
<tr>
<td>Stroop colour interference time</td>
<td>25</td>
<td>106</td>
<td>24</td>
<td>70</td>
</tr>
<tr>
<td>Stroop color interference decre</td>
<td>25</td>
<td>39</td>
<td>24</td>
<td>26</td>
</tr>
<tr>
<td>Trailmaking A Time</td>
<td>25</td>
<td>48</td>
<td>23</td>
<td>25</td>
</tr>
<tr>
<td>Trailmaking B Time</td>
<td>25</td>
<td>113</td>
<td>23</td>
<td>49</td>
</tr>
<tr>
<td>Trailmaking test decrement</td>
<td>20</td>
<td>66</td>
<td>23</td>
<td>23.5</td>
</tr>
<tr>
<td>Wisconsin card sort test categories</td>
<td>20</td>
<td>4.6</td>
<td>23</td>
<td>5</td>
</tr>
<tr>
<td>Wisconsin card sort test perseverations</td>
<td>20</td>
<td>3.12</td>
<td>23</td>
<td>2.1</td>
</tr>
<tr>
<td>FAS test verbal fluency</td>
<td>24</td>
<td>29</td>
<td>22</td>
<td>54</td>
</tr>
</tbody>
</table>

*Items in bold represent executive effects of interest.

Relationship between CES function and other measures of executive function

Since the CES allocates attention between two tasks, performance decrement on the dual-task paradigm should be a measure of this aspect of working memory. A relationship between these decrements and other executive measures would suggest the operation of the central executive in working memory and standard executive function tests. A principal components analysis was performed to investigate a possible overlap between these cognitive functions. The raw TBI data for the seven variables (both dual-task reaction time decrements, the Stroop Interference Decrement, the Trail-making Decrement, the FAS Verbal Fluency Measure, and the two Wisconsin Card Sort Test Measures) were entered into a principal components analysis with Varimax rotation and the component structure for a two factor solution is shown in Table 5 with the individual component loading for each variable included. The tests loading heavily on component one were those which assessed executive function while those loading on component two were those affecting CES capacity. This two component system accounts for 57% of the variance after rotation, and the eigenvalues for the two components were 2.02 and 1.98, respectively. Principal components analysis using other rotations and performed with ranked data yielded almost identical results.

In fact, this relationship between performance on the Stroop Test, Trail-making Test and Dual-task Measures does not occur in our control subjects. In controls, unlike TBI patients, the Stroop Interference and Trail-making tests did not load on the factor with the CES tests (see Table 6), with 61% of the variance explained by these two rotated components. Again, the results did not change when the analysis was performed on ranked data or rotated differently.

Discussion

The results of this study show that the CES component of working memory as measured by dual-task performance, is impaired after TBI. The working memory slave system performance was also worsened, suggesting a more widespread working memory impairment in these subjects. The results also lend support to the hypothesis that the other executive deficits in this patient population may be related to the dysfunction of their CES. Specifically, the performance by individuals with TBI on tests sensitive to CES dysfunction was related to that on some commonly used clinical tests of executive function.

Table 5. Principle components analysis for TBI patients

<table>
<thead>
<tr>
<th>TEST</th>
<th>Raw data</th>
<th>Ranked data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Comp 1</td>
<td>Comp 2</td>
</tr>
<tr>
<td>Wisc. card sort categories</td>
<td>0.902</td>
<td>0.090</td>
</tr>
<tr>
<td>Wisc. card sort perseverations</td>
<td>-0.896</td>
<td>-0.108</td>
</tr>
<tr>
<td>FAS verbal fluency test</td>
<td>0.518</td>
<td>-0.379</td>
</tr>
<tr>
<td>Reaction time + counting deer</td>
<td>0.061</td>
<td>0.736</td>
</tr>
<tr>
<td>Trailmaking decrement</td>
<td>-0.128</td>
<td>0.667</td>
</tr>
<tr>
<td>Reaction time + digit span deer</td>
<td>0.335</td>
<td>0.656</td>
</tr>
<tr>
<td>Stroop color interference deer</td>
<td>-0.057</td>
<td>0.636</td>
</tr>
</tbody>
</table>

Eigenvalues are 2.13, 1.88, 1.29, 0.76, 0.61, 0.19, and 0.14 respectively.
In this study, both individuals with TBI and demographically comparable control subjects exhibited slowed reaction times during dual-task performance which measures CES capacity. The greater performance decrement in TBI patients during dual tasks, however, suggests a CES function impairment related to TBI. This result remained true even when baseline performances were matched, thus eliminating lower arousal level and slower response speed as explanations for this worsened performance profile. Although relatively little work has been done evaluating working memory, and specifically CES capacity, in individuals with TBI, the presence of CES capacity deficits is consistent with a similar study by Hartman, Pickering, and Wilson [45]. Since, in addition, the subjective complaint of inability to do two things at once correlates highly with the inability to return to work [46], dual-task performance may be a very sensitive measure of ‘real-world’ function for this patient population. In fact, since most activities of daily living are performed with other tasks or planning of tasks concurrently, this appears to be a useful direction for further study.

Performance of TBI patients on the more standard clinical executive function tests was also examined in this study. Difficulty with the Trail-making and FAS test after TBI confirmed previous clinical studies [45, 47–51]. A performance decrement on the Stroop Color Interference Test for TBI patients was also found in this study. The evidence in the literature for a stroop effect in TBI patients is mixed. Careful review of these studies reveals many potential causes for these conflicting results including sampling differences: in level of injury severity [52], length of recovery time [52], etiology of injury, location of injury [53], and method of stroop effect measurement. Finally, the lack of impairment on the Wisconsin Card Sorting Test performance appears surprising, since numerous studies have verified poorer performance in patients with focal frontal lobe lesions [2, 54–56, 47, 57]. However, other studies have found that some patients with clear frontal pathology have no difficulty with the test [4, 58]. Still other studies which specifically tested TBI patients have not shown this impairment [59, 60, 61] and even among TBI patients who had anosmia, and

<table>
<thead>
<tr>
<th>TEST</th>
<th>Raw DATA</th>
<th>Ranked DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Comp 1</td>
<td>Comp 2</td>
</tr>
<tr>
<td>Stroop interference test decrec</td>
<td>0.844</td>
<td>-0.094</td>
</tr>
<tr>
<td>Trailmaking test decrecent</td>
<td>0.779</td>
<td>0.137</td>
</tr>
<tr>
<td>Wise. card sort test categories</td>
<td>-0.745</td>
<td>-0.144</td>
</tr>
<tr>
<td>Wise. Card sort test perseverations</td>
<td>0.671</td>
<td>-0.054</td>
</tr>
<tr>
<td>FAS Verbal Fluency Test</td>
<td>-0.424</td>
<td>0.438</td>
</tr>
<tr>
<td>Reaction time + Digit span decrec</td>
<td>0.276</td>
<td>0.886</td>
</tr>
<tr>
<td>Reaction time + counting decrec</td>
<td>-0.036</td>
<td>0.827</td>
</tr>
</tbody>
</table>

Eigenvalues are 2.6, 1.69, 1.01, 0.72, 0.48, 0.34 and 0.14, respectively.
were thus likely to have focal frontal lobe damage, only 8 of 20 individuals had abnormal performance [62]. A further study of TBI patients showed no significant performance difference between individuals with or without frontal lobe brain damage [63].

The principal components analysis revealed some linkage between performance on the dual-task paradigm and two measures of executive function. This result provides some insight for distinguishing between differentiated and unified accounts of prefrontal function. Close examination of the Trail-making Test and the Stroop Interference Test, the tests which shared a common factor with the CES tests reveals some striking similarities among the tests. Both of these tests consist of a baseline level task which measures arousal level, task attention, and processing speed and a more difficult task level which measures functions analogous to those defined as requiring CES function. The Trail-making B Test requires maintenance and manipulation of two sets of data, numbers and letters; effectively functioning as a dual task. The Stroop Color Interference Test, by requiring the subject to suppress a practiced, automatic response pattern and apply a new response pattern, conforms again to Baddeley's definition of the CES as "controlling cognitive function when novel tasks are performed or when existing habits have to be overridden" [1]. TBI subject performance on these tests was strikingly similar to performance on the dual-task paradigm. Interestingly, the relationship between performance on the dual-task paradigm and these two tests occurred only in subjects with TBI.

The previously mentioned study of dual-task performance after TBI also suggested a relationship with executive task function, but for both patients and controls [45]. This study used correlation coefficients, however, and was performed with raw Stroop Conflict and Trail-making B results, rather than the performance decrements for each of these tests. These correlations, therefore, could be explained simply by injury severity producing slower performance. In fact, we did not find significant correlations between performance decrements and dual-task performance (Rho = 0.01–0.39, P = 0.823–0.066), although correlations did increase when run on raw data from the Stroop and Trail-making tests analogous to the method used by Hartman et al. (Rho = 0.562, 0.510, respectively).

The relationship between CES capacity and only two of the executive function measures in our study suggests that the prefrontal cortex supports different types of executive processes, and that CES impairment may only be related to one type. Good performance on the Stroop and Trail-making Tests may require good CES capacity to be able to hold information on-line in order to manipulate or act on it. Since the verbal fluency appears to be a different type of ability, one of generating rather than holding and shifting information, it is not surprising that it is not related to dual-task performance. The lack of relationship with Wisconsin Card Sorting Test is more surprising since this test does, in fact, require the ability to hold information on-line while shifting set. However, our TBI patients did not have any significant impairment in performance of this test. This hypothesis, that some but not all executive functions are related to CES capacity, lends itself to sub specialization of PFC function, a concept that is gaining support from anatomical data [31]. A difficulty with this explanation that tasks with related performance share an executive process is that we would expect to find this relationship in control subjects as well as TBI patients. We did not find the relationship, though, possibly because the performance variance in CES functions among controls was small in contrast to variance in content-specific performance which obscured the relationship.

An alternative explanation of our results is that these tasks that were related indeed tap cognitively distinct operations, but they are all damaged together because they are supported by anatomic structures which lie in close proximity. This explanation would account for finding a relationship in TBI patients but not in control subjects.

In addition, there are two other possible explanations for these findings which are not theoretically driven. One possibility is that the relationship between measures seen is simply related to injury severity in this diffusey injured population, so that individuals with more significant executive function deficits also exhibit more significant CES impairment. However, severity is not sufficient to explain the relationship between dual-task performance and the Stroop and Trails tests, since performance on the FAS test of verbal fluency was more strongly affected by traumatic brain injury [Mann–Whitney U (24,22) = 501.5] than any other test, but was unrelated to performance on dual tasks. These relationships do not necessarily support the idea that different brain regions support different executive functions, since one region with different disruption thresholds for these tasks (verbal fluency being the lowest) could also account for this data.

The other possible confounding factor which may explain our findings is that all three related tasks are time-pressured tasks; since TBI patients are well known to have slower processing speeds, these tests might be related simply because of their slowed processing. Verbal fluency did not appear to be a time-pressured task in our subjects. The clinical intuition from testing our TBI subjects suggested that they generally did not produce words slowly and steadily, but rather that they produced a few words, and then stopped or persevered on words already produced. Statistical tests confirm this notion: (Spearman correlations between fluency and reaction time rho's of 0.07 and -0.286, P = 0.756 and 0.186 for control subjects and TBI patients, respectively). Thus, any intrinsic relationship between working memory and executive functions might be overshadowed by a global slowing in processing. This last explanation could be tested by evaluating the relationship between executive function
tests and a dual-task paradigm which measures performance quality rather than speed.

In conclusion, impairment on the dual-task paradigm after traumatic brain injury reflects a specific cognitive deficit within working memory, an impaired central executive system. This impaired performance was related to difficulties with two of the more standard measures of executive function, Stroop and Trails, after TBI. Although the cause of this relationship is ambiguous from our data, CES dysfunction may account for some of the impaired performance on executive tasks that is commonly found in these patients, through shared cognitive operations or anatomic localization. With either explanation, dual-task performance can be used as a sensitive marker for the higher level cognitive deficits these patients experience. In addition, although these impairments are generally described empirically, working memory theory may provide a framework which would enable us to better define and measure these executive deficits, and may aid in the ability to find and test treatments for the associated disabilities experienced after frontal lobe injury.

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