PERGAMON

Neuropsychologia 40 (2002) 2369–2385

NEUROPSYCHOLOGIA

www.elsevier.com/locate/neuropsychologia

Effects of divided attention on episodic memory in chronic traumatic brain injury: a function of severity and strategy

Jennifer A. Mangels [a,*], Fergus I.M. Craik [b,c], Brian Levine [b,c,e], Michael L. Schwartz [d,f], Donald T. Stuss [b,c,g]

[a] Department of Psychology, Schermerhorn Hall, Columbia University, 1190 Amsterdam Avenue, New York, NY 10027, USA
[b] The Rotman Research Institute, Baycrest Centre for Geriatric Care, University of Toronto, Toronto, Ont., Canada
[c] Department of Psychology, University of Toronto, Toronto, Ont., Canada
[d] Department of Neurosurgery, Sunnybrook Health Sciences Center, University of Toronto, Toronto, Ont., Canada
[e] Department of Medicine (Neurology), University of Toronto, Toronto, Ont., Canada
[f] Department of Surgery, University of Toronto, Toronto, Ont., Canada
[g] Department of Medicine (Neurology, Rehabilitation Medicine), University of Toronto, Toronto, Ont., Canada

Received 16 July 2001; received in revised form 10 June 2002; accepted 10 June 2002

Abstract

Eleven patients with mild traumatic brain injury (MTBI) and 13 patients with moderate-to-severe TBI (STBI) were compared to 10 matched controls on episodic memory for pictorial scene–object associations (e.g. kitchen–bread) and a range of standardized neuropsychological tests of memory and frontal-lobe functions. We tested the hypothesis that deficits in episodic memory result from impaired attentional resources and/or strategic control by manipulating attentional load at encoding (focused versus divided attention) and environmental support at retrieval (free recall and recalled cued by scene versus recognition of object and scene). Patients with TBI were disproportionately affected by the divided attention manipulation, but this effect was modulated by injury severity and encoding strategy. Overall, MTBI patients were impaired only when items were encoded under divided attention, indicating memory deficits that were secondary to deficits in the executive control. STBI patients could be differentiated into two distinct functional subgroups based on whether they favored a strategy of attending to the encoding or digit-monitoring task. The subgroup favoring the digit-monitoring task demonstrated deficits in the focused attention condition, and disproportionate memory deficits in the divided attention condition. In contrast, the subgroup favoring the encoding task demonstrated intact performance across all memory measures, regardless of attentional load, and despite remarkable similarity to the other STBI subgroup on demographic, neuropsychological, and acute injury severity measures. We discuss these outcome differences in terms of the relationship between strategy and executive control and highlight the need for more sensitive anatomical and behavioral measurement at both acute and chronic stages of injury.
© 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Executive control; Frontal-lobe; Outcome; Neuropsychology

1. Introduction

Patients with traumatic brain injury (TBI) commonly report residual deficits in memory and attention that interfere with their everyday lives, often preventing them from returning to work or school at their pre-injury level [16,39,40,43,63]. Indeed, a recent report found that both patients and their close relatives find poor memory to be the most troubling problem associated with the long-term (>6 years) outcome of TBI [45]. Yet, it is not uncommon for these subjective reports to contrast with intact performance on objective clinical measures of cognitive functions, particularly when acute injury is mild or moderate and/or medial temporal lobe structures are intact [6,41,59]. The goal of the present study is to test one hypothesis that has emerged to account for this apparent paradox: that memory deficits are largely due to deficits in attention and/or executive control, and thus, may only be apparent when task demands on attention and its strategic allocation are sufficiently high [34,49,60].

Dual-task conditions provide an experimental environment in which to test both attentional capacity and the ability to exert control over the allocation of attentional resources. Numerous behavioral and neuroimaging studies have demonstrated that divided attention limits the likelihood that information will be processed to a deep, semantic level in temporal and inferior prefrontal corticies,

* Corresponding author. Tel.: +1-212-854-7560; fax: +1-212-854-3609.
E-mail address: mangels@psych.columbia.edu (J.A. Mangels).

0028-3932/02/$ – see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S0028-3932(02)00084-2

and interferes with strategic organization of the material, a process putatively subserved by dorsolateral prefrontal regions [3,12,19,32]. Thus, we would expect that divided attention would interfere with episodic memory formation not only in TBI patients, but also in control subjects. However, encoding under divided attention is not only a function of the quantity of available resources, but also the ability to allocate these resources in an efficient, goal-directed manner [4,50,51]. The finding that dual-task performance can faithfully reflect instructed trade-offs (i.e. primary-task emphasis, secondary-task emphasis, or equal emphasis) demonstrates that attention is a resource whose distribution is under control of a supervisory or executive control process [2,8]. Thus, performance on the primary (memory) task can only be properly evaluated when performance on the secondary task, and any potential strategic trade-offs that may occur between tasks, are taken into account.

If executive control processes were impaired by TBI, we would expect the degree of impairment when information is encoded under divided attention to be disproportionate to that of control subjects, and to be unaccounted for by performance on either task alone [5]. Deficits in executive control have been associated with damage to the prefrontal cortex, but may also occur as the result of damaged connections between the prefrontal cortex and posterior regions [11,38]. Fronto-temporal damage and diffuse axonal shearing, particularly of longitudinal connections, are common sequelae of the typical deceleration/acceleration injury associated with TBI [25]. In particular, orbitofrontal and anterior temporal regions are vulnerable to TBI because of the jagged internal geometry of the skull around the orbits and cranial nerve processes, although lesions occasionally occur more superiorly [34]. Thus, the hypothesis that executive control deficits form a core feature of TBI appears to fit with the neurophysiological profile of the typical TBI patient.

It is therefore surprising that many behavioral studies have failed to provide unambiguous support for a specific deficit in executive control (for review see [49]). For example, when required to simultaneously perform a dot-counting task while engaged in a driving simulator, no disproportionate deficits were found in subacute patients (<30 days post-injury) when slowing on the single-tasks was taken into account [40,64]. Vilkki et al. [65] also failed to find dual-task deficits in either subacute patients or patients with focal frontal lesions. Deficits were found, however, in acute patients, suggesting that time-since-injury influenced performance. Age at the time of injury may also be a factor. Stablum et al. [54] did not find dual-task deficits in MTBI patients under 30 years old, but did find deficits in older patients. Finally, the nature of the secondary task and the degree to which it taxes both attentional resources and executive control is likely to influence performance. Hartman et al. [18] found that conversation with the experimenter caused disproportionate impairment in STBI patients on a visual-motor tracking task, but a digit-span task did not. In contrast, McDowell et al. [36] found that concurrent performance of a digit-span task was sufficient to disrupt simple reaction time in patients with either subacute or acute severe TBI.

Data on the specific effects of dual-tasks on long-term memory in TBI patients is sparser and even less supportive of a clear deficit in attention and/or executive function. To our knowledge, the only studies that have investigated the effects of divided attention on episodic memory performance in chronic patients have used severe TBI patients. In these studies, patients were equally impaired in both focused and divided attention conditions, rather than disproportionately impaired in the divided attention condition, as would be predicted by a specific deficit in executive control [48,66]. The effects of divided attention on the memory performance of patients with mild and moderate-to-severe TBI also have not been compared directly. Whereas patients with severe TBI may sustain chronic deficits in their ability to encode new information into episodic memory regardless of attentional load, mild TBI may result in a memory deficit that is only revealed under the greater attentional demands of dual-task processing. In addition, these previous studies only assessed performance on retrieval tasks that provided some type of environmental support (i.e. cued recall, recognition). Thus, far, the effects of divided attention in TBI have not been evaluated on retrieval tasks that are specifically associated with effortful processing and frontal-lobe function, such as tests of free recall and source memory [67]. Even in normal adults, divided attention at encoding affects source memory to a greater extent than item memory [62].

In the present study we investigate the extent to which attention and/or executive control resulting from TBI influence episodic memory performance. Specifically, we hypothesize that in the case of mild TBI, deficits in the executive control of attention interfere with the ability of intact memory processes to function optimally, whereas in moderate-to-severe TBI, deficits in executive control only further exacerbate primary memory deficits. Indeed, for patients with more severe TBI, a basic impairment in episodic encoding, rather than executive control of attentional resources, may constitute the core deficit.

To address these hypotheses, we measured episodic memory in a paradigm where we carefully controlled and/or manipulated the patient, stimulus, and test factors over which attention and executive control processes would likely vary. Specifically, patients with mild or moderate-to-severe TBI were compared to age, education, and SES matched controls on memory for item (object) and context (scene) associations under conditions of focused or divided attention at encoding. We explored the extent to which factors in the acute stage of TBI predicted cognitive outcome by subdividing patients for analysis in two ways. First, patients were divided a priori according to differences in injury severity (i.e. Glasgow Coma Score (GCS), loss of consciousness (LOC), and post-traumatic amnesia (PTA)) and evaluated in terms of behavioral differences. Then patients were subdivided a posteriori according to differences in behavioral performance in the dual-task condition (i.e. apparent differences in strategic trade-offs between primary and secondary tasks) and evaluated in terms of neurobehavioral and demographic differences.

With regard to stimuli, we manipulated the extent to which objects were semantically congruent with their associated scene. Given that attention appears to be a necessary condition for deep, elaborative processing, deficits resulting from reduced resources might be exacerbated when the association between object and scene is incongruous (e.g. kitchen–clown). For incongruous associations, lack of pre-existing semantic associations may make the integration of object and scene more effortful, and thus, more susceptible to disruption from increased attentional load. Similarly, we predicted that impaired attention would produce greater deficits on memory tests that required greater integration of source/context with item information, such as tests of free and source-cued recall, as is often found in patients with dorsolateral prefrontal damage (e.g. [14,21,31,56,67]). Therefore, we assessed memory using free recall, scene-cued recall, object recognition and object–scene recognition tests, and measured not only total correct responses, but also intrusion errors and strategic organization.

To preview our results, although we did not find straightforward interactions between group (TBI versus controls) and attention condition (focused versus divided) for most memory measures, exploratory post hoc comparisons and measures of divided attention "cost" did provide some evidence that the TBI patients experienced greater declines in memory performance under divided attention than control subjects, garnering some support for the hypothesis that deficits in the executive control of attention contribute, at least in part, to memory problems in TBI. Yet, the magnitude of these impairments was relatively uninfluenced by the stimulus and test manipulations that we hypothesized would be diagnostic of reduced attentional resources. One explanation for this somewhat unexpected pattern of results is that TBI influenced the ability to strategically allocate resources across multiple tasks more than the absolute amount of available resources.

The importance of considering allocation strategy in interpreting TBI memory performance was even more evident when we scrutinized individual differences in trade-offs between the encoding and digit-monitoring task. In this a posteriori analysis, we found that moderate-to-severe TBI patients could be characterized according to whether they appeared to bias attention toward encoding or digit-monitoring tasks in the dual-task condition. Those patients who biased attention toward the digit-monitoring task demonstrated a pattern of performance consistent with a primary deficit in memory encoding, such as deficits on both free recall and standardized neuropsychological memory performance tested under focused attention conditions, whereas patients who biased attention toward the encoding task performed with normal limits on all tasks. Although the groups resulting from this subdivision were small, and therefore caution must be exercised in interpreting the results, we use these findings to emphasize the importance of considering how TBI patients strategically allocate attention in interpreting their performance in multi-tasking situations.

2. Method

2.1. Subjects

Patients were recruited from a series of consecutive admissions to a major medical trauma center for participation in a larger prospective study on cognitive and behavioral outcomes from TBI. Criteria for inclusion in this larger study were hospitalization for TBI, no visual field defect, and a willingness to cooperate in the project. Patients in the present study were tested approximately 3–4 years post-injury (mean = 3.6 years). Patients who had sustained serious medical or psychiatric illness, engaged in substance abuse, refused to participate, or could no longer be contacted were excluded, resulting in a total of 24 subjects who were available for testing. All but one subject had participated in an earlier TBI study at approximately 1.5 years post-injury [30], at which time the majority of neuropsychological tests were administered (see Table 1).

Subjects were initially subdivided by injury severity according to the standard GCS criteria [61]. This classification resulted in 11 patients with mild TBI (MTBI; GCS: 13–15), 5 patients with moderate TBI (GCS: 9–12), and 8 patients with severe TBI (GCS: 3–8). Because of the relatively small sample size of the moderate TBI group, they were combined with the severe TBI group to form a single group of 13 patients (STBI). As may be seen in Table 1, patients in the STBI group had a longer duration of post-traumatic amnesia (PTA) than MTBI patients. PTA was defined as the number of days from injury onset required to achieve a score of 75 or greater on the Galveston Orientation and Amnesia Test (GOAT; [26]) for 2 consecutive days. STBI patients also had higher scores on the Word Recall Latency-Adjusted (WRLA) indicating a greater delay in recovery of the ability to perform a 24-h delay free recall test for three words without error [57,58].

These patients also had a higher incidence of focal or diffuse lesions on acute CT scans. Acute CT scans, which were read by the attending neurosurgeon (M.L.S.) and classified according to a standardized scheme [33], revealed intracranial swelling and diffuse or focal lesions in 8 out of 12 STBI and 1 out of 10 MTBI patients for which scans were available. Of the six patients with focal damage, four had damage in the frontal lobes (one bilateral, two left, one right), one had damage in the right parietal lobe and one had damage in the right temporal lobe.

Ten age- and education-matched control subjects without history of neurological or psychiatric disorders were recruited. In order to minimize confounds related to the psychosocial cohort from which TBI patients are drawn [10],

Table 1
Subject characteristics

	Controls	MTBI	STBI		
			All	Digit-bias	Encoding-bias
Demographics					
n[a]	10	11	13	8	5
Gender	5M, 5F	5M, 6F	7M, 6F	4M, 4F	3M, 2F
Handedness	1L, 9R	1L, 10R	1L, 12R	1L, 7R	5R
Age (years)	32.3 (3.0)	29.4 (3.3)	30.1 (1.9)	28.5 (2.4)	32.6 (3.1)
Education (years)	14.7 (0.8)	13.1 (0.6)	13.2 (0.8)	13.1 (1.1)	12.6 (1.4)
Time since injury (years)	–	3.7 (0.2)	3.6 (0.2)	3.6 (0.4)	3.6 (0.3)
GCS	–	14.5 (0.2)	7.2 (0.7)[f]	7.4 (1.0)[f]	6.9 (1.0)[f]
PTA (days)	–	7.2 (4.3)	25.1 (2.4)[f]	23.7 (4.4)[f]	26.5 (2.3)[f]
WRLA (days)	–	9.2 (1.9)	30.8 (3.0)[f]	27.9 (5.3)[f]	33.8 (2.7)[f]
Neuropsychological tests					
Picture naming (BNT)[c]	55.7 (1.3)	54.1 (2.3)	54.1 (1.1)	54.8 (0.9)	53.2 (2.4)
WAIS-R subtests					
Information[b]	18.4 (2.3)	16.1 (1.3)	18.3 (1.5)	16.9 (1.9)	20.2 (2.4)
Vobabulary[b]	48.7 (4.7)	46.3 (3.1)	48.2 (3.3)	47.5 (4.5)	49.0 (5.3)
Digit-span[b]	12.4 (0.8)	11.6 (0.7)	12.3 (0.4)	12.0 (0.7)	12.6 (0.4)
Digit-symbol[b]	64.2 (3.4)	66.7 (1.8)	57.1 (3.7)[f]	55.6 (4.2)[f]	59.2 (7.2)
WMS-R subtests					
Figural memory immediate[b]	38.1 (1.0)	37.6 (0.5)	37.9 (0.9)	37.3 (1.4)	38.8 (0.7)
Figural memory delayed[b]	35.7 (1.1)	36.3 (1.0)	35.3 (1.5)	33.3 (2.2)[g]	38.2 (1.3)
Paired association immediate[b]	21.2 (0.9)	22.1 (0.5)	20.3 (1.0)	19.7 (1.6)	21.0 (0.6)
Paired association delayed[b]	7.9 (0.1)	7.7 (0.1)	8.0 (0)	8.0 (0)	8.0 (0)
Story recall immediate[b]	29.2 (2.4)	31.3 (2.0)	27.4 (2.1)	24.7 (2.1)[f]	31.2 (3.7)
Story recall delayed[b]	25.8 (2.2)	28.5 (1.4)	24.6 (1.9)	21.6 (1.7)[f,g]	28.8 (3.1)
Tests of frontal function					
WCST % per errors[b]	17.3 (3.0)	16.0 (1.2)	14.4 (1.0)	14.6 (1.6)	14.2 (1.1)
Concept generation[b]	4.6 (0.4)	5.0 (0.3)	4.2 (0.4)	3.7 (0.5)[f,h]	5.0 (0.5)
Stroop interference (ms)[c]	93.6 (4.4)	102.5 (10.9)	107.3 (8.5)	110.6 (11.7)	102.8 (13.3)
Stroop interference errors[c]	1.8 (0.7)	2.5 (0.5)	2.8 (1.0)	3.6 (1.7)	1.8 (0.2)
Trails A (ms)[c]	19.9 (1.9)	19.4 (2.5)	27.1 (3.4)[e]	25.3 (5.0)	29.6 (4.3)[d]
Trails B (ms)[c]	45.5 (2.4)	51.5 (5.1)	57.2 (3.3)[e]	54.7 (4.5)	60.6 (5.0)[d]
Trails B–A (ms)[c]	25.6 (2.3)	32.2 (4.0)	30.1 (2.2)	29.4 (1.8)	31.0 (5.0)
Trails B errors[c]	0.5 (0.2)	0.5 (0.3)	0.4 (0.1)	0.4 (0.2)	0.4 (0.2)
Phonemic fluency[b]	43.6 (2.0)	35.0 (1.6)[d]	37.6 (2.9)	33.7 (2.8)[d]	43.0 (5.0)
Semantic fluency[b]	30.1 (2.5)	26.0 (2.8)	25.9 (1.5)	25.0 (2.3)	27.0 (2.0)

Standard errors of the mean are shown in parentheses.
[a] Some controls and TBI patients were not available for all neuropsychological testing, resulting in a reduced *n* (maximum two subjects missing per group for any given test).
[b] Tested ∼1.5 years post-injury.
[c] Tested ∼3.6 years post-injury (part of current test-battery).
[d] Significantly different from controls ($P < 0.05$).
[e] Marginally different from controls ($P = 0.05$–0.07).
[f] Significantly different from MTBI.
[g] Significantly different from encoding-bias STBI.
[h] Marginally different from encoding-bias STBI.

these controls were recruited from the family and friends of the patients. As shown in Table 1, control subjects did not differ from either the MTBI or STBI group on standardized tests of pre-morbid intelligence (i.e. WAIS-R Information and Vocabulary subtests), immediate and delayed memory (e.g. WAIS-R Digit Span and WMS-R subtests), or picture naming (i.e. Boston Naming Test (BNT)). Overall, performance on tests of set-switching and interference associated with frontal-lobe function, such as the WCST, Stroop, and Trails test, also appeared normal in the patient groups. Yet, the MTBI group generated significantly fewer words than controls on phonemic fluency.

2.2. Stimuli and procedure

Subjects memorized pairs of pictures under focused and divided attention. Each pair of pictures consisted of a photograph of an everyday scene presented to the left of a line drawing of a common object. Each photograph and line drawing pair was projected simultaneously from slides onto a white wall 72 in. from the subject. The total area of the two adjacent pictures was 72 in. × 22 in. The scenes consisted of a kitchen, living room, bedroom, and garage (set A), or workshop, street, park, and beach (set B). Although each scene contained objects that helped to specify its location and identity, none of the objects contained within the scene were used as target or distractor objects. Line drawings of the objects were taken from the Snodgrass and Vanderwart [53] picture norms.

During the study phase of the experiment, subjects were presented with a total of 48 scene–object pairs at a rate of 5 s per pair. These pairs were constructed by pairing each of the four scenes in set A or B with 12 different objects. Six of the objects paired with each scene were highly congruous with the scene (e.g. bedroom: shoe), and six were highly incongruous with the scene (e.g. bedroom: snowman). Incongruous objects were selected to have minimal congruity with the other scenes in that set. The sequence of 48 scene–object pairs was presented in one of four possible pseudo-random orders that were constructed so that no scene could occur twice in a row. The order of slide pair presentation was counterbalanced across subjects.

Subjects were instructed to remember the scene and object together for later memory tests and were fully informed about the nature of these upcoming tests. Each set of 48 scene–object pairs was memorized under either focused attention or while performing an auditory digit-monitoring task (divided attention), and was always tested under focused attention. Each subject received both attention conditions, counterbalanced with stimulus set (A/B), across two test sessions separated by approximately 50 min.

In the auditory digit-monitoring task, subjects listened to a stream of odd and even digits presented at a rate of 1 digit/s. When the subject detected a sequence of 3 odd-digits in a row, they were to write that sequence down on a sheet of paper without looking away from the picture presentation. They practiced this task alone until they performed it without error and without looking down. Subjects in all groups were able to learn this task rapidly, usually in one practice run. They were instructed to divide their attention equally across the encoding and digit-monitoring tasks because performance on both tasks would be scored.

Following a 1-min distractor task, in which subjects counted backward by threes from a three-digit number, three memory tests were given in the following order: free recall, scene-cued recall, and recognition. For the free recall test, subjects were instructed to recall the names of all the objects they could remember from the set without regard to the scene with which it had been paired. For the scene-cued recall test, each of the four scenes was presented, one at a time, and subjects were instructed to recall only the objects that had been shown with that scene. In the recognition test, 48 target and 48 distractor objects were presented. Distractor objects were selected such that half were congruous with one of the studied scenes (six objects per scene) and half were incongruous with any of the scenes. Subjects first classified an object as “old” or “new,” and then for “old” items, chose the scene it had been paired with from a reminder card listing the names of the four scenes.

2.3. Data analysis

Digit-monitoring performance was measured as the percent of 3-digit sequences correctly detected out of a maximum of 11 sequences. Subjects were not given credit for partial recall of a sequence. Object names that were given during free recall and scene-cued recall tests were scored by two independent judges using strict scoring criteria. An item was counted as correct only if the subject gave the exact Snodgrass and Vanderwart [53] name, a strong synonym (e.g. “tumbler” for “glass”), or the name of a highly perceptually and semantically similar object (e.g. “crocodile” for “alligator”). Unacceptable items included those that were semantically similar, but perceptually different (e.g. “vase” for “watering can”), or too general (e.g. “bug” for “grasshopper”). These responses were scored as intrusion errors, along with any recalled items that were unrelated to the target objects.

Intrusion errors were divided into three categories: extra-experimental errors, intra-experimental list-source errors, and intra-experimental scene-source errors. Extra-experimental errors refer to intruded items that were not shown at any point in the experiment. List-source errors refer to intrusions of items from the first test session during the second test session. Scene-source errors, which could only occur in the scene-cued recall test, refer to intrusions when the subject recalled the item correctly but associated it with the incorrect scene. We analyzed errors as a function of the percentage of total responses in a given condition.

Given that the objects could be grouped according to the four scenes, we also examined the use of organizational strategies in free recall using the adjusted ratio of clustering (ARC) [42]. ARC measures the extent to which items from the same category (i.e. scene) are grouped together at recall, while adjusting for total items recalled and chance. This measure ranges from around 0 to 1.0, although negative numbers are possible if observed clustering is less than chance.

For recognition memory, we measured both “hit–hit” recognition, which included only those items that were correctly identified and assigned to the correct scene, and “hit–miss” recognition which included both “hit–hit” items and items that were correctly recognized but assigned to the incorrect scene (i.e. item recognition regardless of scene recognition).

Post hoc comparisons involving groups with $n < 10$ were only reported as significant when both post hoc parametric (Tukey’s HSD test) and non-parametric tests (Mann–Whitney *U*-test) were $P < 0.05$, although for clarity only the results from the parametric tests will be reported.

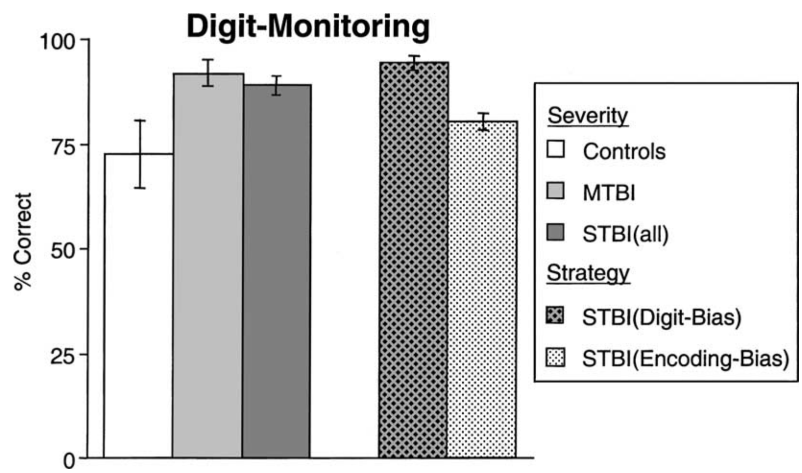

Fig. 1. Digit-monitoring performance of TBI patients and control subjects. TBI patients were subdivided according to GCS severity, and STBI patients were additionally divided according to strategy (see text for explanation). Error bars represent S.E. of the mean.

3. Results

3.1. Digit-monitoring task

3.1.1. Overall analysis

As shown in Fig. 1, both MTBI and STBI patient groups performed significantly better than the control group on the digit-monitoring task, $F(2, 31) = 4.3$, $P < 0.02$. These differences persisted even when an outlier in the control group with a score of 9.1% was excluded, $F(2, 30) = 3.4$, $P < 0.05$. The superior performance of the patient groups to the control group was unexpected. Because it could have arisen from differences in strategy (i.e. where control subjects biased attention in favor of the encoding task and TBI patients biased attention in favor of the digit-monitoring task), we investigated the relationship between these two tasks before proceeding.

3.1.2. Relationship between digit-monitoring and memory performance

Fig. 2 shows performance on the digit-monitoring task plotted against performance on the free recall and scene-cued recall tests. In the control group, performance on the digit-monitoring task was not significantly correlated with any of the memory tests, even when the outlier described above was removed. Likewise, in the MTBI group, there was no correlation between digit-monitoring and free recall ($r = -0.23$) or recognition (hit–miss: $r = 0.10$, hit–hit: $r = 0.01$). Digit-monitoring and scene-cued recall performance at first appeared somewhat correlated in this group ($r = -0.62$, $P = 0.05$), but further analysis indicated that this correlation was heavily influenced by an outlier who scored more than 2 S.D. above the group mean. When this subject was removed from the analysis, the correlation disappeared ($r = -0.33$). When interpreting these results, we must consider that performance on the two tasks reflects the subject's underlying ability on each individual task, as well as the strategic allocation of attention across tasks. Furthermore, primary ability on a given task may influence how much attention one allocates to that task. Nonetheless, our examination of performance trade-offs between memory and digit-monitoring tasks failed to reveal any consistent group-wide relationships in the control and MTBI groups.

A consistent relationship was found in the STBI group, however. Digit-monitoring was significantly correlated with both free recall ($r = -0.81$, $P < 0.001$) and scene-cued recall ($r = -0.80$, $P < 0.001$), although it did not correlate with either recognition task (object only: $r = 0.08$, object–scene: $r = 0.32$). As shown in Fig. 2, the scatterplot of these recall correlations revealed that the STBI group was composed of two well-defined subgroups: (1) patients scoring <85% correct on digit-monitoring and >15% correct on recall, and (2) patients scoring >85% correct on digit-monitoring and <15% correct on recall. Relative to the STBI group as a whole, the performance pattern of the first subgroup ($n = 5$) indicated a bias toward the encoding task (encoding-bias (EB)), whereas the pattern of the second subgroup ($n = 8$) indicated a bias toward the digit-monitoring task (digit-bias (DB)). As expected, the STBI(DB) subgroup performed significantly better than controls on the digit-monitoring task, whereas the STBI(EB) group did not differ from controls.

We were concerned that if combined into a single group, the contrasting biases of these two STBI subgroups might cancel each other out and mask potential group differences. Therefore, we created two a posteriori subgroups within the STBI(all) group by dividing this group according to whether subjects demonstrated the digit- or encoding-bias strategies described above. As such, all analyses of memory performance were conducted on TBI groups defined both a priori by severity (i.e. MTBI and STBI(all) groups versus controls), and a posteriori by strategy (i.e. STBI(EB) and STBI(DB) versus MTBI and controls). The MTBI group could not be divided by strategy because clear performance-based subdi-

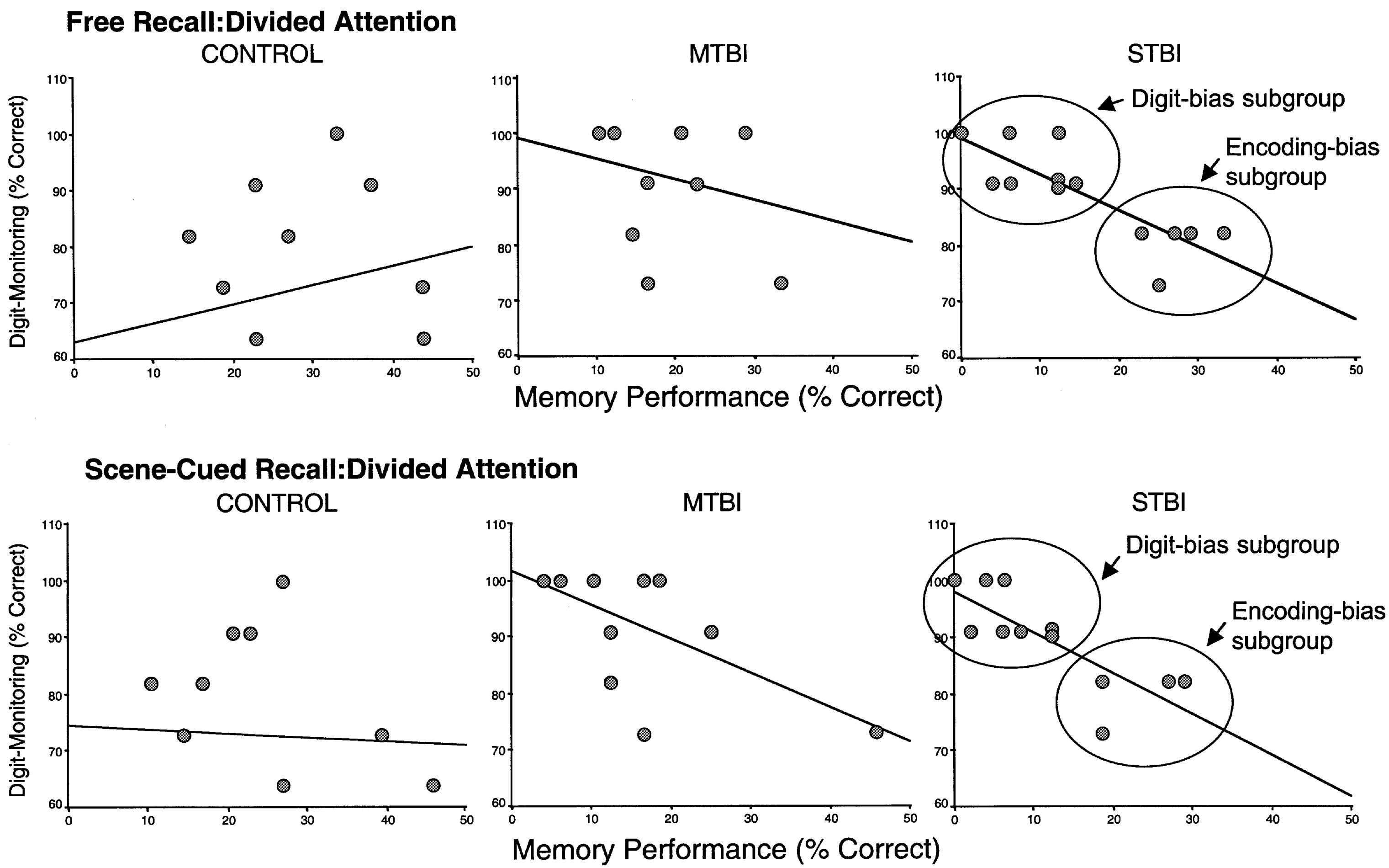

Fig. 2. Scatterplots illustrating subject performance on the digit-monitoring task (% correct out of 11) plotted against memory performance (% correct out of 48) on free recall (top) and scene-cued recall (bottom) tasks in the divided attention condition. The line in each plot represents the linear regression line. The outlier in the control group was removed so that the performance of the three groups could be plotted on comparable axes. Scatterplots may illustrate fewer points than the *n* for each subject group due to coincident points.

visions did not emerge, but was included in this latter analysis for comparison against the two STBI subgroups.

Although it was possible to counterbalance condition order (i.e. focused and divided attention) within group when subjects were subdivided by severity, it was not possible to do this for the division by strategy. As a result, there were more patients in the STBI(DB) than the STBI(EB) group who had received the divided attention condition second. To determine whether this difference influenced any of the results, order of condition was entered into each of the analyses described below. It had no significant effect on any result.

3.2. Memory tests

3.2.1. Congruity effects

A main effect of congruity between scene and object was found for all memory measures ($P < 0.0001$), except hit–miss recognition ($P = 0.3$). Overall, congruent objects were remembered better than incongruent objects. A significant interaction between congruity and attention was found for hit–hit, $F(1, 30) = 6.9$, $P < 0.01$, and hit–miss recognition, $F(1, 30) = 4.8$, $P < 0.05$. As expected, in both cases, divided attention impaired memory for incongruent scene–object pairs more than for congruent pairs. However, interactions between subject group and congruity did not approach significance for any recall or recognition measures. Thus, to simplify the analyses that follow, memory performance was collapsed over congruous and incongruous items.

3.2.2. Overall recall performance

Overall free and scene-cued recall performance is shown in Fig. 3. Two-factor (attention × subject type) ANOVAs conducted on these two recall measures yielded similar results. As expected, subjects recalled significantly more items in the focused attention condition than the divided attention condition on both tests (free recall: $F(1, 30) = 165.6$, $P < 0.0001$; scene-cued recall: $F(1, 30) = 120.7$, $P < 0.0001$). In addition, for free recall, there was a main effect of subject type, regardless of whether the TBI groups were subdivided by severity, $F(2, 31) = 4.3$, $P < 0.05$, or strategy, $F(3, 30) = 6.8$, $P < 0.005$. Overall, the STBI group recalled fewer items relative to controls. Yet, when this group was subdivided according to strategy, it was only the STBI(DB) group that was significantly impaired. The STBI(EB) group was superior to the STBI(DB) group and equivalent to the control and MTBI groups. The difference between the MTBI group and control group failed to reach significance ($P = 0.1$). For scene-cued recall, there was a marginal effect of subject type when analyzed as a function of strategy, $F(3, 30) = 2.8$, $P = 0.06$, although there was only a weak trend for this effect when analyzed as a function of severity, $F(2, 31) = 2.3$, $P = 0.1$. Post hoc analyses for scene-cued recall were in the same direction as those for free recall.

The interaction of attention and subject type did not reach significance, regardless of how subjects were grouped or whether recall was free or cued by scene (e.g. strategy: free recall: $F(3, 30) = 1.3$, $P = 0.3$; scene-cued recall: $F(3, 30) = 1.2$, $P = 0.3$). Yet, it is possible that the large

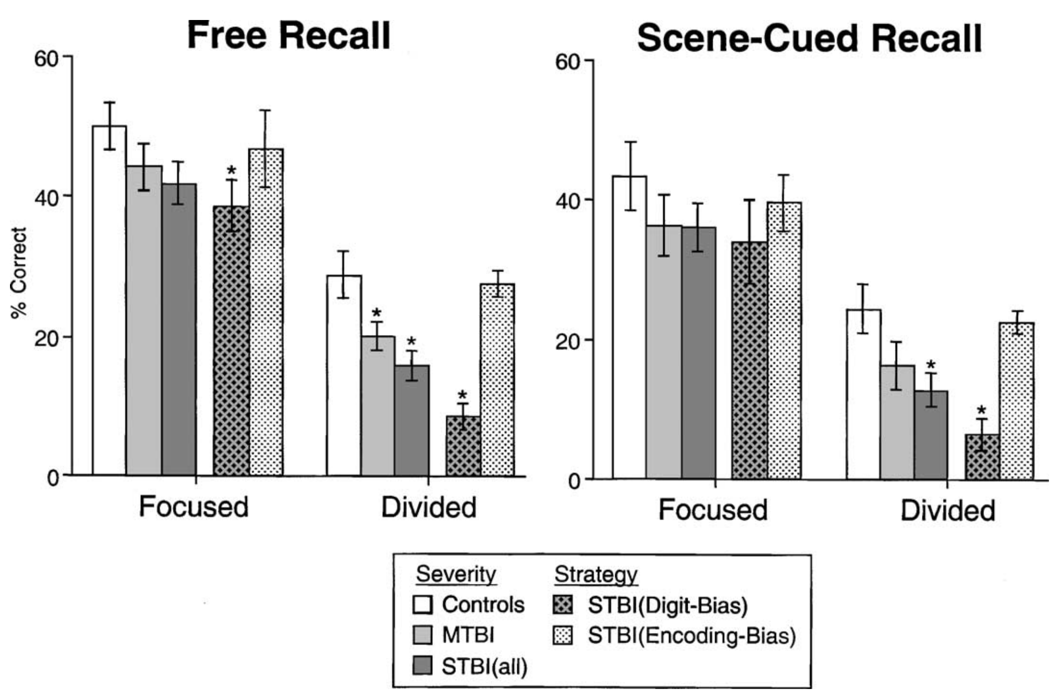

Fig. 3. Overall free recall (left) and scene-cued recall (right) performance. TBI patients were subdivided according to severity, and STBI patients were additionally divided according to strategy (see text for explanation); error bars represent S.E. of the mean and asterisks indicate differences from the control group ($P < 0.05$).

effect of attention on all groups and the numerically poorer performance of the TBI groups in the focused attention condition may have masked a disproportionate deficit in the TBI groups in the divided attention condition. Because we predicted a priori that any recall memory deficits in the TBI groups would be more evident when information was encoded under conditions of high attentional load, we opted to explore this hypothesis further by analyzing group performance in focused and divided attention conditions in separate single-factor analyses.

For both free and scene-cued recall, these analyses indicated that groups significantly differed in the divided attention condition (free recall: $F(3, 30) = 12.3$, $P < 0.0001$; scene-cued recall: $F(3, 30) = 5.9$, $P < 0005$), but not the focused attention condition (free recall: $F(3, 30) = 1.7$, $P = 0.2$; scene-cued recall: $F(3, 30) = 0.8$, $P = 0.5$). Post hoc comparisons confirmed that when items were encoded under focused attention, there were no significant differences between patients and controls ($P > 0.2$), with the exception of the STBI(DB) group, which was significantly impaired on free recall relative to controls ($P < 0.04$). The STBI(DB) group was also largely responsible for the group effect in the divided attention condition. The STBI(DB) group was impaired in the divided attention condition for both free recall and scene-cued recall. In contrast, the STBI(EB) group did not differ from controls on either free or scene-cued recall, when encoded under either focused or divided attention conditions, and even performed better than the MTBI group on the free recall test in the divided attention condition. The MTBI group was impaired on free recall-divided attention relative to the control group, although they were significantly better than the STBI(DB) group. The MTBI group did not differ from any of the other subject groups on the scene-cued recall test.

3.2.3. Intrusion errors

The percentage of total free recall responses (i.e. correct and incorrect combined) that were classified as extra- and intra-experimental list-source errors (see Section 2) is shown in Fig. 4. The relative percentage extra-experimental, list-source, and scene-source errors on the scene-cued recall test is shown in Fig. 5. In both figures, the error rates are stacked to illustrate the total error percentage; however it should be noted that the probability of making these errors was not equivalent. Whereas extra-experimental and scene-source errors could occur on either the first or second list, list-source errors could only occur on the second list.

For all error types, participants most often intruded names of objects that were semantically related to a target object. It was less common for subjects to intrude a completely unrelated item and quite rare for subjects to intrude items that were only perceptually similar to a target object. Yet, given the small numbers of errors overall, we could not analyze the effect of error relatedness further. All reported analyses were conducted on total errors of a given type, regardless of their relatedness to the target.

On both free recall and scene-cued recall tests, list-source errors did not differ as a function of attention ($P > 0.5$), nor was there an interaction between attention and either group variable ($P > 0.3$). Although the effect of severity was not significant, the effect of strategy on list-source errors was marginally significant for both free recall, $F(3, 29) = 2.6$, $P = 0.07$, and scene-cued recall, $F(3, 29) = 2.5$, $P = 0.08$. For free recall, this effect was driven by the STBI(DB)

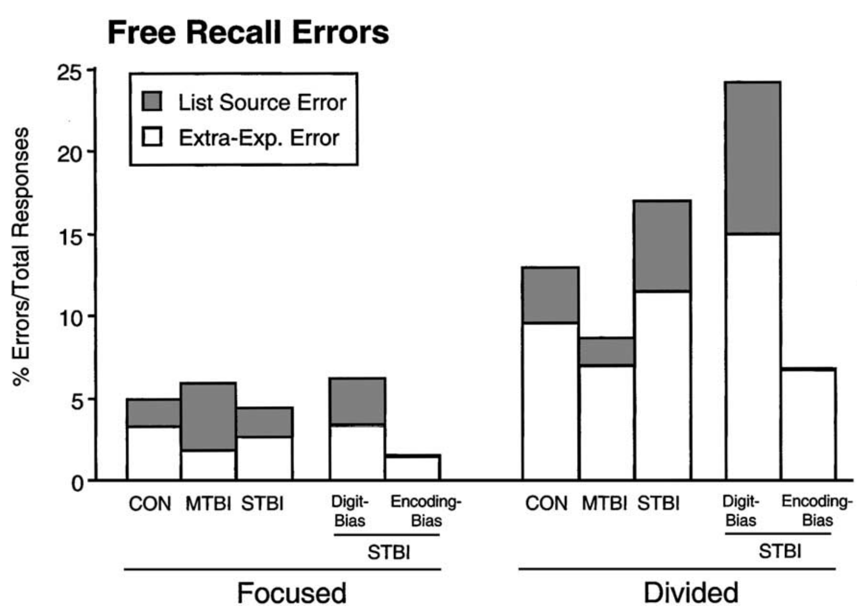

Fig. 4. Intrusion errors in free recall performance. Error rates for each type of error were calculated as a percentage of total responses. Error rates are stacked to illustrate overall error rate in each group.

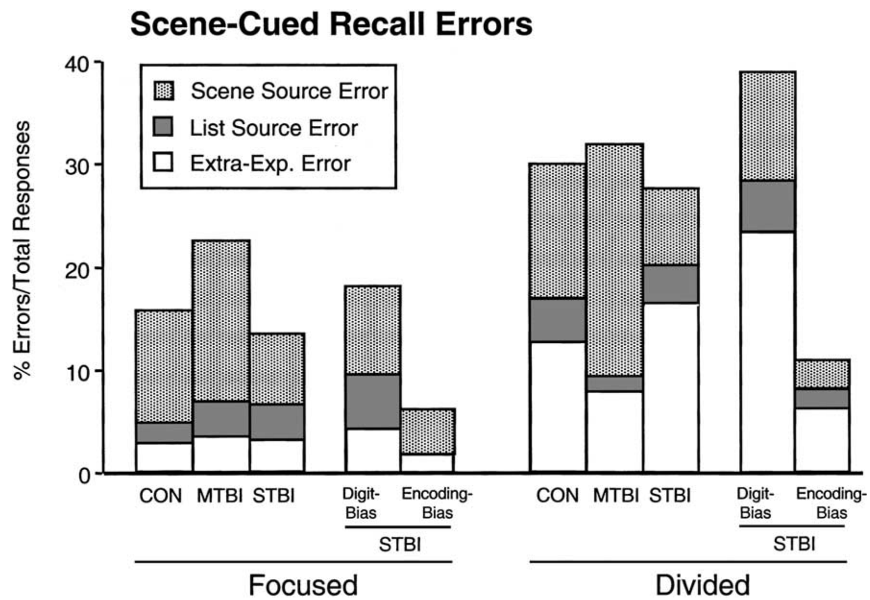

Fig. 5. Intrusion errors in scene-cued recall performance. Error rates for each type of error were calculated as a percentage of total responses. Error rates are stacked to illustrate overall error rate in each group.

group, who made significantly more errors than either the STBI(EB) or MTBI patients ($P < 0.03$), and marginally more errors than controls ($P = 0.08$). Indeed, only one of the patients in the STBI(EB) group made any list-source errors, whereas all but one of the STBI(DB) group made list-source errors. Notably, the one patient in the STBI(DB) group who did not make any list-source errors simply did not produce any items during the second list test. For scene-cued recall, the pattern was similar, but post hoc comparisons did not reach statistical significance.

Divided attention led to an increase in extra-experimental errors in both free recall, $F(1, 31) = 5.6$, $P < 0.05$, and scene-cued recall, $F(1, 31) = 8.3$, $P < 0.01$. There was no effect of group on extra-experimental errors, nor did attention interact with group ($P > 0.5$).[1] These results suggest that subjects in all groups were relying more on semantic gist and guessing at retrieval when items were encoded under divided attention.

Scene-source errors were significantly affected by group, $F(2, 31) = 3.6$, $P < 0.05$, but not attention ($P > 0.1$). Somewhat surprisingly, it was the MTBI patients who produced significantly more scene-source errors overall than either STBI subgroup (STBI(DB): $P < 0.05$, versus STBI(EB): $P < 0.05$), although the MTBI patients did not differ significantly from controls. The STBI(EB) subgroup actually produced marginally fewer scene source errors than controls. There was no interaction between attention and group.

3.2.4. Free recall organization: clustering

Scene-related clustering in free recall provides an index of semantic organization at retrieval. A 2(attention) × 4(group-strategy) ANOVA indicated that clustering levels were lower when items were encoded under divided attention as compared to focused attention, $F(1, 30) = 4.8$, $P < 0.05$. This main effect of attention was also observed when subjects were divided according to severity. Although there was no overall effect of subject type, $F(3, 30) = 1.2$, $P = 0.3$, post hoc analyses indicated that only the STBI(all) group demonstrated a significant decrease in clustering when attention was divided at encoding (focused: mean = 0.25, S.E.M. = 0.07; divided: mean = −0.10, S.E.M. = 0.19), relative to controls (focused: mean = 0.32, S.E.M. = 0.09; divided: mean = 0.13, S.E.M. = 0.07). Clustering in the MTBI group did not differ as a function of attention (focused: mean = 0.22, S.E.M. = 0.93; divided: mean = 0.22, S.E.M. = 0.18). The poorer performance of the STBI(all) in the divided attention condition was largely due to the significant effect of attention on the STBI(DB) group (focused: mean = 0.23, S.E.M. = 0.89; divided: mean = −0.31, S.E.M. = 0.29). The STBI(EB) group did not show a significant change in clustering as a function of attention (focused: mean = 0.29, S.E.M. = 0.11; divided: mean = 0.23, S.E.M. = 0.9).

3.2.5. Recognition

Table 2 illustrates the percentage of objects that were correctly recognized and associated with the correct scene (hit–hit recognition), the percentage of objects correctly rec-

[1] The apparent high extra-experimental error rate for the STBI(DB) group under divided attention was due to a single outlier with a 71% extra-experimental error rate on the free recall test and 80% extra-experimental error rate on the scene-cued recall test. Interestingly, this individual was also the only TBI patient whose acute CT scan demonstrated bilateral frontal damage.

Table 2
Recognition memory performance

	Controls	MTBI	STBI		
			All	Digit-bias	Encoding-bias
Hit–hit					
Focused	69.2 (4.7)	65.9 (4.5)	72.3 (4.5)	69.3 (5.8)	77.1 (7.2)
Divided	53.5 (4.3)	43.2 (3.2)[b]	46.6 (4.1)	40.6 (4.2)[a]	56.3 (6.5)[c,d]
Hit–miss					
Focused	86.5 (6.3)	92.8 (1.3)	90.9 (3.3)	88.5 (4.9)	94.6 (3.5)
Divided	81.3 (4.7)	70.6 (2.2)[a]	73.2 (5.2)	69.3 (6.7)[a]	79.6 (8.1)
False alarms					
Focused	4.0 (1.5)	6.8 (2.2)	5.8 (1.9)	7.8 (2.7)	2.5 (2.1)
Divided	11.3 (2.5)	16.3 (3.7)	16.5 (3.6)	19.0 (4.5)	12.5 (6.1)

Hit rates for object–scene (hit–hit) and object-only (hit–miss) recognition, and false alarms. Standard errors of the means are given in parentheses.
[a] Significantly different from controls ($P < 0.05$).
[b] Marginally different from controls ($P = 0.05$–0.07).
[c] Marginally different from MTBI.
[d] Significantly different from encoding-bias STBI.

ognized, but associated with the incorrect scene (hit–miss recognition), and false alarm rate.

Hit–miss recognition was corrected for false alarm rate, which did not differ across groups, $F(3, 30) = 0.6$, $P = 0.6$. For this corrected hit–miss recognition, there was a main effect of attention, $F(1, 31) = 72.4$, $P < 0.0001$, and a significant interaction between attention and severity, $F(1, 31) = 3.8$, $P < 0.05$. The interaction with strategy, however, was only marginally significant, $F(1, 30) = 2.6$, $P = 0.07$. As with the recall analyses, post hoc comparisons indicated that there were no group differences in the focused attention condition, but that in the divided attention condition, MTBI patients were impaired relative to controls ($P < 0.05$). The difference between controls and STBI patients in the divided attention condition failed to reach significance ($P = 0.1$), yet the MTBI and STBI patient groups also did not significantly differ from each other. When divided into STBI subgroups, only the STBI(DB) patients were significantly impaired relative to the controls ($P < 0.04$). STBI(EB) patients did not differ significantly from any of the other groups ($P = 0.2$).

When we turned our analysis to hit–hit recognition, we found only a significant effect of attention, $F(1, 31) = 95.3$, $P < 0.0001$. The group × attention interaction did not reach significance regardless of whether it was analyzed as a function of severity or strategy ($P > 0.3$). Nonetheless, because we had predicted a priori that group differences would be more apparent when scene–object pairs were encoded under divided attention, we again cautiously explored post hoc comparisons within each level of attention. There were no group differences when the scene–object pairs were encoded under focused attention. In the divided attention condition, however, the STBI(EB) performed significantly better than the STBI(DB) group ($P < 0.04$), and marginally better than the MTBI group ($P = 0.06$), but did not differ from controls. The STBI(DB) group was significantly impaired relative to controls ($P < 0.04$) and the MTBI group was marginally impaired relative to controls ($P = 0.07$).

3.3. Relative "cost" when items were encoded under divided attention (all retrieval measures)

The single-factor analyses and post hoc comparisons across all four retrieval measures consistently demonstrated that the MTBI and STBI(DB) groups suffered from disproportionate deficits in the divided attention conditions. Nonetheless, two-factor (group × attention) ANOVAs on these retrieval measures failed to yield any significant interactions, with the exception of hit–miss recognition when analyzed as a function of severity. It is likely that the numerically lower, though not statistically lower, performance of the TBI groups on the focused attention conditions may have weakened our potential to detect these interactions. Therefore, we also calculated performance in the divided attention (DA) condition as a proportion of performance in the focused attention (FA) condition (% retrieved in DA condition/% retrieved in FA condition), thereby treating focused attention performance as a baseline. Consistent with the single-factor analyses of divided attention performance, the STBI(DB) group was impaired relative to controls on all types of retrieval ($P < 0.05$). Yet, this group was only impaired relative to MTBI or STBI(EB) groups on free and scene-cued recall tasks, perhaps suggesting that the absolute magnitude of the STBI(DB) impairment was somewhat related to the amount of environmental support at retrieval. The MTBI patients demonstrated a significantly greater "cost" from divided attention than controls on hit–miss recognition ($P < 0.02$) and scene-cued recall ($P = 0.05$). For the STBI(EB) group, the effect of divided attention was equivalent to controls across all tasks, and also equivalent to MTBI patients for all tasks except scene-cued recall, where they were marginally better ($P = 0.08$).

Table 3
Memory performance, neurobehavioral and neurological status at time of injury of STBI subgroups

Subgroup	Free recall		Scene-cued recall		Neurobehavioral/neurological status				
	Focused	Divided	Focused	Divided	GCS	PTA	LOC	Lesion	Edema
Digit-bias									
KW	22.9	0	22.9	0	3.0	37.9	144	None	No
NH	50.0	12.5	31.3	6.2	9.0	NA	<0.5	R-pariet	No
TW	52.1	14.6	56.3	12.5	5.0	12.5	96	L-front	No
MH	39.6	6.2	29.2	4.2	10.0	17.5	NA	Bi-front	No
KM	31.2	4.2	25.0	2.1	11.0	22.9	32	L-front	Yes
JK	47.9	6.2	41.7	8.3	6.0	27.9	72	None	No
KP	35.4	12.5	25.0	6.3	9.0	NA	39	None	Yes
LL	29.2	12.5	39.6	12.5	6.0	NA	NA	NA	NA
Mean	38.5	8.6	33.9	6.5	7.4	23.7	63.9		
Encoding-bias									
TP	27.1	27.1	22.9	18.8	9.0	26.9	48	R-Temp	Yes
MS	41.7	29.2	29.2	27.1	3.0	22.9	48	None	No
LD	54.2	33.3	41.7	29.2	7.5	33.9	128	None	Yes
BH	54.2	25.0	50.0	18.8	7.5	28.5	96	None	No
MM	56.2	22.9	54.2	18.8	7.5	20.5	24	None	No
Mean	46.7	27.5	39.6	22.5	6.9	26.5	68.8		

3.4. *Encoding-bias STBI versus digit-bias STBI*

Despite differences in functional outcome on the current study, these two subgroups were similar, both to each other and to the other groups, with regard to many subject characteristics, including age, education and gender distribution, as well as tests of pre-morbid intelligence (i.e. Information and Vocabulary subtests of the WAIS-R) and frontal-lobe function (see Table 1). Notable differences between the STBI(DB) group and the other groups included poorer performance on standardized neuropsychological tests of delayed memory (i.e. Delayed Figural Memory and Story Recall subtests of the WMS-R) and some tests of speeded performance (i.e. Digit-Symbol subtest of the WAIS-R, phonemic fluency), as well as fewer categories achieved on a concept generation test that measures mental flexibility [29], similar to the California Card Sort Test [9]. In contrast, the STBI(EB) group was not only statistically equivalent to controls on the majority of neuropsychological tests, but actually performed numerically better than controls on five out of six WMS-R memory subtests. The notable exception for this group was slower overall performance on both trails A and B, although there was no evidence of disproportionate slowing on trails B. It is unclear whether this slowing is evidence of a speed–accuracy trade-off, as number of errors did not differ between groups.

With regard to neurological and neurobehavioral status at time of injury, there were no differences between these subgroups on standard indices of injury severity (i.e. GCS and PTA), number of hours unconscious, or presence/absence of edema (see Table 3). Yet, there appeared to be a higher incidence of focal brain damage in the STBI(DB) group. Over half of the STBI(DB) patients with available CT scans had observable focal lesions (three frontal, one parietal), whereas focal lesions were apparent in only one of the five STBI(EB) patients. Notably, the STBI(EB) patient who had focal damage in the right temporal lobe demonstrated a different pattern of performance than the other patients. Although he performed within the range of STBI(EB) patients on the divided attention tasks, his performance on the focused attention tasks was quite low, and unlike the other patients in this group, his performance did not decline as a function of divided attention.

4. Discussion

In the present investigation, memory deficits in TBI patients classified as either mild or moderate-to-severe with standard clinical measures were most evident when the executive control of attention was challenged by dual-task encoding conditions. However, there was significant heterogeneity in the nature and degree of deficit when we examined performance carefully as a function of both injury severity and task bias. Although these patterns were only evidenced when we explored the data through single-factor ANOVAs and post hoc comparisons, the internal consistency of the data was encouraging and warrants discussion. We observed similar patterns of memory performance in these groups regardless whether memory was tested with tasks that taxed strategic processing at retrieval (i.e. recall) or provided more environmental support (i.e. recognition). Semantic congruity between object and scene also did not interact with group. Both TBI patients and controls found the semantically congruent objects easier to remember than the incongruent objects across all encoding and test conditions.

This pervasive memory deficit in the TBI patients as a whole across stimulus and test manipulations designed to be sensitive to differences in attentional resources was unexpected and suggests that, in our patients, the quantity of available resources was affected less than the ability to allocate these resources as effectively as possible. In general, these patients may spend more time attending to the digit-monitoring task and/or take longer than controls to switch attention between tasks. Yet, when attention is eventually switched to the memory task, the resources available are such that encoding processes may take place as they would in control subjects, or at least at the level that the patient was capable of under focused attention. Such an interpretation is consistent with the findings of some previous studies, in which the degree of dual-task deficit differed as a function of demand that the secondary task placed on switching processes or could be accounted for wholly by performance deficits on the single-tasks alone [18,40,64]. Indeed, the heterogeneity that we observed as a function of injury severity and task bias may be best understood in terms of differences in baseline ability and strategic allocation of attention. We will now address these differences in detail.

MTBI patients demonstrated a unique pattern of intrusion errors. They made significantly more scene-source errors than controls—analogous to the type of source monitoring deficits observed in patients with dorsolateral prefrontal damage (e.g. [21]). In addition, although MTBI patients demonstrated significant impairment on only one of the administered tests of frontal-lobe function (i.e. phonemic fluency), performance on this test was negatively correlated with the decline in scene-cued recall performance in the divided attention condition ($r = -0.71$, $P < 0.02$). Frontal-lobe test performance and memory performance did not correlate in any of the STBI subgroups. Finally, although both the MTBI group and the STBI(DB) subgroup (described below) were disproportionately impaired in the divided attention condition, unlike the STBI(DB) group, the MTBI group did not demonstrate impaired performance on standardized neuropsychological tests of immediate and delayed memory.

Taken together, these results suggest that MTBI patients suffer from a milder deficit in memory and executive control than STBI patients, and overall, demonstrate a pattern of memory deficits similar to that of frontal-lobe patients. Although the damage in MTBI may not be severe enough to elicit clinically significant memory impairment when encoding takes place under focused attention, it may lead to a “fragility” of cognitive function in which this “normal” focused attention performance is accomplished only with maximal effort. This leaves little reserve for when performance demands are increased further. Neuroimaging studies of MTBI patients have also shown evidence of hypermetabolism in task-relevant areas on tests of working memory and sustained attention [17,35], suggesting that these patients require greater effort to perform these tasks.

The pattern of performance exhibited by moderate-to-severe TBI (STBI) patients appeared similar to the MTBI group when first analyzed as a whole (i.e. a priori analysis). Importantly, however, very different results emerged within this group when functional differences in strategy were taken into account (i.e. a posteriori analysis). Specifically, there appeared to be two distinct subgroups of STBI patients: one group who appeared to bias their attention more toward either the digit-monitoring task than the memory task (STBI(DB)) and one that appeared to bias attention more toward the encoding task or at least equally between the two tasks (STBI(EB)).

The cognitive bias of the STBI(DB) group proved maladaptive. It led to superior performance on the digit-monitoring task, but severely impaired memory performance on both recall and recognition tests. Evidence of poor strategy use was apparent in other aspects of their performance as well. Strategic retrieval was impaired, as suggested by impaired overall free recall even in the focused attention condition, as well as impaired semantic clustering. Yet, unlike the MTBI patients, the STBI(DB) group did not demonstrate significantly more intrusion errors of any type, although one subject produced a heightened number of extra-experimental errors.

Notably, patients with severe memory deficits, arising from either basal forebrain damage [37] or medial temporal lobe damage [46,47,52], appear more likely than normal controls to make extra-experimental source errors or intrude items that are unrelated to target items. Yet, these subjects are less likely to make intra-experimental source errors or errors based on semantic gist. Melo et al. [37] propose that the latter type of error requires the extraction and retention of at least some semantic information about target items and will not occur in patients where memory deficits are severe enough that little item information is retained. Because STBI(DB) produced normal intrusion rates, but impaired performance on delayed Figural and Story Recall subtests of the WMS-R, we cannot rule out the possibility that this group not only had severe deficits in executive control, but also suffered from basic memory encoding deficits similar to those found in patients with medial temporal lobe amnesia.

One possible explanation for the bias of the STBI(DB) group is that they were aware of their episodic memory encoding deficit, and may have adapted to this deficit by allocating effort only to tasks that they knew they might be able to accomplish with some level of proficiency, such as the on-line digit-monitoring task. On the other hand, their bias may not have represented a conscious choice, but rather, may have resulted from involuntary distraction by the potentially greater saliency of the digit-monitoring task. TBI patients have difficulty in maintaining attention to a primary task, a deficit that may be exacerbated when distracting stimuli are present in the environment [68,69]. Event-related potential (ERP) studies have shown that chronic moderate-to-severe TBI patients elicit enhanced neural responses related to the involuntary orienting of attention (i.e. P3a, MMN) at the onset of novel, unexpected stimuli, suggesting that they suffer from increased reactivity and distractibility [22,23]. In contrast, ERP components associated with the working memory and the conscious detection of task-relevant events (i.e. P3b), show attenuation and increased latency (for review see [7]).

Alternatively, the bias of the STBI(DB) patients toward the secondary task may represent a deficit in shifting attention. Using a strategy application task (R-SAT), Levine et al. [30] demonstrated that both mild and moderate-to-severe TBI patients have difficulty in executing task-appropriate strategies in the face of distracting stimuli [30]. Yet, a subsequent study found that only the more severe TBI patients were impaired when efficient performance required spontaneous shifting from a previously reinforced response pattern to a new pattern even though learning and retention of task instructions was intact [28]. In the present study, the digit-monitoring task was always practiced at least once before the dual-task commenced, and the experimenter started the presentation of the digits approximately 5 s before the presentation of the pictures during the actual task. Thus, STBI(DB) patients may have had difficulty shifting attention from the digit-monitoring task, despite understanding the instruction to divide attention equally across tasks.

The intact performance of the STBI(EB) group, however, indicates that severe TBI at the acute stage does not *necessarily* resign one to debilitating, chronic impairments in attention and memory. Although they were less accurate on the digit-monitoring task than the STBI(DB) group, their performance on this task was not impaired relative to controls. The STBI(EB) patients also performed within normal limits on all standardized neuropsychological tests and on all of the experimental memory tests regardless of attentional load. Not only did this group exhibit superior encoding even under conditions of high attentional load than the other TBI groups, but also better retrieval monitoring. STBI(EB) patients exhibited very low error rates across all error types and were marginally better than controls and significantly better than MTBI patients in minimizing scene-source errors. It is possible that these patients were less prone to intrusions because awareness of the severity of their initial injury made them more motivated than control or MTBI patients to monitor slips (also see [28]). Indeed, the relative bias of this group toward the encoding task may have represented a deliberate strategy to compensate for concerns about poor memory.

What factors at the time of injury might account for the behavioral differences in chronic outcome between STBI subgroups? Unfortunately, detailed analysis of demographic and neurobehavioral profiles at the time of injury provide little insight. We propose two possible hypotheses for the poor predictive validity of these measures. First, there may be differences in quantity and quality of acute injury that our injury severity measures were too crude to detect. It is not unprecedented for standard behavioral severity measures, such as LOC and PTA, to fail to account for differential recovery within TBI groups [24,41]. Although there was some suggestion of greater focal damage in the more impaired STBI group, there was insufficient power to analyze lesion effects. Moreover, acute CT may underestimate the extent of focal and diffuse neuropathology in chronic TBI patients, which is better revealed by MRI [13,25] or functional imaging [15,20] acquired in the chronic phase. Functional neuroimaging may also reveal altered functional networks that distinguish subgroups of patients, even when structural neuroimaging findings are otherwise similar [27].

A second possibility is that these two subgroups differed in "cognitive reserve," operationally defined as the degree to which one can withstand neurological insult without demonstrating clinically-significant behavioral impairment (for review see [55]). The cognitive reserve hypothesis has been used to explain why demographic variables, such as age, education, and occupation, have sometimes yielded more success than acute severity measures in explaining variance in long-term cognitive outcome after TBI [41,44]. Specifically, advanced age, lower education or premorbid intellectual ability, a stressful occupation, and a previous history of neurological or psychiatric problems have been associated with poorer recovery, potentially because they leave the individual with less neural resources and/or a smaller dynamic range of strategies with which to deal with the effects of brain trauma. In the present sample, however, there was no difference between STBI subgroups, or between the good memory STBI group and the MTBI group, on measures of age, education, or standardized neuropsychological tests of pre-morbid IQ. Similar to the problems of low resolution associated with CT scans, however, these measures also serve as only a crude indicator of the "active reserve" that may endow individuals with a larger and more efficient set of strategies for approaching a task.

Intact executive control may have contributed to the optimal strategy of the STBI(EB) group. As a result, this group was able to compensate for acute injury that, at least with the measures available, appeared as severe as the STBI(DB) group. Given that the mean of the MTBI group was typically between that of the good and poor STBI groups, however, we cannot rule out the possibility that there also were some MTBI patients who adopted more (or less) optimal strategies than others, even though the group as a whole demonstrated deficits commensurate with impaired executive control. One reason that trade-offs may have been less apparent in the MTBI group is that the digit-monitoring task was not as difficult for them, and therefore did not force patients to bias attention consistently toward one of the two tasks. Future studies with TBI patients could investigate possible differences in dual-task trade-offs more systematically by assessing performance when explicitly instructed to emphasize one task over the other, then comparing this performance with performance when the two tasks are given equal emphasis, similar to Craik et al. [8]. Such a comparison could potentially reveal whether a patient characteristically exhibits a particular type of bias, as well as whether the patient is capable of exerting cognitive control over the allocation of resources.

5. Conclusions

Using sensitive tests of effortful episodic encoding and retrieval we were able to discern executive control deficits in patients with both mild and moderate-to-severe TBI. Yet, had TBI groups been subdivided only on the basis of acute severity (i.e. a priori), and outcome been measured only according to performance on focused attention and/or standardized neuropsychological tests of attention and memory, no significant differences between controls and either MTBI or STBI(all) groups would have emerged. Indeed, regardless of injury severity, psychometric test performance appeared largely intact in these patients, indicating clinical evidence of relatively "good" recovery of function [59]. Rather impairments were most evident in the TBI patients when information was encoded under divided attention—conditions that may more realistically simulate the multi-tasking demands associated with the activities that these patients find most challenging in everyday life.

The demands of dual-task performance also revealed functional heterogeneity within the STBI group. When subdivided according to performance trade-offs, different patterns of memory performance emerged not only on all experimental measures, but also on standardized memory tests that were given 1–1.5 years prior to current testing. Thus, our experimental measures revealed persistent and pervasive memory and executive control deficits in the STBI(DB) subgroup, rather than deficits specific only to our tasks. Admittedly, these subgroups were small and their evaluation was necessarily post hoc, however if we had not assessed the relationship between encoding and digit-monitoring tasks, interesting strategy differences would have remained obscured and the pattern of results would have been weaker and more ambiguous. Although these results need to be replicated by future studies that directly manipulate strategic resource allocation, our current findings are valuable in suggesting that the variability of results from previous dual-task studies may be a product of uncontrolled variability in patient strategy. Indeed, by combining direct manipulation of task emphasis with more precise neurobehavioral and neurophysiological assessment at the time of acute injury, it may be possible to determine what combination of organic and behavioral factors predict these strategy differences.

More precise characterization of a patient's response to dual-task challenge also may have important consequences for choices of rehabilitative treatment. For example, Alderman [1] found that the ability to appropriately allocate resources under dual-task conditions better discriminated whether patients would benefit from a behavioral program of rehabilitation than measures of general intelligence, memory, or frontal-lobe function. Although in the present study, heterogeneity of strategy could only be observed in the group effect, manipulation of task emphasis may be able to reveal strategy differences on an individual basis, where it could provide important information regarding the direction and success of an individual's rehabilitation program.

Acknowledgements

Portions of this data were presented in a poster at the 1999 Rotman Research Institute Conference on Traumatic Brain Injury. We thank J. Perretta and C. Tebolt for assistance in collection and analysis of the data for this project. We also acknowledge the contributions of R. Macdonald, J. Hong, F. Carruth, and M. Binns to the collection and analysis of acute and 1–1.5 year post-injury data. This research was funded by Ontario Mental Health (M. Schwartz et al.) and CIHR (D. Stuss et al.) grants and a Post-Doctoral Rotman Research Fellowship to J.A. Mangels.

References

[1] Alderman N. Central executive deficit and response to operant conditioning methods. Neuropsychological Rehabilitation 1996;6:161–86.
[2] Anderson ND, Craik FIM, Naveh-Benjamin M. The attentional demands of encoding and retrieval in younger and older adults. I. Evidence from divided attention costs. Psychology and Aging 1998;13:405–23.
[3] Anderson ND, Idaka T, Cabeza R, Kapur S, McIntosh AR, Craik FI. The effects of divided attention on encoding- and retrieval-related brain activity: a PET study of younger and older adults. Journal of Cognitive Neuroscience 2000;12:775–92.
[4] Baddeley A. Working memory. Oxford, UK: Oxford University Press, 1986.
[5] Baddeley A, Della Sala S, Papagno C, Spinnler H. Dual-task performance in dysexecutive and nondysexecutive patients with a frontal lesion. Neuropsychology 1997;11:187–94.
[6] Binder LM, Rohling ML, Larrabee GJ. A review of mild head trauma. Part I. Meta-analytic review of neuropsychological studies. Journal of Clinical and Experimental Neuropsychology 1997;19:421–31.
[7] Campbell KB, de Lugt DR. Event-related potential measures of cognitive deficits following closed-head injury. In: Boller F, Grafman J, editors. Handbook of neuropsychology, vol. 10. Amsterdam: Elsevier, 1995. p. 269–97.
[8] Craik FIM, Govoni R, Naveh-Benjamin M, Anderson ND. The effects of divided attention on encoding and retrieval processes in human memory. Journal of Experimental Psychology: General 1996;125(2):159–80.
[9] Delis DC, Squire LR, Bihrle A, Massman P. Componential analysis of problem-solving ability: performance of patients with frontal lobe damage and amnesic patients on a new sorting test. Neuropsychologia 1992;30:683–97.
[10] Dikmen SS, Ross BL, Machamer JE, Temkin NR. One year psychosocial outcome in head injury. Journal of the International Neuropsychological Society 1995;1:67–77.
[11] Eslinger PJ. Conceptualizing, describing and measuring components of executive function: a summary. In: Lyon GR, Krasnegor NA, editors. Attention, memory and executive function. Baltimore, MD: Paul H. Brookes Publishing Co., 1996. p. 367–96.
[12] Fletcher PC, Frith CD, Grasby PM, Shallice T, Frackowiak RSJ, Dolan RJ. Brain systems for encoding and retrieval of auditory-verbal memory: an in vivo study in humans. Brain 1995;118:401–16.

[13] Gentry LR, Godersky JC, Thompson B, Dunn VD. Prospective comparative study of intermediate-field MR and CT in the evaluation of closed head trauma. American Journal of Neuroradiology 1988;9:101–10.
[14] Gershberg FB, Shimamura AP. The role of the frontal lobes in the use of organizational strategies in free recall. Neuropsychologia 1995;13:1305–33.
[15] Gray BG, Ichise M, Chung D, et al. Technietium-99m-HMPAO SPECT in the evaluation of patients with a remote history of traumatic brain injury: a comparison with X-ray computed tomography. Journal of Nuclear Medicine 1992;33:52–8.
[16] Gronwall D, Wrightson P. Memory and information processing capacity after closed head injury. Journal of Neurology, Neurosurgery, and Psychiatry 1981;44:889–95.
[17] Gross H, Kling A, Henry G, Herndon C, Lavretsky H. Local cerebral glucose metabolism in patients with long-term behavioral and cognitive deficits following mild traumatic brain injury. Journal of Neuropsychiatry and Clinical Neuroscience 1996;8:324–34.
[18] Hartman A, Pickering RM, Wilson BA. Is there a central executive deficit after severe head injury? Clinical Rehabilitation 1992;6:133–40.
[19] Idaka T, Anderson ND, Kapur S, Cabeza R, Craik FIM. The effect of divided attention on encoding and retrieval in episodic memory revealed by positron emission tomography. Journal of Cognitive Neuroscience 2000;12:267–80.
[20] Jacobs A, Put E, Ingels M, et al. Prospective evaluation of technetium-99m-HMPAO SPECT in mild and moderate traumatic brain injury. Journal of Nuclear Medicine 1994;35:942–7.
[21] Janowsky JS, Shimamura AP, Squire LR. Source memory impairment in patients with frontal lobe lesions. Neuropsychologia 1989;27:1043–56.
[22] Kaipio M, Alho I, Escera C. Event-related brain potentials reveal covert distractibility in closed injuries. NeuroReport 1999;10:2125–9.
[23] Kaipio ML, Cheour M, Ceponiene R, Ohman J, Alku P, Naatanen R. Increased distractibility in closed head injury as revealed by event-related potentials. NeuroReport 2000;11:1463–8.
[24] Levin HS. Prediction of recovery from traumatic brain injury. Journal of Neurotrauma 1995;12:913–22.
[25] Levin HS, Mendelsohn D, Lilly MA, Yeakley H, Song J, Scheibel RS, et al. Magnetic resonance imaging in relation to functional outcome of pediatric closed head injury: a test of the Ommaya-Gennarelli model. Neurosurgery 1997;40:432–41.
[26] Levin HS, O'Donnell VM, Grossman RG. The Galveston Orientation and Amnesia Test: a practical scale to assess cognition after head injury. Journal of Nervous and Mental Disorders 1979;169:675–84.
[27] Levine B, Cabeza R, McIntosh AR, Black SE, Grady CL, Stuss DT. Functional reorganization of memory following traumatic brain injury: a study with $H_2{}^{15}O$ PET. Journal of Neurology, Neurosurgery and Psychiatry, in press.
[28] Levine B, Dawson D, Boutet I, Schwartz ML, Stuss DT. Assessment of strategic self-regulation in traumatic brain injury: its relationship to injury severity and psychosocial outcome. Neuropsychology 2000;14:491–500.
[29] Levine B, Stuss DT, Milberg WP. Concept generation: validation of a test of executive functioning in a normal aging population. Journal of Clinical and Experimental Neuropsychology 1995;17:740–58.
[30] Levine B, Stuss DT, Milberg WP, Alexander MP, Schwartz M, Macdonald R. The effects of focal and diffuse brain damage on strategy application: evidence from focal lesions, traumatic brain injury, and normal aging. Journal of the International Neuropsychological Society 1998;4:247–64.
[31] Mangels JA. Strategic processing and memory for temporal order in patients with frontal lobe lesions. Neuropsychology 1997;11:207–21.
[32] Mangels JA, Picton TW, Craik FIM. Attention and successful episodic encoding: an event-related potential study. Cognitive Brain Research 2001;11:77–95.
[33] Marshall LF, Marshall SB, Klauber MR, Van Berkum Clark M, Eisenberg HM, Jane JA, et al. The diagnosis of head injury requires a classification based on computed axial tomography. Journal of Neurotrauma 1992;9:S287–92.
[34] Mattson AJ, Levin HS. Frontal lobe dysfunction following closed head injury. Journal of Nervous and Mental Disease 1990;178:282–91.
[35] McAllister TW, Saykin AJ, Flashman LA, Sparling MB, Johnson SC, Guerin SJ, et al. Brain activation during working memory 1 month after mild traumatic brain injury: a functional MRI study. Neurology 1999;53:1300–8.
[36] McDowell S, Whyte J, D'Esposito M. Working memory impairments in traumatic brain injury: evidence from a dual-task paradigm. Neuropsychologia 1997;35:1341–53.
[37] Melo B, Winocur G, Moscovitch M. False recall and false recognition: an examination of the effects of selective and combined lesions to the medial temporal lobe/diencephalon and frontal lobe structures. Cognitive Neuropsychology 1999;16:343–59.
[38] Miller EK, Cohen JD. An integrative theory of prefrontal cortex function. Annual Review of Neuroscience 2001;24:167–202.
[39] Niemann H, Ruff RM, Kramer JH. An attempt towards differentiating attentional deficits in traumatic brain injury. Neuropsychology Review 1996;6:11–46.
[40] Ponsford J, Kinsella G. Attentional deficits following closed head injury. Journal of Clinical and Experimental Neuropsychology 1992;14:822–38.
[41] Ponsford J, Willmott C, Rothwell A, Cameron P, Kelly A-M, Nelms R, et al. Factors influencing outcome following mild traumatic brain injury in adults. Journal of the International Neuropsychological Society 2000;6:568–79.
[42] Roenker DL, Thompson CP, Brown SC. Comparison of measures for the estimation of clustering in free recall. Psychological Bulletin 1971;76:45–58.
[43] Ruff RM, Crouch A, Troster AI, Marshall F, Buschsbaum MS, Lottenberg S. Selected cases of poor outcome following a minor brain trauma: comparing neuropsychological and positron emission tomography assessment. Brain Injury 1994;10:551–66.
[44] Ruff RM, Marhsall LF, Crouch J, Klauber MR, Levin HS, Barth J, et al. Predictors of outcome following severe head trauma: follow-up data from the Traumatic Coma Data Bank. Brain Injury 1993;7:101–11.
[45] Santos ME, Castro-Caldas A, Sousa L. Spontaneous complaints of long-term traumatic brain injured subjects and their close relatives. Brain Injury 1998;12:759–67.
[46] Schacter DL, Harbluk JL, McLachlan DR. Retrieval without recollection: an experimental analysis of source amnesia. Journal of Verbal Learning and Verbal Behavior 1984;23:593–611.
[47] Schacter DL, Verfaellie M, Pradere D. The neuropsychology of memory illusions: false recall and recognition in amnesic patients. Journal of Memory and Language 1996;35:319–34.
[48] Schmitter-Edgecombe M. Effects of divided attention and explicit memory performance following severe closed head injury. Neuropsychology 1996;10:155–67.
[49] Schmitter-Edgecombe M. Effects of traumatic brain injury on cognitive performance: an attentional resource hypothesis in search of data. Journal of Head Trauma Rehabilitation 1996;11:17–30.
[50] Shallice T. Specific impairments of planning. In: Broadbent DE, Weiskrantz L, editors. The neuropsychology of cognitive function. London: The Royal Society, 1982. p. 199–209.
[51] Shallice T, Burgess P. Higher-order cognitive impairments and frontal lobe lesions in man. In: Levin HS, Eisenberg HM, Benton AL, editors. Frontal lobe function and dysfunction. New York: Oxford University Press, 1991. p. 125–38.
[52] Shimamura AP, Squire LR. A neuropsychological study of fact memory and source amnesia. Journal of Experimental Psychology: Learning, Memory and Cognition 1987;13:464–73.

[53] Snodgrass JG, Vanderwart M. A standardized set of 260 pictures: norms for name agreement, image agreement, familiarity, and visual complexity. Journal of Experimental Psychology: Human Learning and Memory 1980;6:174–215.

[54] Stablum F, Mogentale C, Umilta C. Executive functioning following mild closed head injury. Cortex 1996;32:261–78.

[55] Stern Y. What is cognitive reserve? Theory and research application of the reserve concept. Journal of Clinical and Experimental Neuropsychology 2002;58:1182–8.

[56] Stuss DT, Alexander MP, Palumbo CL, Buckle L, Sayer L, Pogue J. Organizational strategies of patients with unilateral or bilateral frontal lobe injury in word list learning tasks. Neuropsychology 1994;8:355–78.

[57] Stuss DT, Binns MA, Carruth FG, Levine B, Brandys CF, Moulton RJ. The acute period of recovery from traumatic brain injury: post-traumatic amnesia or post-traumatic confusional state? Journal of Neurosurgery 1999;90:635–43.

[58] Stuss DT, Binns MA, Carruth FG, Levine B, Brandys CF, Moulton RJ. Prediction of recovery of continuous memory after traumatic brain injury. Neurology 2000;54:1337–44.

[59] Stuss DT, Ely P, Hugenholtz H, Richard MT, LaRochelle S, Poirier CA. Subtle neuropsychological deficits in patients with good recovery after closed head injury. Neurosurgery 1985;17:41–7.

[60] Stuss DT, Gow CA. "Frontal-dysfunction" after traumatic brain injury. Neuropsychiatry, Neuropsychology, and Behavioral Neurology 1992;5:272–82.

[61] Teasdale G, Jennett B. Assessment of coma. Lancet 1974;2:81–4.

[62] Troyer AK, Winocur G, Craik FI, Moscovitch M. Source memory and divided attention: reciprocal costs to primary and secondary tasks. Neuropsychology 1999;13:467–74.

[63] Van Zomeren AH, Van Den Burg W. Residual complaints of patients 2 years after severe head injury. Journal of Neurology, Neurosurgery, and Psychiatry 1985;48:21–8.

[64] Veltman JC, Brouwer WH, Van Zomeren AH, van Wolffelaar PC. Central executive aspects of attention in subacute severe and very severe closed head injury patients: planning, inhibition, flexibility, and divided attention. Neuropsychology 1996;10: 357–67.

[65] Vilkki J, Virtanen S, Surma-Aho O, Servo A. Dual task performance after focal cerebral lesions and closed head injuries. Neuropsychologia 1996;34:1051–6.

[66] Watt S, Shores EA, Kinoshita S. Effects of reducing attentional resources on implicit and explicit memory after severe brain injury. Neuropsychology 1999;13:338–49.

[67] Wheeler MA, Stuss DT, Tulving E. Frontal lobe damage produces episodic memory impairment. Journal of the International Neuropsychological Society 1995;1:525–36.

[68] Whyte J, Polansky M, Cavallucci C, Fleming M, Lhulier J, Coslett HB. Inattentive behavior after traumatic brain injury. Journal of the International Neuropsychological Society 1996;2:274–81.

[69] Whyte J, Schuster K, Polansky M, Adams J, Coslett HB. Frequency and duration of inattentive behavior after traumatic brain injury: effects of distraction, task and practice. Journal of the International Neuropsychological Society 2000;6:1–11.