Slowing Down after a Mild Traumatic Brain Injury: A Strategy to Improve Cognitive Task Performance?

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Abstract

Long-term persistent attention and memory difficulties following a mild traumatic brain injury (TBI) often go undetected on standard neuropsychological tests, despite complaints by mild TBI individuals. We conducted a visual Repetition Detection working memory task to digits, in which we manipulated task difficulty by increasing cognitive load, to identify subtle deficits long after a mild TBI. Twenty-six undergraduate students with a self-report of one mild TBI, which occurred at least 6 months prior, and 31 non-head-injured controls took part in the study. Participants were not informed until study completion that the study’s purpose was to examine cognitive changes following a mild TBI, to reduce the influence of “diagnosis threat” on performance. Neuropsychological tasks did not differentiate the groups, though mild TBI participants reported higher state anxiety levels. On our working memory task, the mild TBI group took significantly longer to accurately detect repeated targets on our task, suggesting that slowed information processing is a long-term consequence of mild TBI. Accuracy was comparable in the low-load condition and, unexpectedly, mild TBI performance surpassed that of controls in the high-load condition. Temporal analysis of target identification suggested a strategy difference between groups: mild TBI participants made a significantly greater number of accurate responses following the target’s offset, and significantly fewer erroneous distracter responses prior to target onset, compared with controls. Results suggest that long after a mild TBI, high-functioning young adults invoke a strategy of delaying their identification of targets in order to maintain, and facilitate, accuracy on cognitively demanding tasks.

Keywords: Head injury; Traumatic brain injury; Learning and memory; Attention; Executive functions; Everyday functioning; Anxiety

Introduction

Memory and concentration problems are frequent cognitive complaints long after experiencing a mild traumatic brain injury (TBI; Alves, 1993; Meares et al., 2011; Vanderploeg, Curtiss, Luis, & Salazar, 2007; Villemure, Nolin, & Le Sage, 2011); yet long-term impairments have not been reliably documented in the literature. Several meta-analyses report no significant long-term cognitive effects of a mild TBI, based on performance on standard neuropsychological tests (Belanger, Curtiss, Demery, Lebowitz, & Vanderploeg, 2005; Binder, Rohling, & Larrabee, 1997; Frencham, Fox, & Maybery, 2005; Rohling et al., 2011), though a few studies have reported residual deficits on standard neuropsychological tasks at least 3 months after mild TBI limited to the cognitive domains of attention (Chan, 2002; Potter, Jory, Bassett, Barrett, & Mychalkiw, 2002; Solbakk, Reinvang, Neilsen, & Sundet, 1999; Vanderploeg, Curtiss, & Belanger, 2005) and information processing speed (Bernstein, 2002; Johansson, Berglund, & Ronnback, 2009; Potter et al., 2002). Results may be null or inconsistent across studies because the effects are small, the tests are insensitive, and/or the measures of functioning are too coarse. The current study examines these possibilities.

A study by Vanderploeg and colleagues (2005) suggests deficits following a mild TBI are evident only using non-standard and more sensitive measures of performance. They report no effect of a past mild TBI on cognitive functioning using standard neuropsychological measures. They did, however, find higher discontinuation rates (a non-standard measure) on a task...
measuring attention and working memory abilities (on the Paced Auditory Serial Addition Test; PASAT) in individuals who sustained a mild TBI at least 1 year prior to testing compared with non-head-injured controls. Thus, novel assessments of attention and working memory can reveal deficits. Moreover, increasing task complexity in controlled experimental studies can indicate significant cognitive impairments in participants long after mild TBI compared with non-head-injured controls. For example, dividing attention between two concurrently performed tasks decreased information processing speed (Cicerone, 1996; Pare, Rabin, Fogel, & Pepin, 2008), as well as accuracy (Bernstein, 2002; Pare et al., 2008), in mild TBI participants in the post-acute phase compared with controls, highlighting an attention deficit. Thus, non-standard tasks and novel measures of performance can illuminate the long-term effects of a mild TBI. In the current study, we created a new computerized working memory task that permitted us to manipulate attentional demand, as well as obtain accuracy and sensitive response time measures, in order to more specifically investigate the long-lasting effects of one mild TBI on cognitive functioning.

As previously mentioned, whereas meta-analyses of neuropsychological functioning long after mild TBI have found no significant differences in these individuals compared with controls (Belanger et al., 2005; Binder et al., 1997; Frencham et al., 2005; Rohling et al., 2011), slowing of information processing speed has shown larger effect sizes (Frencham et al., 2005). In fact, compared with other neuropsychological measures, information processing speed was the only measure to differentiate individuals with moderate-severe TBI from mild TBI participants (Martin, Donders, & Thompson, 2000). Yet, distinguishing individuals with mild TBI from non-head-injured controls has proven to be more difficult and depends on whether the task measures simple attention and reaction time, or complex information processing speed. Simple reaction time tasks require a button press in response to a single pre-determined target among non-targets, whereas more complex tasks, such as choice- or semantic-reaction time tests, increase information processing demand by requiring participants to press one button for a specific stimulus (or specific category of stimuli) and another button for all other non-target stimuli (or another category of stimuli). In other words, the complex tasks require participants to hold an additional set of rules or information in mind while simultaneously processing target information. Whereas severe TBI individuals have been shown to perform significantly slower compared with controls and mild TBI participants on three reaction time tasks that ranged from simple to complex (Tombaugh, Stormer, Harrison, & Smith, 2007), mild TBI had longer mean reaction times on only the most complex tasks compared with controls within 1 month of after injury (Tombaugh et al., 2007) and up to 3 months post-injury (Hugenholtz, Stuss, Stethem, & Richard, 1988). Taken together, these results suggest that simple neuropsychological measures of processing speed may be sensitive to injury severity within the TBI population, but more complex tasks are required to distinguish a mild TBI population from healthy non-head-injured controls, particularly when trying to uncover long-term consequences of mild TBI.

The value of using sensitive response time measures as a clinical tool along with neuropsychological test batteries in the TBI population was recognized long ago (Ferraro, 1996), but this tool has not been widely recognized in research investigating long-term cognitive effects long after a single mild TBI. From the extant mild TBI literature, it still remains difficult to disentangle whether a past mild TBI results in specific deficits in higher level cognitive functioning (decreased accuracy on divided attention tasks; Bernstein, 2002; Pare et al., 2008), in a general slowing of information processing (largest effect size in meta-analysis; Frencham et al., 2005), in both (slowing observed only on cognitive demanding tasks; Cicerone, 1996; Hugenholtz et al., 1988; Martin et al., 2000; Pare et al., 2008), or neither of the two (no neuropsychological deficits reported in meta-analyses; Belanger et al., 2005; Binder et al., 1997; Frencham et al., 2005; Rohling et al., 2011). To better define these potentially long-lasting, but subtle deficits, it is essential to obtain both sensitive response time measures and accuracy rates in low-demanding and highly demanding cognitive task conditions in order to better define lasting changes in information processing following a single mild TBI. The employment of such rigorous methodology may also help to disentangle whether mild TBI results in a deficit in a specific cognitive domain, such as working memory, or a more general slowing of information processing speed, which then contributes to deficits in specific cognitive domains (Chiara­valotti, Christodoulou, Demaree, & DeLuca, 2003).

The purpose of the present study was to examine the possible long-term residual effects of one mild TBI on accuracy and information processing speed on a working memory task with varying levels of attentional load. Specifically, we administered a modified version of the Repetition Detection working memory task (Bopp & Verhaeghen, 2007) in which participants are asked to identify a repeated digit in both low- and high-load working memory conditions. In the low-load condition, participants were instructed to identify a visually presented repeated digit within a string of random digits. Such a working memory task requires storage (holding a string of digits in mind) and simultaneous manipulation of information (determining if the presentation of a new digit matches one of the digits held in mind). In the high-load condition, attentional demand was increased by asking participants to identify a repeated digit, but only when it was enclosed by a square of the same color. Thus, participants were still required to simultaneously store and manipulate information, but also to monitor (selectively attend to color) and control output (identify target digits that repeat in same color and ignore distracter digits that repeat in
two different colors). The design of our task permitted us to not only to examine accuracy across a group of mild TBI and control participants, but also allowed us to obtain sensitive response time measures, including the average time to accurately respond to a target per trial, and the position of accurate and distracter responses relative to the target within each trial. Keeping in mind previous research suggesting a lasting impairment in information processing speed following a mild TBI, we lifted response time restrictions in our task and, instead, permitted participants an unlimited response time window (see “Methods” section for more details). The use of sensitive response time measures in two different working memory conditions that vary in task complexity may allow for the detection of more subtle changes associated with a remote mild TBI.

In addition, we administered standard neuropsychological tasks to each participant to measure cognitive functioning and simple information processing speed within various cognitive domains. Moreover, we obtained self-report measures of cognitive and affective functioning. Two questionnaires, the Attention-Related Cognitive Error Scale (ARCES) and the Memory Failures Scale (MFS), were used to document frequency and type of participants’ everyday lapses in attention and memory failures, respectively (Cheyne, Carriere, & Smilek, 2006). The State-Trait Anxiety Inventory (STAI) and the Beck Depression Inventory (BDI) were also administered to assess potential long-lasting effects of a mild TBI on affective functioning.

Studying the mild TBI population has not only shown to be difficult due to the subtlety of deficits, but also due to various confounding variables. In addition to screening for common extraneous variables such as neuropsychiatric, neurological, and affective problems, this study was designed reduce the influence of a variable relatively recently shown to influence cognitive performance in the mild TBI population called “diagnosis threat.” The term can be related to the well-known phenomenon of “stereotype threat,” in which a member of a specific group may display poor task performance simply because he/she is aware that the task is thought to be performed poorly by members of that group. A handful of studies have demonstrated that mild TBI participants exposed to “diagnosis threat” (i.e., told that they may be experiencing cognitive problems post-injury), show poorer performance on neuropsychological tasks, slower average psychomotor speed (Suhr & Gunstad, 2002, 2005) and higher reports of everyday attention and memory lapses (Ozen & Fernandes, 2011) compared with “neutral” mild TBI participants and “neutral” controls who were unaware of the study’s purpose. In an attempt to mitigate the effects of “diagnosis threat,” control and mild TBI participants in the current study were not informed of the study’s purpose until after task completion; the same protocol used in Ozen and Fernandes’ (2011) “neutral” condition.

We hypothesized that regardless of group membership, all participants would be less accurate and slower to identify a repeated digit in the high versus low cognitive processing load condition on our Repetition Detection working memory task. Moreover, we anticipated that mild TBI participants would perform more slowly, but no less accurately in the low-load working memory condition. However, with the additional increase in attentional demand, we expected that mild TBI participants would perform both more slowly and less accurately, compared with controls, during the high-load working memory condition. Similar to the majority of previous reports, we did not expect any group differences to emerge on the neuropsychological tasks, nor on our cognitive self-report measures. We did anticipate, however, that mild TBI participants would report higher levels of anxiety compared with controls, a result previously reported in the mild TBI literature (Dischinger, Ryb, Kufera, & Auman, 2009; Westcott & Alfano, 2005) and in participants who were not exposed to “diagnosis threat” (Ozen & Fernandes, 2011).

Methods

Classification of Mild TBI

Participants were recruited from the University of Waterloo’s Research Experience Group, which consists of undergraduate students enrolled in psychology courses who receive course credit for participating in research. At the beginning of every semester, undergraduate students who are enrolled in at least one psychology course complete an online multiple-choice prescreen questionnaire, later used by researchers throughout the semester to recruit participants for their studies. The questions range from those asking about demographic information to medical history to relationship status. For this study, we embedded five questions in the 90-item questionnaire in order to obtain information about head injury history and severity (Appendix). Because our head injury questions were among many other questions, it is very unlikely that participants anticipated that we were examining the effects of head injury on cognition when they later signed up for our specific study. Moreover, the prescreen questionnaire was filled out anywhere from 1 to 3 months prior to participation in our study, which, depending on study length, was only one in up to 10 studies per course that each student was required to complete for course credits.

In order to group participants based on head injury status, two studies with identical titles were posted on the University of Waterloo’s Research Experience Group website: one that was only visible to undergraduate students who had indicated never experiencing a prior head injury and one that was only visible to students who reported sustaining a past mild TBI (the
experiment management computer system makes this procedure possible based on answers provided by students to head injury questions on prescreen questionnaire. If participants were interested in this study, they would then voluntarily sign up for a specific time slot posted online.

A mild TBI was defined as any strike to the head or any acceleration/deceleration force (i.e., whiplash) that resulted in a loss of consciousness (LOC) lasting at least a couple of seconds and no longer than 30 min (Kay et al., 1993). Participants could also report experiencing memory loss (brief amnesia), confusion (inability to focus attention), and/or disorientation (loss of physical bearings), all not exceeding 24 h (as in Kay et al., 1993); in addition to LOC (Table 1). We only included participants in our study if they fit the criteria of a mild TBI, and if they sustained their mild TBI at least 6 months prior to testing.

Exclusion Criteria

In order to confirm the responses provided by participants on the online prescreen questionnaire, participants were asked the same demographic- and health-related questions in person, by the researcher, at the end of the experiment. If inconsistencies were found between the two questionnaires, participants were excluded from the study, as group membership could not be reliably established. This resulted in three control participants being excluded from the study: all three reported, in person, experiencing a concussion in the past. Five mild TBI participants were excluded from the study: three reported that they did not lose consciousness following their head injury and two hit their head as a result of fainting for an unknown reason (we excluded such participants as a pre-existing condition may have caused them to faint and may have affected cognition prior to the head injury).

Participants

Fifty-seven undergraduate students signed up online to participate in this experiment for course credit; 26 participants who experienced a prior mild TBI (13 women) and 31 had no history of head injury (17 women). The mean age of control

Table 1. Demographic and head injury characteristics

<table>
<thead>
<tr>
<th>Gender</th>
<th>Age</th>
<th>Education</th>
<th>TSI</th>
<th>LOC</th>
<th>Memory loss</th>
<th>Confusion</th>
<th>Disorientation</th>
<th>Cause of injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>F 19</td>
<td>13.0</td>
<td>0 &gt; 1 min</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tripped and hit head on door</td>
</tr>
<tr>
<td>M 23</td>
<td>13.5</td>
<td>16.0</td>
<td>0 &gt; 1 min</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>Hit on head with an ice block</td>
</tr>
<tr>
<td>M 23</td>
<td>14.0</td>
<td>5.00</td>
<td>0 &gt; 1 min</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>Hit head on goal after playing football</td>
</tr>
<tr>
<td>F 25</td>
<td>16.0</td>
<td>9.00</td>
<td>1 &gt; 5 min</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>Hit on head with a discus</td>
</tr>
<tr>
<td>F 23</td>
<td>15.5</td>
<td>0.83</td>
<td>0 &gt; 1 min</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td>Fell snowboarding and hit back of head</td>
</tr>
<tr>
<td>M 19</td>
<td>13.5</td>
<td>1.17</td>
<td>1 &gt; 5 min</td>
<td>*</td>
<td></td>
<td></td>
<td>*</td>
<td>Tripped and hit head on table</td>
</tr>
<tr>
<td>F 19</td>
<td>13.5</td>
<td>10.00</td>
<td>1 &gt; 5 min</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>Hit on head with tire swing</td>
</tr>
<tr>
<td>F 19</td>
<td>13.0</td>
<td>4.00</td>
<td>1 &gt; 5 min</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td>Hit heads with another player during baseball</td>
</tr>
<tr>
<td>M 19</td>
<td>13.0</td>
<td>10.00</td>
<td>1 &gt; 5 min</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>Rode into wall while riding bike</td>
</tr>
<tr>
<td>M 22</td>
<td>16.0</td>
<td>9.00</td>
<td>1 &gt; 5 min</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>Fell and hit head on ice during hockey</td>
</tr>
<tr>
<td>F 18</td>
<td>12.0</td>
<td>10.00</td>
<td>0 &gt; 1 min</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>Fell during red rover and hit head on ground</td>
</tr>
<tr>
<td>F 19</td>
<td>13.0</td>
<td>2.00</td>
<td>1 &gt; 5 min</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td>Hit head against boards during hockey</td>
</tr>
<tr>
<td>M 18</td>
<td>12.0</td>
<td>4.00</td>
<td>0 &gt; 1 min</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>Pushed into boards, fell, and hit head on ice</td>
</tr>
<tr>
<td>F 22</td>
<td>15.5</td>
<td>2.25</td>
<td>0 &gt; 5 min</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td>Fell from tree branch and hit head on ground</td>
</tr>
<tr>
<td>F 21</td>
<td>14.5</td>
<td>5.00</td>
<td>0 &gt; 1 min</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Car accident—hit head on door frame</td>
</tr>
<tr>
<td>F 22</td>
<td>14.0</td>
<td>9.00</td>
<td>0 &gt; 1 min</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fell rock climbing and hit head on ground</td>
</tr>
<tr>
<td>F 18</td>
<td>12.0</td>
<td>4.00</td>
<td>1 &gt; 5 min</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td>Hit on head with baseball</td>
</tr>
<tr>
<td>M 19</td>
<td>13.0</td>
<td>12.00</td>
<td>0 &gt; 1 min</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td>Fell off ladder and hit head on ground</td>
</tr>
<tr>
<td>M 21</td>
<td>13.5</td>
<td>13.00</td>
<td>1 &gt; 5 min</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>Pushed and hit head on bench</td>
</tr>
<tr>
<td>M 18</td>
<td>12.0</td>
<td>2.00</td>
<td>0 &gt; 1 min</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>Hit on head with lacrosse stick</td>
</tr>
<tr>
<td>M 19</td>
<td>12.5</td>
<td>7.00</td>
<td>1 &gt; 5 min</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>Hit head on goal after playing football</td>
</tr>
<tr>
<td>M 20</td>
<td>13.5</td>
<td>7.00</td>
<td>0 &gt; 1 min</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Hit head on wall playing handball</td>
</tr>
<tr>
<td>F 26</td>
<td>22.0</td>
<td>10.00</td>
<td>0 &gt; 1 min</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>Hit on head with discus</td>
</tr>
<tr>
<td>M 20</td>
<td>13.5</td>
<td>4.00</td>
<td>0 &gt; 1 min</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Hit by car while walking across the street</td>
</tr>
<tr>
<td>F 22</td>
<td>15.5</td>
<td>2.00</td>
<td>1 &gt; 5 min</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td>Fell and hit head on ice while skating</td>
</tr>
<tr>
<td>M 22</td>
<td>15.0</td>
<td>6.00</td>
<td>0 &gt; 1 min</td>
<td></td>
<td>*</td>
<td></td>
<td>*</td>
<td>Hit on head with soccer ball</td>
</tr>
<tr>
<td>Mean</td>
<td>20.62</td>
<td>13.96</td>
<td>6.82</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>2.23</td>
<td>1.74</td>
<td>4.19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: TSI = time since injury in years; LOC = duration of loss of consciousness; F = female; M = male. Means and standard deviations given for age, education, and TSI. Asterisks indicate that participant experienced the specific side effect (<24 h) listed in column header.
participants was 20.48 ($SD = 1.59$) and 20.62 ($SD = 2.23$) for mild TBI participants, which did not significantly differ, $t(55) = -0.26$, $p > .05$. Similarly, the mean education level did not significantly differ, $t(55) = 0.20$, $p > .05$, between control ($M = 14.03$ years, $SD = 0.94$) and mild TBI groups ($M = 13.96$, $SD = 1.74$). All participants were fluent English speakers and if English was not their first language, it had to be learned before age 5 for inclusion in the study. Moreover, all participants had to report that they were free from any psychological (including clinical anxiety and depression) or neurological disorders at the time of testing to be included in the study (questions included in the prescreen questionnaire). Participants were also required to have normal or corrected-to-normal hearing and vision, according to self-report, and were right handed. All procedures were performed in compliance with University of Waterloo’s ethics laws and guidelines for human research and were approved by the University’s Office of Research Ethics.

**Working Memory Task**

**Materials.** The Repetition Detection working memory task from Bopp and Verhaeghen (2007) was adapted for use in our study. The task was administered with a computer, using E-Prime version 1.2 (Psychology Software Tools Inc., Pittsburgh, PA, USA) and was composed of two conditions: low and high load. Target stimuli in each condition were identical, but task instructions were varied. Digits (1–9) were presented in 100-point Arial font and enclosed by a 10.63 cm $\times$ 10 cm red- or blue-colored square. For both load conditions, a trial consisted of eight single digits (each presented within a red- or a blue-colored square), one at a time in the center of the computer screen, on a white background (Fig. 1).

**Procedure.** Each condition consisted of 20 trials, plus 5 practice trials. Participants sat at a comfortable distance from the computer screen. Each trial began with a fixation cross displayed for 1,000 ms, followed by the stimulus onset for 1,750 ms. There was an inter-stimulus interval (white blank screen) of 250 ms. After the offset of the last stimulus was an inter-trial interval (blank screen) of 1,000 ms, followed by another fixation cross, with “Press spacebar to continue” [the next trial] written below.

In the low-load condition, one of the eight digits was repeated in each trial. Participants were instructed to press the corresponding number on the keyboard when they identified the repeated digit as quickly and accurately as possible. In the high-load condition, participants were also required to identify the repeated digit, but only if it was enclosed by the “same” colored square (e.g., two number “3”’s enclosed in red squares or two number “3”’s enclosed in blue squares, but not one “3” enclosed in a red square and one “3” enclosed in a blue square). Participants were warned that a digit may repeat in two “different” colored squares (one in red and one in blue), but that these were distracters and a response should not be made. In the low-load condition, the digits were also presented in alternating red and blue squares, but no mention of color was made by the experimenter until the high-load condition when color was relevant to task performance (Fig. 1).

Participants were instructed to press the corresponding number as soon as they identified the repeated target, although they could make their response anytime following the target (even during the blank screens or presentation of other digits). They were told that their response would be recorded, but that each trial would continue until all stimuli had been presented. If, by the end of the presentation of the eight digits, they were unsure of which one was repeated, they could respond by pressing the “0”

![Fig. 1](image-url).

In both conditions of the Repetition Detection working memory task, eight single digits appeared one at a time on the screen for each trial. All numbers were enclosed by a colored square: red or blue. In the low-load condition, participants were instructed to press the corresponding number on the keyboard when they identified that a number had repeated within a trial. In the high-load condition, participants were also asked to identify the repeated digit, but this time only if the repeated digit was enclosed by the same color square in which it was originally presented. They were told to ignore a repeated digit if it was not enclosed by the same color square (distracter stimuli; red 6 and blue 6). The number to the right of the vertical line indicates the correct answer for each condition (red 7 and blue 2).
key. Even though they had until the end of each trial to respond, participants were told at the beginning of each condition that they should respond as quickly and accurately as possible, and to attempt to respond during the presentation of the repeated stimulus. A lag of three stimuli between target repeats was used in both conditions. A lag of two stimuli between distracter repeats was used in the high-load condition.

Neuropsychological Tests

Working memory span was assessed using the Digit-span forward and backward tasks (Wechsler, 1997). The Trail-making tests A and B (Reitan & Wolfson, 1985) were used to examine processing speed and cognitive flexibility, respectively. Performance on trial 1 of list 1 of the California Verbal Learning Test (CVLT; Delis, Kramer, Kaplan, & Ober, 1987) was used to obtain a measure of immediate verbal memory. Participants also completed a 5-min computerized version of the Stroop task administered with E-prime v.1.2 (Psychology Software Tools Inc.) software to measure selective attention, cognitive flexibility, and processing speed. They were informed that a string of letters (“xxxx”, “red”, or “green”; presented in Courier New font, with 18 point size) would appear one at a time on the computer screen, and to press the “z” key if the font color was red and “m” if the font color was green (counterbalanced). The task was made up of 138 trials: 46 of which were neutral (“xxxx” shown in red or green), 46 congruent (the word “red” in red-color font and the word “green” in green-color font), and 46 incongruent (the word “red” in green-color font and the word “green” in red-color font). Participants’ accuracy and response time in each condition were recorded.

Self-Report Scales

All participants completed the demographic/health form, BDI (Beck, Steer, & Brown, 1996), STAI (Spielberger, Gorsuch, & Lushene, 1970), ARCES, and MFS (Cheyne et al., 2006). The latter two scales are composed of 12 questions that ask participants to respond by choosing one of five responses on a Likert scale ranging from “Never” to “Very Often.” The scales were originally developed by selecting items from the Cognitive Failures Scale (Broadbent, Cooper, FitzGerald, & Parkes, 1982), Reason’s diary studies (Reason & Mycielska, 1982) in which participants recorded descriptions of slips of action in their daily lives, and from the authors’ own experiences, based on personal diaries of attention and memory lapses.

Experiment Procedure

All participants began the experiment by reading the Information Letter and signing the Consent form. The Letter informed participants that we were studying working memory and attention in young adults using a variety of tasks, but no mention of head injury was made until the experimental session was complete. The Repetition Detection task was the first to be completed, with the low-load condition always administered prior to high load. Participants then completed the Digit Span, Trail Making, and trial 1 of the CVLT. Next, the STAI and BDI were administered, followed by the Stroop task, ARCES, and MFS. The researcher then asked all participants questions from the demographic/health questionnaire to obtain additional details about their head injury, should they have had one, and to confirm answers on the prescreen questionnaire. Finally, the researcher provided participants with feedback sheets and debriefed them on the actual purpose of the study: to investigate the residual effects of a mild TBI on cognitive functioning. Participants were also informed of their group membership (control or mild TBI) and that group membership was determined by answers to head injury questions on the prescreen questionnaire completed online.

Results

Working Memory Task

Two repeated-measure analyses of variance (ANOVA) with “working memory load” as the within-subject variable (low and high load) and “group” as the between-subject variable (control and mild TBI) were used to examine accuracy and response times on the working memory task. Participants whose median response times were 2.5 SD above or below the group mean were tagged as outliers and subsequently removed from the working memory analyses. This resulted in the removal of two control participants: one had a median response time of 4 SD and another with 2.5 SD above the control group mean.
**Hit Rate**

The hit rate was calculated by dividing each participant’s total number of accurate responses by 20, the total possible number of accurate responses. These proportions were averaged across participants in each group to yield a control and mild TBI mean group hit rate. As predicted, there was a main effect of working memory load, $F(1,53) = 94.51, p < .001$, $\eta^2 = 0.64$, such that participants’ mean hit rate was higher in the low-load, $M = 0.97$, $SD = 0.04$, compared with high-load condition, $M = 0.73$, $SD = 0.19$, regardless of group membership (Fig. 2). A significant two-way interaction emerged, $F(1,53) = 9.62, p < .004$, $\eta^2 = 0.15$, such that the groups differed only in the high-load condition, $t(53) = -2.94, p < .006$. Unexpectedly, mild TBI participants had significantly higher hit rates, $M = 0.81$, $SD = 0.15$, compared with controls, $M = 0.67$, $SD = 0.20$. No significant differences in the hit rate, $t(53) = 0.32, p > .75$, emerged between mild TBI, $M = 0.97$, $SD = 0.04$, and control participants, $M = 0.97$, $SD = 0.05$, in the low-load condition.

**Response Times**

For each participant, the median response time was calculated for accurate trials in both the low- and high-load conditions. Following this, group mean response times were calculated by averaging individual median response times in each condition. In line with our hypothesis, participants had significantly slower response times, $F(1,53) = 41.56, p < .001$, $\eta^2 = 0.44$, in the high-load, $M = 2,703.28$ ms, $SD = 1,626.47$, compared with low-load condition, $M = 1,822.18$ ms, $SD = 1,668.79$, regardless of group membership (Fig. 2). In addition, a main effect of group emerged, $F(1,53) = 8.18, p < .007$, $\eta^2 = 0.13$, such that mild TBI participants responded significantly slower, $M = 2,889.52$ ms, $SD = 2,193.28$, compared with control participants, $M = 1,700.78$ ms, $SD = 979.02$. The interaction was not significant, $F(1,53) = 2.34, p > .13$.

**Temporal Analysis of Target Identifications**

Due to the unexpected higher average hit rate in the mild TBI group compared with the controls in the high-load condition, post hoc analyses were conducted to determine when, within each trial, participants were making correct repeat identifications. As noted by Vanderploeg and colleagues (2005), novel and non-standard measures of task performance (PASAT

![Fig. 2. Hit rate: The top graph shows a significant interaction, such that the proportion of correctly identified targets did not differ between controls and mild TBI participants in the low-load condition of the Repetition Detection working memory task. However, in the high-load condition, mild TBI participants accurately identified a larger proportion of targets compared with controls. Mean response time: The bottom graph shows a main effect of median response time (in ms), such that mild TBI participants were significantly slower compared with controls, regardless of working memory task condition.](image-url)
discontinuation rates in their case) may be more likely to be sensitive to the cognitive approach of mild TBI participants. As extant literature points to slowed cognitive processing in TBI patients, we devised a means of examining how this might be used as a strategy, on our task, in the mild TBI group. We anticipated that a possible explanation for the increased hit rate, in mild TBI participants compared with controls in the high-load condition, was that mild TBI participants were taking advantage of the unlimited response time window, allowing for more correct responses to be made after the target offset compared with controls.

For each participant, the total number of targets accurately identified was split into two categories: repeats identified “during” the target presentation (During Target) and repeats identified “after” the target offset (After Target). Two repeated-measure ANOVAs with working memory load as the within-subject variable (low and high load) and group as the between-subject variable (control and mild TBI) were used to examine accurate responses made either during the presentation of the target or after the offset of the target. The first ANOVA examined mean number of During Target responses, and the second ANOVA examined mean number of After Target responses.

In the first ANOVA, a main effect of Condition was identified, $F(1,53) = 104.60, p < .001, \eta^2 = 0.66$, such that in the low-load condition participants identified significantly more correct repeats During Target, $M = 15.76, SD = 6.62$, compared with when in the high-load condition, $M = 10.18, SD = 5.59$ (Fig. 3). A significant interaction, $F(1,53) = 23.78, p < .001, \eta^2 = 0.31$, revealed group differences in the low-load condition, $F(1,53) = 9.06, p < .005, \eta^2 = 0.15$, but not the high-load condition, $F(1,53) = 0.012, p > .91, \eta^2 < 0.001$. Specifically, in the low-load condition only, control participants correctly identified more repeats During Target, $M = 18.14, SD = 2.79$, compared with mild TBI participants, $M = 13.12, SD = 8.50$.

In the second ANOVA, the main effects for Condition and Group were non-significant. A significant interaction emerged, $F(1,53) = 6.25, p < .017, \eta^2 = 0.11$, such that in the low-load condition, mild TBI participants accurately identified significantly more repeats After Target, $M = 6.19, SD = 8.32$, compared with control participants, $M = 1.24, SD = 2.49, F(1,53) = 9.34, p < .005, \eta^2 = 0.15$ (Fig. 3). The same pattern was seen in the high-load condition (mild TBI; $M = 5.92, SD = 5.63$, control participants; $M = 3.24, SD = 2.89), F(1,53) = 5.10, p < .029, \eta^2 = 0.09$ (though the effect size was somewhat smaller). In other words, in the high-load condition, in which the mild TBI group outperformed the controls in terms of the hit rate, they made significantly more of their correct responses following the target offset.

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**Fig. 3.** Responses during target: The top graph shows a significant interaction, such that controls accurately identified a significantly higher number of targets during the target presentation in the low-load condition of the Repetition Detection working memory task, but no group differences were found in the high-load condition. Responses after target: The bottom graph shows a significant interaction, such that mild TBI participants accurately identified significantly more targets after the target offset in the low-load condition and in the high-load condition. The interaction stems from the larger effect size in the low-load condition compared with the high-load condition.
Temporal Analysis of Error Responses

In addition to describing the temporal occurrence of accurate responses, we were also interested in examining the timing of different types of error responses, particularly in the high-load condition. Such analyses may provide insight into why the controls had a mean lower hit rate compared with mild TBI participants. The next set of analyses was implemented to investigate where the error responses occurred within each trial in the high-load condition and to determine if the types of errors made in each group differed from one another.

As mentioned in the “Methods” section, in the high-load condition, participants were not only asked to identify repeated targets within the same color, but also to ignore distracters (digit repeated in two different colors). Along with a target repeat presented in each trial, a distracter repeat was presented either prior to (on 50% of trials) or after the presentation of the target (on 50% of trials). Thus, participants could potentially make four different types of errors: distracter responses made before the target (Distracter Before), distracter responses made after the target (Distracter After), an incorrect response that was a number other than a distracter or target (Error), or a “0” response at the end of the trial (Miss). Independent-samples T-tests were used to determine if there group differences within these four different types of error responses.

Significant differences were found between groups in the mean number of Distracter Before responses, \( t(53) = 3.06, p < .004 \) (Fig. 4). Specifically, controls made significantly more Distracter Before responses, \( M = 2.69, SD = 2.27 \), compared with the mild TBI group, \( M = 1.08, SD = 1.52 \). No other significant differences were found between groups. In sum, the only incorrect response type to distinguish the groups was Distracter Before responses. Given this group difference, we then examined whether the mean number of Distracter Before responses was correlated with the mean number of Target After responses. There was a significant negative correlation between the number of Distracter Before responses and the Target After responses, \( r = -.51, p < .001 \) (see scatter plot in Fig. 4). In other words, as the number of incorrect responses to distracters prior to target presentation increased, the number of accurate responses to the target after its presentation decreased. This finding may help explain the decreased number of Target After responses in control participants as they had a significantly higher number of Distracter Before responses. The scatter plot in Fig. 4 also shows the trend that the majority of Distracter Before responses were made by controls compared with mild TBI participants and that the larger the number of Distracter Before responses, the fewer Target After responses.

**Fig. 4.** Mean number of distracter responses: The top graph shows a significant interaction, such that, in the high-load condition, controls had a higher mean number of distracter responses (errors) before the target compared with controls, but no group differences were found in the mean number of distracter responses made after the target. Scatter plot: The bottom graph shows a significant negative correlation between the timing of accurate and distracter responses, such that as the number of distracter responses made before the target increases, the number of accurate responses made after the target decreases. The graph also shows that controls made the majority of their distracter responses before the target and mild traumatic brain injury participants made the majority of their accurate responses after the target.
Self-Report Questionnaires and Neuropsychological Tests

between groups were found on the state anxiety inventory, t (55) = 2.20, p < .04, regardless of group membership, participants had higher mean accuracy on neutral trials (M = 0.97, SD = 0.03) compared with incongruent trials (M = 0.94, SD = 0.05); F (1,55) = 46.20, p < .001, and higher mean accuracy on congruent trials (M = 0.98, SD = 0.03) compared with incongruent trials, F (1,55) = 35.17, p < .001. A main effect of Group did not emerge, nor did a significant interaction. For each participant, the median response time was calculated for accurate trials in all three trial types. Following this, group mean response times were calculated by averaging individual median response times in each trial type. Similar to the accuracy results, there was no main effect of Group nor a significant interaction. There was a main effect of trial type, F (2,54) = 13.8; p < .001. As expected, participants had longer response times on incongruent (M = 455.45 ms, SD = 90.88), compared with neutral (M = 435.84, SD = 73.20); F (1,55) = 21.56, p < .001, and congruent trials (M = 431.39 ms; SD = 67.93), F (1,55) = 27.90, p < .001. No other trial differences were significant.

Self-Report Questionnaires and Neuropsychological Tests

Independent-samples t-tests were used to compare group means on all self-report scales (ARCES, MFS, STAI, and BDI) and neuropsychological tests (Digit Span Forward and Backward, Trail Making A and B, and CVLT trial 1). Significant differences between groups were found on the state anxiety inventory, t (55) = −2.20, p < .04, such that mild TBI participants reported higher levels of state anxiety at the time of testing, M = 38.19, SD = 8.98, compared with control participants, M = 32.94, SD = 9.01 (Table 2). Similarly, a trend emerged on the trait anxiety inventory, which represents the self-reported anxiety level experienced on a daily basis, t (55) = −1.85, p < .08. Specifically, mild TBI participants reported higher levels of trait anxiety, M = 41.69, SD = 9.54, compared with controls, M = 37.29, SD = 8.43. No significant differences were found on the other self-report scales or on any of the neuropsychological tests (Table 2).

To ensure that our main finding of slowing during the working memory task was not influenced by state anxiety, it was added as a covariate in the repeated-measures ANOVAs for the hit rate and response time analyses on the Repetition Detection task. Anxiety did not account for a significant amount of variability in the response time ANOVA, F (1,52) = 2.61, p > .11, or the accuracy ANOVA, F (1,52) = 0.01, p > .93. Moreover, the addition of state anxiety as a covariate into both analyses did not change the original pattern of results.

Discussion

The major finding in this study was that young adults who sustained a mild TBI in their distant past took significantly longer, on average, to accurately identify targets on a working memory task and reported higher levels of anxiety following task completion, compared with non-head-injured controls. Moreover, mild TBI participants had identical accuracy performance

<table>
<thead>
<tr>
<th>Task/questionnaire</th>
<th>Control</th>
<th>Mild TBI</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digit Span Forward</td>
<td>8.58 (2.32)</td>
<td>8.65 (1.50)</td>
<td>.89</td>
</tr>
<tr>
<td>Digit Span Backward</td>
<td>7.35 (2.03)</td>
<td>7.85 (2.42)</td>
<td>.41</td>
</tr>
<tr>
<td>Trail Making A</td>
<td>17.85 (5.05)</td>
<td>18.39 (4.29)</td>
<td>.67</td>
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<tr>
<td>Trail Making B</td>
<td>40.19 (11.49)</td>
<td>35.50 (9.00)</td>
<td>.10</td>
</tr>
<tr>
<td>CVLT Trial 1</td>
<td>8.06 (1.79)</td>
<td>7.81 (1.96)</td>
<td>.61</td>
</tr>
<tr>
<td>Stroop (mean accuracy)</td>
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<td>0.97 (0.04)</td>
<td>.29</td>
</tr>
<tr>
<td>Stroop (mean RT)</td>
<td>441.88 (77.34)</td>
<td>439.71 (79.72)</td>
<td>.94</td>
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<tr>
<td>ARCES</td>
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<td>33.19 (6.73)</td>
<td>.63</td>
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<td>MFS</td>
<td>29.16 (6.44)</td>
<td>27.85 (6.63)</td>
<td>.45</td>
</tr>
<tr>
<td>STAI (state)</td>
<td>32.94 (9.01)</td>
<td>38.19 (8.98)</td>
<td>.03*</td>
</tr>
<tr>
<td>STAI (trait)</td>
<td>37.29 (8.43)</td>
<td>41.69 (9.54)</td>
<td>.07</td>
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<tr>
<td>BDI</td>
<td>9.19 (7.72)</td>
<td>10.77 (7.32)</td>
<td>.43</td>
</tr>
</tbody>
</table>

Notes: Values represented are the mean group scores (SD in parentheses). Bold items indicate significant different between groups. TBI = traumatic brain injury; CVLT = California Verbal Learning Test; ARCES = Attention-related Cognitive Error Scale; MFS = Memory Failures Scale; STAI = State-Trait Anxiety Inventory; BDI = Beck Depression Inventory.
compared with controls in the low-load working memory condition and, unexpectedly, surpassed control performance in the high-load condition. Post hoc temporal analyses of responses, conducted to investigate the unpredicted accuracy boost, revealed that, on average, mild TBI participants made significantly more of their accurate repeat identifications following the target offset in both low- and high-load conditions compared with controls.

We suggest that mild TBI participants used a slowing strategy that resulted in hit rates that were no different from controls in the low-load condition and rates that were significantly higher than controls in the high-load condition. It is likely that a ceiling effect prevented mild TBI participants from successfully applying this slowing strategy, to outperform controls, in the low-load condition. To our knowledge, this is the first study to show significant slowing of information processing speed, with no decrement, but rather a boost in accuracy rates, during a working memory task in young adults who have sustained one mild TBI in the distant past. The current findings suggest that the decreased processing speed observed in mild TBI participants is a lasting consequence of their head injury. This slowing down in response time also had the unexpected effect of allowing mild TBI individuals to be less susceptible to distracting information, on a higher-order cognitive task. We suggest that slowed information processing, and elevated anxiety levels, may be long-term consequences of a mild TBI.

**Slowing of Information Processing Speed after Mild TBI**

Our cognitive findings emphasize the importance of using non-standard and sensitive measures when examining long-lasting cognitive changes in the mild TBI population. In this study, mild TBI participants did not differ from controls on simple processing speed measures, Trail Making Tests, and Stroop Task, but did significantly differ in average response times on a non-standard assessment of visual working memory, our Repetition Detection Task. The classic Stroop Effect was evident, such that all participants, regardless of group, were significantly slower and less accurate on the incongruent condition compared with the neutral and congruent conditions. That even the incongruent condition, the most complex of the three, did not distinguish mild TBI participants from controls is likely due to the relatively low load placed on available cognitive resources on this task, and the little demand placed on working memory. Whereas a few studies have reported slower processing speeds on standard neuropsychological tests in the post-acute phase following one mild TBI (Bernstein, 2002; Potter et al., 2002; Solbakk et al., 1999), the lack of differences between groups on all our standard neuropsychological measures is in line with the majority of reports finding no effect of a single mild TBI on neuropsychological functioning (for meta-analyses, see Belanger et al., 2005; Binder et al., 1997; Frencham et al., 2005; Rohling et al., 2011). At least one meta-analysis has found that compared with all other neuropsychological measures, mild TBI had the largest affect on processing speed (Frencham et al., 2005). However, this effect size was not significant, further emphasizing the need for more sensitive and non-standard measures of performance when examining long-lasting cognitive deficits, or compensatory cognitive strategies, following a mild TBI, such as our working memory task.

It has more recently been shown that severe TBI participants were slower compared with both mild TBI and control participants on all three reaction time tests that progressively increased in the amount of information to be processed (Tombaugh et al., 2007). However, within 1 month of injury (Tombaugh et al., 2007) and up to 3 months post-injury (Hugenholtz et al., 1988), mild TBI participants have been shown to perform slower than controls only on only the most complex of all three reaction time tasks, the one that placed the largest demand on attention and processing resources. Therefore, relatively simple reaction time tasks, which are successful in detecting impairments following moderate to severe TBI, may be too coarse to detect residual deficits, or changes in strategy, long after a mild TBI, necessitating the need for developing alternative ways of assessing performance, such as our temporal analysis of accurate and error responses.

In so doing, we found that in the low-load condition, the delayed responding observed in the mild TBI group may have helped them maintain hit rates comparable with controls. Temporal analysis of erroneous responses in the high-load working memory condition revealed that the control group, on average, made significantly more erroneous responses to distracting stimuli prior to the target onset compared with the mild TBI group; moreover, correlations revealed that the higher the average number of Distracter Before responses, the lower number of accurate Target After responses. These analyses suggest that the decreased hit rate in control participants in the high-load condition is due, at least in part, to their increased susceptibility to distracting stimuli before the correct target appeared.

The slowing observed on our attention-demanding working memory task may also help highlight a mechanism by which general everyday self-reported memory problems arise in individuals long after a mild TBI. For example, these individuals may experience slower information processing speeds while completing common daily tasks that tap into working memory (e.g., remembering to select a specific brand of cereal from the shelf that matches the appropriate item in a grocery list currently held in the mind). It is this specific type of slowing that may be captured during one-on-one interviews or self-report questionnaires in the mild TBI literature and described as general “memory problems” (Alves, 1993; Meares et al., 2011; Vanderploeg et al., 2007; Villemure et al., 2011).
The Boost in Accuracy after Mild TBI

Although information processing speed impairments have been well documented in the mild TBI literature, a boost in accuracy as a result of slowing has not previously been reported. One reason for our novel finding may lie in the specific design of our Repetition Detection task. Even though participants were instructed to perform as quickly and accurately as possible, they were also told that they could respond any time during the trial following the offset of the target stimulus if they were unsure of the answer (i.e., during the presentation of subsequent stimuli or upon the completion of the trial). As our temporal analysis revealed, the unlimited time window permitted mild TBI participants to make significantly more correct responses following the target offset, compared with controls, in both the low- and high-load working memory conditions. In addition, because mild TBI participants took their time while responding, it likely aided their proficiency at ignoring distracting information presented prior to the target on each trial. If time constraints were imposed, in the present study, differences in accuracy, and response time, may not have been observed. The slowing in the current study may be a strategy used by high-functioning young adults who have sustained one mild TBI in order to perform optimally in demanding situations.

Our findings highlight the importance of not limiting analysis to only a single dependent variable when examining the effects of mild TBI (Madigan, DeLuca, Diamond, Tramontano, & Averill, 2000), but instead, to consider how a change in strategy might underlie performance. For example, it has been shown that individuals with a moderate to severe TBI performed slower and less accurately compared with controls during an externally paced complex working memory task that required intact sustained attention (PASAT; Madigan et al., 2000); however, when accuracy was controlled for, by increasing the duration of the inter-stimulus interval, TBI participants still performed significantly slower than controls, but no longer showed decrements in accuracy performance. It is a reasonable assumption that if adults with a severe TBI are capable of performing at the level of controls, when provided with more time to make each response, then young adults who have sustained a single mild TBI can surely also use the strategy of slowing to outperform controls when time restrictions are lifted, as in our study.

Mental slowing is a well-documented finding in individuals following severe TBI and in stroke patients. Consequently, Winkens, Van Heugten, Wade, and Fasotti (2009) have developed a Time Pressure Management (TPM) training program that teaches cognitive strategies to individuals with acquired brain injury in order to mitigate disabilities resulting from mental slowness. A recent randomized controlled trial showed that TPM training was effective at improving speed on everyday tasks in stroke patients, but had no effect on their self-report of mental slowness (Winkens, Van Heugten, Wade, Habets, & Fasotti, 2009). In our study, it is possible that our sample of high-functioning young adults learned through experience that allowing themselves additional processing time, if permitted, will benefit their performance on cognitively demanding tasks. Future research should investigate the effect of time restrictions on cognitive tasks in mild TBI participants, as well as the effect of training/education programs, such as TPM, as a means to improve performance following a head injury.

Potential Study Limitations

Despite the fact that our participants were high-functioning university students with a self-reported remote head injury, we still found that they experienced significant slowing on a higher-order cognitive task compared with controls. We do acknowledge that self-report methods and lack of access to medical records are limitations of the current study that could result in inaccurate reports of head injury history and participant classification. However, that we could document significant effects, even in this sample, shows that a mild TBI experienced long ago can have lasting repercussions on cognitive functioning. We also acknowledge that we did not control for pre-morbid personality characteristics, such as risk-taking tendencies and frequency of sports play; however, we have no reason to believe that our mild TBI and control group would differ significantly on these variables. As well, in the current study, slowing was found in our mild TBI group despite the fact that just over half had injuries due to sports injuries, and so the group was sufficiently variable in origin of injury that this variable is unlikely to have had a systematic effect on the data. We also did not control for the potential effect of other non-TBI injuries on cognitive functioning in the current study, which could influence performance to the same extent as mild TBI, as recently shown in the pediatric population (as in Babikian et al., 2011).

The Importance of Reducing the Influence of Diagnosis Threat

Another possible explanation for the increased accuracy performance observed in our mild TBI participants is that they were high-functioning university students who were likely unaware of the study’s purpose at the time of testing. Prior reports show that undergraduate students who are informed that the purpose of the study is to examine the potential cognitive effects of their past mild TBI (“diagnosis threat” group), display significant neuropsychological deficits (Suhr & Gunstad, 2002, 2005) and are known to report more everyday cognitive errors (Ozen & Fernandes, 2011) compared with mild TBI participants and controls.
who are unaware of their group membership. We suggest that by reducing the risk of expectation bias in the current study, our findings of a slowing strategy in mild TBI are more representative of the long-term cognitive effects of sustaining one mild TBI. Specifically, the present study shows that cognitive slowing can be identified long-after a mild TBI, even in the absence of increased self-reported cognitive complaints (non-significant ARCES and MFS findings). However, while we attempted to reduce the influence of “diagnosis threat” by withholding the study’s purpose from participants until experiment completion, we cannot conclude that it was eliminated without including a proper control condition (“diagnosis threat” condition). Future studies should continue to investigate the influence of “diagnosis threat” by directly manipulating this variable across conditions (i.e., include both a “diagnosis threat” and “neutral” condition), a limitation of the current study. Even though we did not explicitly reveal the purpose of our study to participants before testing, the recently increased media attention on mild TBI may have been enough to influence performance in our mild TBI group, and possibly increase state anxiety levels.

Our current affective findings are also similar to a past report that showed increased self-reported anxiety levels in mild TBI participants compared with controls, only in a group of mild TBI participants who were unaware of their group membership, but not those made aware of their mild TBI status (Ozen & Fernandes, 2011). Prior studies have found increased levels of self-reported anxiety (Dischinger et al., 2009; Westcott & Alfano, 2005) and increased prevalence of anxiety-related disorders (Mooney & Speed, 2001) long after mild TBI. Our findings confirm that self-reported anxiety levels are heightened in individuals long after a mild TBI, even when “diagnosis threat” is an unlikely confound.

**Possible Neural Mechanisms Underlying Cognitive Slowing after Mild TBI**

The significance of our findings of slowed information processing speed is also seen in the context of neurobiological consequences following a mild TBI. Examined 1-month post-injury using functional magnetic resonance imaging, it has been shown that, in the absence of accuracy differences, mild TBI participants had increased frontal lobe activation compared with controls during working memory tasks (McAllister et al., 1999, 2001; Zhang, Johnson, Pennell, & Ray, 2010). This additional neural activation has been suggested to be a compensatory mechanism to allocate the necessary processing resources for successful task completion. Moreover, a fairly recent imaging technique, diffusion tensor imaging, used to examine white matter integrity, has shown that the extent of microstructural axonal damage following a mild TBI correlates with slower information processing speeds on a simple attention task (Niogi et al., 2008). Similarly, electrophysiological measures have been successful at detecting neural abnormalities long after mild TBI. By examining a specific neural component (P300) using event-related potential analysis, researchers have found delayed (Lachapelle, Bolduc-teasdale, Ptito, & Mckerral, 2008) and abnormal (Bernstein, 2002; Lavoie, Dupuis, Johnston, Leclerc, & Lassonde, 2004; Potter et al., 2002; Sivak et al., 2008) attentional resource allocation for successful stimulus classification and evaluation following a single mild TBI, even in the absence of accuracy and response time decrements. We suggest that the slowing of information processing speed found on our working memory task may be another indicator of delayed or abnormal allocation of task-specific cognitive resources long after a mild TBI. Correlating electrophysiological and neuroimaging findings, with performance on cognitive tasks such as ours, would be the next step in characterizing mild TBI—once thought to have little, if any, long-term consequences.

In conclusion, the current study emphasizes the need to use non-standard tasks and measures of performance in order to detect subtle residual cognitive changes in individuals who have sustained a mild TBI in their remote past. As shown in this study, such changes may be advantageous in that, as long as task design permits, slowing down helps mild TBI participants ignore distracting information, and maintain, or even surpass, performance of controls. Our findings may also have a clinical value: cognitive performance may be improved, in young adults who have suffered a mild TBI, by allowing unlimited time to make responses. In daily life, such individuals may experience a boost in performance if they take extra time to complete tasks that place a heavy demand on attentional resources.

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**Conflict of Interest**

None declared.
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Appendix

Please choose one option for each question below.

Have you ever had a concussion (a blow to the head)? If so, did you lose consciousness for:

- 0 seconds (did not experience loss of consciousness)
- 1–59 seconds
- 1–5 minutes
- 5–15 minutes
- 5–30 minutes
- greater than 30 minutes

When did the concussion occur?

- less than 1 month ago
- 1–3 months ago
- 3–6 months ago
- 6 months to 1 year ago
- over 1 year ago

If you have had a concussion, did you experience loss of memory (brief amnesia) for:

- 0 seconds (did not experience)
- 1–59 seconds
- 1–60 minutes
- 1–24 hours
- greater than 24 hours

If you have had a concussion, did you experience confusion (inability to focus attention) for:

- 0 seconds (did not experience)
- 1–59 seconds
- 1–60 minutes
- 1–24 hours
- greater than 24 hours

If you have had a concussion, did you experience disorientation (difficulty with regard to direction or position/loss of physical bearings) for:

- 0 seconds (did not experience)
- 1–59 seconds
- 1–60 minutes
- 1–24 hours
- greater than 24 hours
References


