Divided attention impairments after traumatic brain injury

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Received 26 May 1998; accepted 5 February 1999

Abstract

This research investigated whether people with severe traumatic brain injury (TBI) are impaired on divided attention tasks requiring working memory. In experiment 1, a severe TBI and control group performed two tasks requiring working memory separately and concurrently. Results showed that the TBI group had impaired divided attention when performing the two tasks concurrently, although the two groups did not differ in performance when these tasks were performed separately. Experiment 2 showed that performance on the paced auditory serial addition task improved with increases in the intertrial interval for both TBI and control groups. A meta-analysis showed that TBIs are impaired on divided attention when the tasks require controlled processing, but not when the tasks can be carried out relatively automatically. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Working memory; Controlled processes; Central executive; Traumatic brain injury; Component process model; Meta-analysis

1. Introduction

Difficulties of attention and memory are among the most commonly reported cognitive deficits after traumatic brain injury [17,30,57]. People with moderate to severe closed-head injury commonly reported problems of attention that persisted two years post-trauma [17]. Health care professionals, working with people with traumatic brain injury (TBI), most frequently reported that patients performed slowly on most tasks, and were unable to pay attention to more than one thing at a time [38].

Somewhat surprisingly, controlled studies have not established that people with TBI are impaired in divided attention, that is, in their ability to perform more than one activity at a time [7,14,39,43,54]. In perhaps the most influential of these studies, TBIs and controls performed a manual tracking task and a dot counting task singly and at the same time [7]. Single task difficulty was individually adjusted for each participant. Results showed that TBIs were not impaired in the divided attention condition when the two tasks were performed at the same time.

The few studies reporting impaired divided attention in TBIs are inconclusive. One study, reporting a divided attention deficit, established that TBIs were more impaired when they responded to a complex stimulus compared to a simple stimulus [47], and on that basis concluded that there was a deficit of divided attention. However, that conclusion is uncertain because participants did not have to perform two different tasks at the same time. Another study found some support for a divided attention impairment in TBIs, but the impairment was found in only one out of three conditions, and the size of the impairment was small in the third condition [19]. A third study reported substantial divided attention impairments in TBIs [31]. TBIs performed at a significantly lower level...
than controls when the tasks were performed separately, however, leaving open the possibility that different levels of performance on the single tasks were responsible for the impaired performance when the two tasks were executed concurrently.

Some investigators have proposed that TBI people do not have a specific attention deficit but do have slower, less precise functioning of perceptual, motor, and cognitive subroutines [17,39,53]. Proponents of the *slowed processing hypothesis* have identified several lines of evidence favoring this hypothesis rather than an impaired attention interpretation of the deficit sustained after traumatic brain injury. First, as previously noted, there is no strong evidence that TBIs are impaired on divided attention tasks. Second, TBIs perform a variety of simple tasks more slowly than controls. For example, several studies have shown that TBIs have slowed responses, with the difference in response time between TBIs and controls greater in a choice reaction time task than in a simple reaction time task [32,47,55,56]. Third, the slowed processing hypothesis also explains which clinical tests are effective in measuring the impairments of people with TBI. A recent study showed that the tests of attention that best discriminate severe TBIs from controls were the symbol digits modalities test, simple and choice reaction-time tasks, paced auditory serial addition test (PASAT), and the Stroop test. Ponsford and her colleague proposed that each of these tests measures the presence of a deficit in speed of information [39].

In sum, although people with TBI and health care professionals typically report problems of divided attention, most controlled studies have not found evidence of impaired divided attention. One reason for this discrepancy may have to do with the nature of the tasks used so far to investigate divided attention performance experimentally. At this point, most dual attention tasks have required people with TBI to divide attention between two tasks having perceptual and motor components. The tasks, however, do not depend heavily upon working memory [1,4], that is, upon remembering and using stored information. In many daily activities, tasks can only be executed effectively if we remember previously presented information. For example, reading a book or engaging in a conversation requires us to relate information currently being read or heard to previously processed information in memory.

The general objective of the current paper is to investigate performance of TBIs on tasks requiring divided attention in order to determine whether performance is impaired, and if so, to establish the cause of the impairment. Our working hypothesis is that TBIs have impaired working memory. For this reason we hypothesize that TBIs will be impaired on divided attention tasks when the tasks require working memory, but will not be impaired on divided attention tasks when the tasks do not require working memory. In Experiment 1, we investigate this hypothesis by determining whether people with TBI are impaired on divided attention tasks with a significant memory component as hypothesized. This study will broaden the conditions in which divided attention after TBI has been investigated. Should the study find impairment, it would suggest that people with TBI have a specific impairment when having to perform divided attention tasks requiring working memory. In addition, it would provide one of the first experimental reports of a divided attention deficit after TBI, and it would suggest a possible resolution of the discrepancy between reports of patients and caregivers vs findings from controlled studies.

Experiment 2 further examines the hypothesis that TBI people have impaired working memory. We postulated that the working memory impairments of TBI people are a consequence of interference between current and previously performed operations in working memory. According to this account the difficulties TBI people may have in performing divided attention tasks requiring working memory are a consequence of the interfering effects of performing the two tasks simultaneously. Baddeley has also proposed that interference affects working memory performance on certain tasks [3]. Experiment 2 tested this hypothesis by examining performance of TBIs on the PASAT, a task requiring working memory. We hypothesized that the impairments of TBIs on the PASAT are partly attributable to interference effects and can be reduced by increasing the duration of the delay between presentation of successive PASAT lists.

The third study is a meta-analysis of all published papers that have studied whether there is a divided attention impairment in TBI patients. We conducted it to determine whether the degree of impairment of TBIs on divided attention tasks depends upon the degree to which the tasks require working memory.

2. Experiment 1

Studies investigating the neuropathology of head trauma lend support to the idea that impairment after traumatic brain injury may involve working memory. These studies have shown that the frontal and temporal lobes tend to be selectively damaged after TBI [29,46] dovetailing with results from neuroimaging studies suggesting that working memory is mediated by prefrontal lobes [8,12].

At a theoretical level, this study is concerned with the relation between attention and memory, particularly in situations requiring divided attention. Perhaps best known are the studies by Baddeley and his col-
leagues [1,2,4] who have investigated working memory. Working memory is postulated to consist of three components: a central executive, which is an attention-controlling system; a visuo-spatial sketchpad, which manipulates spatial information; and a phonological loop. The present study will focus on the central executive because that component is presumed to be crucial for performing divided attention tasks.

In recent years Baddeley has proposed that the supervisory activating system model of Shallice and Norman [42], a general model of the control of action, may represent a promising attempt to describe in more detail the operation of the executive component of working memory [3]. A somewhat different framework, developed by Moscovitch and his colleagues [34,35,37], is the component process model of memory. This model describes the role of the central executive in long-term episodic and semantic memory processes. The supervisory activating system and the component process model are similar in that both assume that the executive component of working memory is required when non-routine situations are encountered, and that resource or capacity limitations constrain performance of the central executive.

The two tasks in the first experiment were selected because both tasks are presumed to require the executive component of working memory. One task is the paced auditory serial addition test (PASAT), [16,44], an important clinical test, which has been shown to chart recovery [18], and to predict return to work [6] following a head injury. In the PASAT, a long series of single digits are presented auditorily one at a time. The task is to add the current digit to the preceding digit and say the answer. For example, if presented the numbers 7, 5, 3, 6, the correct responses would be 12, 8 and 9.

The second task in this experiment is a modified version of lag recall, shown by Dobbs and Rule to be a sensitive measure of working memory [13]. To avoid using the same modality as the PASAT, the lag recognition task is presented visually on a computer screen and requires a manual response. In the lag 0 version of the task, participants are shown a series of study letters presented briefly one at a time. Immediately after the studied letter disappears from the screen, two test letters are shown. The participant must decide which of the two test letters matches the just presented study letter, and press the appropriate computer key. The lag 1 recognition test has the same presentation format as the lag 0 task. However, in this condition the task is to report which of the two test letters was studied one trial back.

TBI and control participants were tested in three conditions: carrying out the PASAT alone (single task), or under dual task conditions in which the PASAT is performed concurrently with either the lag 0 recognition memory test, or the lag 1 recognition memory test. Participants performed each task with eight different sets of materials, presented one after another with a short break between successive sets.

Our primary prediction was that people with TBI would be impaired in the dual task conditions relative to the control group. This prediction follows from the hypothesis that people with TBI have a specific impairment in the central executive component of working memory that reduces their ability to perform memory-demanding tasks under conditions of divided attention. In contrast, if TBIs are not impaired in divided attention tasks as some investigators have proposed, TBIs should not be impaired on divided attention provided performance of the two groups does not differ significantly on the single tasks. To ensure that performance levels did not differ between groups, the rate of presentation on the PASAT was individually adjusted so that performance levels on the PASAT were the same for all participants on the PASAT performed by itself.

In addition, we expected that PASAT performance would be lower in the dual task conditions (PASAT at lag 0 and especially at lag 1) than performance on the PASAT alone. This prediction follows from the assumption that the central executive of working memory has a limited capacity. Therefore, carrying out a second concurrent task, requiring working memory, should impair performance on the first task, provided that task also requires working memory [2,4].

This experiment will also determine whether performance on the PASAT and the lag recognition test declines across the eight sets of materials. We hypothesized that performance would decline because as successive sets of materials are presented there is a build-up of interference. Responses to previously presented materials must be inhibited, and as the material increases so does interference and the likelihood of an error.

2.1. Method

2.1.1. Participants

The people with TBI were recruited from individuals assessed by neuropsychologists. The criteria for selection into the study were as follows: no prior history of traumatic brain injury, documented brain injury, and attentional deficits as assessed by a neuropsychologist based on a review of available information about the circumstances of the accident, neuroimaging data (when available), other medical records and results from a neuropsychological assessment. The median duration of post-traumatic amnesia of the sample was 13 days ($M = 21.0, SE = 9.19$), and hence would be classified as having had a severe head injury [26]. The median elapsed time between date of injury and date of test was 6.1 years ($M = 5.5$ years; $SE = 1.45$). Thus,
the sample of TBI people in this experiment differed from the TBI population in the severity of their injury, and the presence of measurable attention deficits. Most people with TBI sustain a mild head injury [25], and problems of attention are a frequent, but not necessary, consequence of TBI [47].

The control group consisted of individuals with no prior history of TBI who were matched and not significantly different from the TBI group in age (TBI group $M = 50.9$ years, $SE = 4.10$; control group $M = 51.4$ years, $SE = 3.7$) or in years of education (TBI group $M = 16.2$ years, $SE = 0.83$; control group $M = 15.3$, $SE = 1.31$). Other measured characteristics of the two groups were handedness (TBIs 5 right, 1 left; controls 6 right) and gender (TBIs 3 male, 3 female; controls 5 female, 1 male).

Results from tests of attention, short-term memory, and working memory, summarized in Table 1, show performance by the TBI group was lower than performance of the control group on all tests. On consonant trigrams, a test used to assess whether TBI patients have attention deficits [45], performance by both groups was perfect at a 0-s delay, but lower for the TBI group at all other delays, and significantly lower at the 3- and 9-s delays. Performance by the control group was within the normal range [48] while that of the TBI group was below the normal range. Performance of the TBI group was also lower and approached significance ($P = 0.06$) on the word span test, a traditional measure of short-term memory, although many investigators believe both primary and secondary memory are involved in this task [11]. Performance by TBIs was lower than controls on the alpha span and lag recall tests, two measures of working memory [9,13], although the difference between the two groups was not statistically significant.

### Table 1

<table>
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<th>Test</th>
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<th>$SE$</th>
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<td>4.7</td>
<td>0.33</td>
<td>0.14</td>
<td></td>
</tr>
</tbody>
</table>

*a* $n = 6$ for each group.

2.1.2. Materials

2.1.2.1. Calibration materials. The PASAT calibration materials consisted of four different lists of 61 digits each, recorded on to audiotape by a female voice. The lists were constructed by randomly selecting the digits 1–9 with the constraint that no digit was repeated on successive trials. The four lists were presented one at a time at a 2.8, 2.4, 2.0, and 1.6-s rate with a 10-s interval between lists.

2.1.2.2. PASAT. The lists for the PASAT were constructed in the same way as the calibration materials. Using this procedure, three sets of test materials of eight lists of 31 digits each, and three lists of practice materials were created, one for each set of test materials.

2.1.2.3. Lag materials. The study letters for the lag 0 and lag 1 recognition tasks were constructed by randomly selecting a letter from A to I with the constraint that the same letter was not repeated on successive trials. The test materials were constructed by selecting the study letter and pairing it with a lure generated by randomly selecting a letter other than the target from A to I. This procedure was used to produce eight lists for each of the two lag recognition tasks presented with the PASAT, and two lists for each of the two lag conditions performed alone.

2.1.3. Design

The two groups of participants (TBI and control) were tested in all other experimental conditions. The two within subjects factors were task condition and test position. The task condition factor has three levels (PASAT alone, PASAT plus lag 0 recognition, and PASAT plus lag 1 recognition), and the test position factor consists of eight lists tested in each of the three conditions. The order of presentation of conditions was counterbalanced across participants.

2.1.4. Procedure

Each participant was tested individually in a quiet room. After being given a series of tests of attention and working memory (consonant trigrams, lag recall, alpha span, and word span), the three phases of the experiment were administered: calibration of the PASAT; presentation of the lag 0 and lag 1 recognition tasks alone; and administration of the PASAT alone, PASAT plus lag 0 recognition, and PASAT plus lag 1 recognition.

2.1.4.1. Calibration of the PASAT. After describing the PASAT task and ensuring the participant understood how to perform the PASAT by providing a short practice list, the PASAT was presented at four rates of...
presentation. Then, the participant was given a 5-min break while the experimenter scored the data, and determined number of correct responses on the first 30 response opportunities at each rate of presentation. The rate of presentation at which performance was closest to 20 correct responses was selected to be the presentation rate for the PASAT in the remainder of the study for that participant.

2.1.4.2. Presentation of the lag 0 and lag 1 recognition tasks. The next phase of the experiment involved presentation of the lag 0 and lag 1 recognition tasks alone. In the lag 0 recognition condition, a participant studies a letter shown in the middle of the computer screen. After 1500 ms the letter disappears and two test letters are presented at the bottom of the screen for 2750 ms. The participant’s task is to press the computer key positioned below the test letter just studied. Prior to presentation of the lag 0 recognition lists on computer, participants learned how to perform the lag 0 task through instruction and by filling out paper and pencil practice sheets.

The lag 1 recognition test has the same presentation format as the lag 0 task. However, in this condition the participant’s task is to report which of the two test letters was shown one trial back. Thus, if the study letters are an ‘A’ and then an ‘F’, and the pair of test letters shown following the ‘F’, are ‘A’ and ‘E’, the participant should press the key corresponding to ‘A’ because that letter was shown one trial back. The training procedures were the same as in the lag 0 condition.

2.1.4.3. Test phase. After a 5-min rest, three conditions were administered: PASAT alone; PASAT plus lag 0 recognition; and PASAT plus lag 1 recognition. In the dual task conditions participants were told that performing the two tasks would be difficult. Participants were instructed to do as well as possible, but that lag recognition was the more important task. Emphasis was placed on the lag recognition task because we wanted performance decrements resulting from divided attention to be reflected predominantly on the PASAT, thus making it possible to compare PASAT performance across the three conditions to evaluate the effects of divided attention on performance. After ensuring that the two tasks were understood by having participants describe them, participants were given two practice lists. Then the test lists were administered. After all eight lists in a given condition had been presented, participants took a self-paced break of 5–10 min, prior to presentation of the next block of lists.

2.1.4.4. Scoring data. The primary dependent measure for the PASAT, lag 0, and lag 1 recognition tasks is the total number of correct responses. Because the PASAT presentation rate is adjusted to ensure that performance levels on the PASAT are about the same for different participants, the length of time it takes to complete a PASAT list varies, and hence the number of items presented in the lag recognition tasks varies as well. We made performance in the lag recognition tasks comparable across participants by calculating the proportion of correct responses for that list and then multiplying that proportion by the number of responses possible had the PASAT been presented at a 2.0-s rate of presentation. The total number of correct responses possible at the 2.0-s rate is 14 in the lag 0 task and 13 in the lag 1 task.

2.2. Results

2.2.1. Calibration and practice performance

The mean presentation rate yielding performance closest to 20 correct responses on the first 30 response opportunities in the calibration of the PASAT was 2.2 s (SE = 0.17) for the TBI group and 2.1 s (SE = 0.17) for the control group. Individual rates of presentation were: 1.6 s, 1 TBI and 1 control; 2.0 s, 2 TBIs and 3 controls; 2.4 s, 2 TBIs and 1 control; 2.8 s, 1 TBI and 1 control.

Participants were given two practice trials immediately prior to performing the tasks in each of the three conditions. Performance on the two PASAT practice lists, presented alone at individually determined rates of presentation, was close to 20, the level targeted in the calibration phase of the study and did not differ significantly (t(10)=0.19, ns) for the TBI (M = 22.8, SE = 2.22) and the control groups (M = 23.3, SE = 1.47).

Performance was averaged across the two practice lists in the PASAT and lag 0 dual task condition. Performance on the PASAT was 11.8 (SE = 1.12) for the TBI group and 13.7 for the controls (SE = 2.11), a non-significant difference (t(10)=0.80, ns). Performance on the lag 0 recognition practice lists (TBI group M = 11.7, SE = 0.96; control group M = 12.7, SE = 0.74) also did not differ between the two groups (t(10)=0.72, ns).

Performance on the PASAT, averaged across the two practice lists in the PASAT and lag 1 condition, was dramatically lower for the TBI group (M = 4.3, SE = 1.22) than for the control group (M = 9.2, SE = 1.78), a difference that was statistically significant (t(10)=2.9, P < 0.05). Although performance on the lag 1 recognition task practice lists in the PASAT and lag 1 recognition condition was lower for the TBI group (M = 5.6, SE = 0.87) than the control group (M = 8.6, SE = 1.28), this difference was not statistically significant (t(10)=1.91, ns).
2.2.2. **PASAT performance**

Fig. 1 shows the mean level of performance on the PASAT for the TBI and control groups averaged across the eight test lists when the PASAT was performed alone or concurrently with the lag 0 or lag 1 recognition task. Performance on the PASAT is highest when the PASAT is performed alone, and is considerably lower when the PASAT is performed concurrently with lag 0 and lag 1 recognition tasks. In addition, performance of the two groups on the PASAT is about the same in the PASAT alone and the PASAT lag 0 recognition condition, but performance of the TBI group is considerably lower than the control group in the PASAT lag 1 recognition condition. These data were analyzed using an ANOVA in which the within subjects factors were condition (PASAT alone, PASAT and lag 0 recognition, PASAT and lag 1 recognition), and test position (test position 1 to test position 8), and the between subjects factor was group (TBI, control). Results of this analysis showed that performance on the PASAT varied significantly across the three conditions \( (F(2,20) = 43.85, P < 0.001) \). Contrary to our hypothesis, performance did not vary significantly across test position. No other effects were statistically significant.

More detailed analyses evaluated specific predictions made prior to the study. One analysis established that as predicted, performance on the PASAT by the TBI and control groups differed significantly in the PASAT and lag 1 recognition condition \( (F(1,10) = 5.83, P < 0.05) \). However, the two groups did not differ significantly in the PASAT alone or the PASAT and lag 0 conditions. These results are consistent with the findings from the practice lists in which there was a significant difference between the two groups in the PASAT and lag 1 condition but not in the other two conditions. It should be noted, however, that contrary to expectation there was no significant condition by group interaction. Fig. 2 presents performance on the PASAT for the TBI and control groups in the PASAT and lag 1 condition at each test position, and shows that the two groups differ consistently across each of the eight test positions.

Results of Bonferroni \( t' \) tests showed that perform-
performance declined significantly across all three conditions: PASAT alone vs PASAT and lag 0 recognition condition ($t’(11)=5.40, P < 0.01$); PASAT alone vs PASAT and lag 1 ($t’(11)=7.85, P < 0.01$); and PASAT and lag 0 versus PASAT and lag 1 ($t’(11)=5.70, P < 0.01$).

2.2.3. Lag recognition results

Preliminary analyses, performed separately on the lag 0 and lag 1 recognition data, established that test position was not a significant factor either on its own or in interaction with any other factor. The remainder of the analyses in this section collapsed across this factor.

Fig. 3 shows the mean number of correct responses in the lag 0 and lag 1 recognition tasks performed alone (single) or concurrently with the PASAT (dual) for the two groups. These data were analyzed by an ANOVA in which the within subjects factors were type of recognition test (lag 0, lag 1) and type of task (single, dual), and the between subjects factor was group (TBI, control). Results showed that lag 0 recognition was substantially higher than lag 1 recognition ($F(1,10)=54.49, P < 0.001$), and performance was higher when the tasks were performed alone than in conjunction with the PASAT ($F(1, 10)=5.52, P < 0.05$). No other effects were statistically significant.

2.2.4. Within list effects

We investigated whether performance declined within a PASAT list by dividing each PASAT list of 30 responses into thirds and scoring performance on the first, second, and third set of 10 responses. Results of this analysis are presented in Fig. 4 and show that performance declined within a list in each condition. A repeated measures ANOVA having group as a between subjects factor and condition (PASAT alone, PASAT and lag 0 recognition, PASAT and lag 1), test position (8 levels), and list third (3 levels) as within subjects factors confirmed that performance declined significantly within a list ($F(2,20)=79.5, P < 0.001$), and that, as previously reported, performance varied across conditions ($F(2,20)=43.8, P < 0.001$). Performance also interacted significantly with group and list third ($F(2,20)=3.7, P < 0.05$), reflecting the fact that performance across list third declined more rapidly for TBIs than for controls. Mean performance for the first, second, and final third of the PASAT for the TBI group was ($M=5.1, SE=0.55; M=3.9, SE=0.47; M=2.9, SE=0.44$) vs ($M=5.9, SE=0.33; M=5.1, SE=0.43; M=4.5, SE=0.20$) for the control group. No other results were statistically significant.

Separate ANOVAs were performed on each condition to determine whether the decline in performance across list third was robust. Results showed that performance dropped significantly in each condition: PASAT alone ($F(2,20)=35.0, P < 0.001$), PASAT and lag 0 ($F(2,20)=19.9, P < 0.001$), and PASAT and lag 1 ($F(2,20)=19.8, P < 0.001$). In the latter analysis TBIs and controls differed significantly, as noted earlier.

We also analysed performance on the lag 0 and lag 1 recognition tasks in the dual task conditions by dividing each list into thirds to determine whether performance on this task also varied by its position within a list. The data were analysed using a repeated measures design having as within subjects factors list third and test position, and group as a between subjects factor. In the lag 0 recognition task a complex pattern of results was obtained, which included a difficult to interpret list third by test position by group triple interaction ($F(14, 140)=1.9, P < 0.05$), and a test position by list third interaction ($F(14, 140)=2.1, P < 0.05$). In the lag 1 recognition task, performance did not differ significantly within a list third ($F(2,20)=3.2, ns$), or between the two groups ($F(1, 10)=0.03, ns$). No other effects were statistically significant.

2.3. Discussion

The current experiment addressed three major questions. First, are people with TBI impaired on divided attention tasks requiring working memory? Results showed the TBI group were impaired in dividing their attention between the PASAT and the lag 1 recognition tasks, although there was no significant difference between the two groups when these were performed alone. The impaired performance by TBIs on the PASAT in the PASAT and lag 1 condition was observed in each of the eight test lists and in the two practice lists, although the expected condition by group interaction was not statistically signifi-
cant. When the two groups performed the PASAT and lag 0 recognition tasks together, the TBI group performed worse than the control group, but this difference was not statistically significant, perhaps because of insufficient statistical power (see Table 4).

A second question was whether performance on the PASAT declined across test position. The findings from this study showed that performance did not decline significantly across successively tested lists, although performance did decline sharply within a list. This pattern of performance was obtained regardless of whether the PASAT was studied by itself or under dual task conditions.

A final question was whether performance on the PASAT was lower when the PASAT is performed along with another activity requiring working memory versus performance when the PASAT is performed by itself. Results from the current experiment show that performance on the PASAT declined substantially for both groups when the PASAT was performed concurrently with either lag 0 or lag 1 recognition tasks relative to performance in the PASAT alone condition.

Some, but not all, of these results are consistent with the version of the slowed processing hypothesis developed to account for the pattern of deficits observed after TBI [17,39,53]. (The general discussion will review whether a version of the slowed processing hypothesis developed by Salthouse can account for these findings [40].) The version of the slowed processing hypothesis developed to explain TBI deficits can account for the decline in performance on the PASAT within a list, but stability in performance across lists. However, the finding of impaired performance by the TBI group on a divided attention task, is clearly at odds with the version of the slowed processing hypothesis proposing that people with TBI have no specific deficits of attention because these investigators have used the finding of no deficits of divided attention [7] as support for the slowed information processing point of view [39,53].

How does the working memory perspective fare? The finding that performance on the PASAT declines when it is performed concurrently with another task requiring working memory is consistent with this perspective, and it implies that the PASAT also requires working memory [2,4]. Perhaps of greater theoretical import, the finding that the TBI group was differentially impaired in the PASAT plus lag 1 recognition dual task condition, suggests that the central executive component of working memory performs less efficiently in the TBI group.

It is not clear what specific aspect of the dual task resulted in impaired performance by the TBI group. One possibility is that the central executive component of working memory of TBI people is differentially susceptible to interference effects. This hypothesis is appealing because it explains why PASAT performance of people with TBI is impaired in the lag 1 recognition dual task condition, but not in the lag 0 recognition condition. In order to perform the lag 1 recognition task, it is necessary to retrieve the item one back, while registering the current item. By contrast, in the lag 0 condition, there is less interference because it is necessary to keep track of only the most recently

<table>
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<th>Study</th>
<th>Characteristics of TBI patients</th>
<th>Description of dual tasks</th>
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<td>Schmitter-Edgecombe [41]</td>
<td>PTA &gt; 6 d</td>
<td>2-tone disc</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pleasantness rating</td>
<td></td>
</tr>
<tr>
<td>Hartman et al. [19]</td>
<td>Coma &gt; 6 h</td>
<td>Tracking</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Conversation</td>
<td></td>
</tr>
<tr>
<td>Current paper</td>
<td>Median PTA = 13 d</td>
<td>PASAT</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>Mean age = 50.9 y</td>
<td>Lag 0 recognition</td>
<td></td>
</tr>
<tr>
<td>Hartman et al. [19]</td>
<td>Coma &gt; 6 h</td>
<td>Tracking</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Digit span</td>
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<tr>
<td>Brouwer et al. [7]</td>
<td>Mean PTA = 52.6 d</td>
<td>Tracking</td>
<td>0.15$^a$</td>
</tr>
<tr>
<td></td>
<td>Mean age = 37.0</td>
<td>Dot counting</td>
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</tr>
<tr>
<td>Hartman et al. [19]</td>
<td>Coma &gt; 6 h</td>
<td>Tracking</td>
<td>0.03</td>
</tr>
</tbody>
</table>

$^a$ Estimated.
presented item. This hypothesis also explains why performance does not decline in perceptually based divided attention tasks, but does decline on memory-based divided attention tasks. The hypothesis of an impaired executive function that is susceptible to interference after TBI also provides a straightforward interpretation of the ‘mental fatigue’ TBIs frequently report while carrying out cognitive activities for a sustained period of time.

Working memory may become increasingly vulnerable to interference because as the PASAT proceeds, the number of prior responses increases, thereby increasing their potential to interfere with ongoing processing in working memory. A difficulty for this explanation is the finding from the current study that performance did not decline across test position although it did deteriorate within a list. One possible resolution of this pattern of results comes from studies that have investigated proactive interference effects. These studies, employing a Brown–Peterson experimental situation, have shown that proactive interference effects can be greatly attenuated, and even neutralized, by increasing the length of the delay between successive lists [27,28]. This finding suggests that the pause between successive PASAT lists in the first experiment may decrease proactive interference effects and hence stabilize performance on the PASAT across lists.

If a pause between PASAT lists plays a similar role to a delay between successive lists in a Brown–Peterson experimental situation, then increasing the duration of the intertrial interval between successive PASAT lists should reduce interference across lists and increase performance on the PASAT. Moreover, if people with TBI are differentially sensitive to interference effects, then increases in the duration of the delay between successive lists should enable a TBI group to improve its performance to a greater extent than the control group. These possibilities are investigated in Experiment 2.

3. Experiment 2

In this experiment, a TBI and control group performed the PASAT at three different delays on different sets of PASAT materials, each set consisting of eight lists. Based on the reasoning just presented, we hypothesized that increasing the time interval between lists would improve performance on the PASAT. We also hypothesized that the TBI group would benefit more from a longer delay than the control group. We based this prediction on the assumption that the impaired working memory of the TBI group would make that group more vulnerable to interference effects, and consequently that group would benefit differentially from longer delays. Finally, we anticipated that, as in the previous study, performance in the PASAT would decline within a list, but would be stable across lists.

The duration of the delay between successively presented PASAT lists was either 10, 20, or 60 s. The 10-s time interval between lists was selected because this delay was used in the previous experiment. The 20- and 60-s intervals were selected because studies, which have investigated the effects of delay on performance in a Brown-Peterson situation, have found that interference effects are attenuated by 60 s [27]. To ensure that performance levels of the TBI and control participants were comparable, the rate of presentation of the PASAT was individually adjusted, based on performance in the calibration phase of the study.

3.1. Method

3.1.1. Participants

The recruitment and selection criteria were the same as Experiment 1. Three participants in Experiment 1 were in Experiment 2. The median duration of post-traumatic amnesia was 6.0 d (M = 17.1, SE = 10.84). Thus, the patients tested in this sample would be classified as having had a severe head injury [26]. The median elapsed time between the date of injury, and the date of testing was 5.1 y (M = 4.9, SE = 1.57). As in Experiment 1, the sample of TBIs included in the present study differed from the population of TBIs in terms of the severity of their injury and the documented presence of attentional deficits. Attentional deficits are a frequent but not inevitable consequence of TBI.

The control group consisted of a sample of individuals with no prior history of head injury, matched for age (TBI group M = 55.5 y, SE = 4.63; control group M = 51.6 y, SE = 3.98; t(10)=0.64, ns) and years of education (TBI M = 14.3 y, SE = 1.89; control

<table>
<thead>
<tr>
<th>Test</th>
<th>Group^a</th>
<th>TBI M</th>
<th>SE</th>
<th>Control M</th>
<th>SE</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
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<tr>
<td>3 s</td>
<td></td>
<td>10.2</td>
<td>1.32</td>
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<td>9 s</td>
<td></td>
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<td>0.11</td>
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<tr>
<td>18 s</td>
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<td>1.28</td>
<td>10.3</td>
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<td></td>
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<td>2.70</td>
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</tr>
<tr>
<td>2</td>
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<td>2.32</td>
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<td>0.33</td>
<td>5.2</td>
<td>0.40</td>
<td>0.36</td>
</tr>
<tr>
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<td>0.48</td>
<td>5.7</td>
<td>0.33</td>
<td>0.03</td>
</tr>
</tbody>
</table>

^a n = 6 for each group.
$M = 16.5 \, y, \ SE = 0.84; \ t(10) = 1.13, \ ns$. Other features of the two samples measured were handedness (TBI, 5 right handed; 1 left handed; control 6 right handed) and gender (TBI, 5 male, 1 female; control, 2 male, 4 female).

Table 2 presents mean performance of the TBI and control groups on tests of working memory and attention. Performance by the two groups was perfect on consonant trigrams at 0-s delay and at lag 0 recall, tasks requiring minimal working memory and attention. However, as shown in Table 2, performance by the TBI group is lower than the control group in all other test conditions. The TBI group performed significantly lower than the control group on the alpha span and lag 2 recall tasks, two tests of working memory, and performed lower, although not significantly so, on lag 1 recall, a third test of working memory. Performance by TBIs was lower than controls and approached significance on consonant trigrams, a test used clinically to assess the ability of TBIs to maintain focused attention under conditions of interference. Performance by TBIs was also lower on word span, a test conventionally used to assess short-term memory performance. Taken together, these results suggest that this sample of TBIs is also impaired relative to controls on tests requiring working memory and perhaps attention.

3.1.2. Materials

Using the same procedures described in Experiment 1, 26 PASAT lists, consisting of 31 single digits each, were constructed; eight of these lists were then randomly assigned to each of the three conditions, and the other two served as practice lists.

3.1.3. Design

The TBI and control groups were tested in all other experimental conditions. The three within subjects factors were delay, test position, and list third. The delay between successive lists was 10, 20 or 60 s, the test position factor consisted of the order in which the eight lists were presented, and list third consisted of performance on the first, second, or final third of the list. The order of presentation of the tasks was counterbalanced across participants.

3.1.4. Procedure

The conditions of testing were the same as Experiment 1. After administering a set of psychological tests to assess working memory and attention, PASAT performance was calibrated using the same procedure as in Experiment 1. Then each participant was presented three blocks of the PASAT. Within each block there was a 10-, 20-, or 60-s intertrial interval between each list. Prior to presenting the three blocks of the PASAT, two practice lists were presented at the rate determined by the calibration phase of the study. At the end of each block of eight lists a timed 5-min break was taken. Before the start of each new block, instructions describing the PASAT task were repeated briefly.

3.2. Results

3.2.1. Calibration trials

After reviewing individual performance on the calibration trials, we dropped one TBI participant from the study because 10, the highest score on the calibration trials, was substantially lower than the criterion score of 20.

With this individual dropped, we were left with six participants in each of the two groups. The mean score, at the presentation rate selected for the remainder of the study, was close to the criterion score of 20, and did not differ between the two groups (TBI group $M = 20.5, \ SE = 1.93$; control $M = 19.17, \ SE = 0.54$, $t(10) = 0.67, \ ns$). The individual rates of presentation determined from the calibration phase of the experiment were as follows: 1.6 s, 4 controls; 2.0 s 4 TBIs; 2.4 s, 2 controls; and 2.8 s, 2 TBIs.

3.2.2. Test trials

Table 3 presents the mean number of correct responses on the PASAT for successive list thirds at three different intertrial intervals for the TBI and control groups averaged across the eight test positions. The data were analyzed by a repeated measures ANOVA having test position (8 levels), duration of intertrial interval (3 levels), and position within a list (3 levels) as within subjects factors and group as the
between subjects factor. Results of this analysis showed that performance increased significantly with longer intertrial intervals \((F(2,20)=21.8, P < 0.001)\) and declined within a list \((F(2,20)=41.9, P < 0.001)\). In addition, the analysis showed that performance declined significantly across test position \((F(7,70)=5.1, P < 0.001)\), and the effect of group approached, but did not achieve statistical significance \((F(1, 10)=4.2, ns)\). No other effects were statistically significant.

Results of Bonferroni \(t\) tests established that the difference between performance at the 10-s \((M = 24.1, SE = 1.30)\) vs 20-s intertrial intervals \((M = 24.7, SE = 1.33)\), was not statistically significant. However, the difference between performance at the 20-s \((M = 24.7, SE = 1.33)\) vs 60-s intertrial intervals \((M = 26.3, SE = 1.22)\) was significant \(t’(11)=3.96, P < 0.01\), as was the difference between performance at the 10- and 60-s intertrial intervals \(t’(11)=8.34, P < 0.01\).

3.3. Discussion

A primary finding of the present experiment was that PASAT performance increased substantially with increases in the duration of the intertrial interval. This result was predicted because we had hypothesized that increasing the duration of the intertrial interval would attenuate interference affecting the executive subsystem of working memory. This finding underscores the importance of ensuring that the duration of the intertrial interval while administering the PASAT is the same as for the normative sample. Spreeen and Strauss [44] recommend allowing at least a 60-s break between successive administrations of the PASAT.

Performance also declined within list at all intertrial intervals. This finding replicates results from Experiment 1 and extends the range of conditions under which this decline has been observed. The current study also found a small, but significant decline in performance across test position, unlike the previous experiment which found no statistically significant decline. In this experiment TBI and control groups were equally affected by changes in the duration of the intertrial interval. We had hypothesized that the TBI group would be affected more by interference, and accordingly would benefit more from increases in the delay between successive lists. Instead, results from the two experiments show that TBIs are impaired in their performance only when performing divided attention tasks requiring memory, but not in any other experimental condition. This pattern of results suggests that, at least in the experiments of this study, the impairment of TBIs is associated with a specific process that is executed when divided attention tasks requiring working memory are performed. The plausibility of this hypothesis is strengthened by results from a PET study that show activation of a particular brain region, the prefrontal cortex, when participants performed two tasks at the same time, but not when either task was performed by itself [12].

4. Meta-analysis of divided attention studies after TBI

The next study quantitatively reviews all the published studies we have been able to find that have investigated whether there is divided attention impairment in TBI people. A primary goal of this review is to determine whether the degree of impairment on divided attention tasks by TBI people varies systematically with the type of task, and if so, to characterize the difference between conditions resulting in impairment of divided attention by TBIs vs those that do not. Our hypothesis is that TBIs are impaired relative to controls to the extent that divided attention tasks involve the central executive function of working memory, but are not impaired when the divided attention tasks can be performed relatively automatically.

To be included in this review, a potential study must have compared performance of a TBI and control group when two tasks were performed individually and concurrently. This criterion excludes studies such as one by Stuss and colleagues [47] which investigated whether TBI people had divided attention deficits by comparing performance on a complex task to a simpler task. In addition, only studies that investigated accuracy of performance were included because measures of speed and accuracy may behave differently under single and dual task conditions [10]. As a consequence, some data from a study by Schmitter-Edgecombe and another study were excluded [41,43]. To assess impairment of divided attention, we calculated an effect size estimate, called \(d\), developed and used in meta-analysis studies to permit the comparison of results across studies [20,21]. The statistic \(d\) is defined to be the difference between mean performance by the experimental group \((M_{exp})\) and the control group \((M_{cont})\) divided or standardized by the standard deviation \((S)\); that is, \(d=(M_{exp}−M_{cont})/S\). Impaired divided attention was assessed by determining whether the cost of carrying out the divided attention task was greater for the TBI group than for the control group. If the cost is greater for the TBI group, that is reflected in a positive value for \(d\).

Table 4 summarizes for each study included in the meta-analysis, the characteristics of the TBI group (coma duration, duration of post-traumatic amnesia (PTA), age), the tasks used to study divided attention, and the magnitude of the impairment as assessed by \(d\). The studies are ordered in this table by the magnitude of impairment. The degree of impairment varies considerably, ranging from 1.28 to about 0, a finding that
is consistent with the notion that task differences determine whether or not TBIs are impaired in divided attention.

The possible relation between task differences and impairment in divided attention was investigated further by considering in some detail the tasks used. The two studies with the largest divided attention deficits, $d$s of 1.28 and 1.07, both employed tasks that require the continual updating and retrieval of information from memory. In the PASAT plus lag 1 recognition condition of the current study these processes are necessary in both conditions. In the study by Melamed and colleagues [31], participants had to perform a pursuit motor tracking task while at the same time performing a delayed digit recall task in which a participant hears a digit every 4 s, and is required to recall the digit heard 1 trial back.

Moderate to large degrees of impairment were also evident in the tasks studied by Schmitter-Edgecombe [41]. In one experimental condition, one task was to discriminate between four auditory tones, while the other task was to rate the pleasantness of a series of words presented on a five-point scale. The other experimental condition was similar to the one just described, except that participants had to discriminate between two rather than four auditory tones while rating the pleasantness of words. It seems likely that rating words for pleasantness requires fairly involved non-routine retrieval and evaluation of information [22] from semantic memory [52].

The next largest effect comes from an experimental condition in which participants had to talk about their memories of recently experienced events while manually tracking a target [19]. Although performance by TBIs was significantly impaired compared to controls, it is surprising that the degree of impairment is not greater. Perhaps the conversation of the TBI group was less fluent, and marked by longer pauses than that of the control group. This possibility cannot be assessed because conversation was not monitored in that study.

The next two conditions have smaller degrees of impairment. In the task described in the current paper, participants performed a lag 0 recognition task and PASAT concurrently. Although the PASAT does require working memory, as discussed previously, the lag 0 recognition task differs from the lag 1 recognition task in that it involves almost no storage or retrieval from memory. In the other condition participants had to perform a manual tracking task and a digit span task [19] simultaneously. The resulting impairment was modest ($d = 0.26$), relative to a study by Melamed and his colleagues [31] that also used a tracking task, but instead used a delayed digit recall task and reported a large impairment ($d = 1.07$). Although both tasks require the storage of information, the amount of processing, manipulation, and retrieval demands are considerably greater in delayed digit recall than digit span, suggesting that the impairment of TBI people lies more in the controlled processing of stored information, than in its registration or straightforward retrieval.

The final two tasks to be considered have negligible degrees of impairment associated with them. In a study requiring participants to perform dot counting and manual tracking [7], two tasks making modest demands on memory, we estimate that the degree of impairment was 0.15. Finally, there was negligible impairment ($d = 0.03$) when participants performed a tracking task while hearing verbal feedback about their performance [19].

5. General discussion

The major findings across the three studies are as follows. Experiment 1 showed that when the TBI group performed the PASAT and lag 1 recognition tasks concurrently, performance was impaired relative to a control group. The two groups did not differ, however, when these two tasks were performed alone, or when the two groups performed the PASAT and lag 0 recognition tasks together. The magnitude of the impairment was comparable to that found in another study investigating divided attention using a task requiring working memory [31], although in that study performance of the TBI and control groups differed when the tasks were performed alone making it difficult to determine whether their TBI group had a divided attention deficit.

The quantitative review of divided attention studies showed that the degree of impairment of TBIs on divided attention is task-dependent. The review showed that TBI people are impaired on divided attention tasks when the tasks require controlled memory processes acting either on episodic or semantic memory [52]. People with TBI are not impaired on divided attention tasks with perceptual or motor components that do not depend on controlled retrieval of stored information, or on tasks requiring straightforward storage or retrieval of information.

Another important result was a substantial reduction in performance on the PASAT within a list. This finding was obtained in all conditions of Experiments 1 and 2, and suggests that performance on the PASAT is sensitive to interference effects, but that these effects are attenuated when there is even a short delay between lists. These results are consistent with studies showing that proactive interference effects can be attenuated, and even neutralized by increasing the length of the delay between successive lists [27,28] in a Brown–Peterson experimental paradigm. A related
assumes that people with TBI have a general slowing of processing, but no specific deficit of attention [39,53].

A more elaborated version of the slowed processing hypothesis, developed to account for age effects in cognition [40], may also be able to account for the results of this study. According to this theory, performance on a task may deteriorate because the relevant cognitive operations are executed too slowly to be completed successfully in the available time. An assumption of this type could account for the pattern of results from this study by proposing that TBIs perform less well on the PASAT when it is performed concurrently with the lag 1 task because a greater number of cognitive operations need to be executed in this condition than in the other conditions of Experiment 1. A similar explanation could also be given of the pattern of results obtained in the quantitative review. The critical difference between the slowed processing hypothesis of Salthouse and the controlled processing hypothesis is that the former hypothesis proposes deficits arise because of the number of cognitive operations that must be performed whereas the latter hypothesis postulates the deficits are attributable to the type of cognitive operations carried out.

The overall pattern of results in this paper is consistent with recent theories that specify the operation of the central executive function of working memory. According to the supervisory attentional system, routine actions are performed fairly automatically using contention scheduling procedures, whereas non-routine activities are performed by a limited capacity supervisory attentional system [3,42]. The component process model of memory also distinguishes between straightforward actions executed automatically by different modules of memory, and strategic operations performed by a central system frontal lobe component that consumes considerable cognitive resources.

In the next few paragraphs, we will describe in more detail how the component process model of memory [34,35,37] explains the primary results from this study. According to the component process model, memory is not unitary but depends upon the operation of four different components that typically interact with each other: a non-frontal neocortical component consisting of perceptual modules; a modular medial temporal/hippocampal component that mediates the encoding, storage, and retrieval of episodic information; a basal ganglia component that mediates performance on sensori-motor tests; and a central system, frontal lobe component that operates across modalities and domains, and mediates performance on tasks that are strategic and under voluntary control. The central system in the component process model roughly corresponds to the executive component in the working memory framework.

As noted previously, an important feature of the component process model is the distinction between modules and central systems. Modules are postulated to process information automatically, and therefore consume few cognitive resources. By contrast, the central system frontal component allows for information to be inspected, performance to be controlled, and requires more cognitive resources for its operation. Thus, interference between tasks during divided attention should be greater when the tasks require the central system frontal component than when the tasks can be executed automatically by one or more modules.

If people with TBI have impaired functioning of the central system component, then the degree of impairment during divided attention will depend upon the extent to which controlled processing involving central system frontal component is required. According to this model, there should be a substantial impairment in divided attention tasks requiring controlled processing, such as was found in the lag 1 recognition and PASAT conditions of the present study and in the study that used delayed digit recall [31]. In contrast, there should be much less impairment on straightforward memory tasks such as the forward digit span task that do not require the non-routine manipulation of stored information [19].

Semantic memory tasks requiring strategic control should also impair performance in divided attention tasks according to this model. Moscovitch tested this implication by having undergraduate students perform
a divided attention task that involved a complex sequence of finger tapping requiring the central frontal component of memory together with either a letter or category fluency task [36]. He found, as predicted on the basis of neuropsychological findings, that finger tapping interfered more with word generation to a letter cue than to a category cue. Neuropsychological studies have shown that left frontal damage lowers letter more than category fluency [5,33]. (Troyer and colleagues have refined these ideas [50,51].) The finding of no impairment of divided attention on the perceptual and motor tasks [7] is also consistent with the component process model because these tasks can be performed rather automatically by the non-frontal perceptual and basal ganglia modules.

Because the sample was small, the results of Experiment 1 are to be interpreted with some caution. The results gain strength, however, from the meta-analysis, which showed that the degree of impairment of TBIs in divided attention tasks across studies depends upon on the degree to which the divided attention tasks require controlled processing.

In summary, the component process model of memory can explain the results from this study. A critical assumption of this model is that information processed by modules consumes relatively few cognitive resources, whereas processing by the central system, needed to perform strategic or non-routine activities, requires considerable resources. As noted previously, the supervisory attentional system of Shallice and Norman makes a similar assumption, and hence also can account for the primary results of this paper.

This paper extends the applicability of the component process model to the attention domain and to people with TBI. Previous applications of this model have focused on performance in episodic, and to some extent, semantic memory tasks and have not considered the performance of TBIs. The component process model can also explain the pattern of memory impairment of TBIs. For example, a levels of processing experiment found greater improvement in recognition memory performance under semantic encoding conditions for the control group compared to the TBI group that showed only modest degrees of improvement [15]. One interpretation of this finding is that the TBI group performed less well in the semantic condition because the controlled processes required in the semantic encoding condition were impaired. In a follow-up study Toth found, using the process-dissociation procedure developed by Jacoby and his colleagues [23,24], no statistically significant difference in automatic memory performance between the TBI and control groups, but a large impairment in controlled memory performance for the TBI group, particularly in the semantic encoding condition [49].

Taken together with the results in the current study, these findings suggest that performance by people with TBI on attention and memory tasks is impaired when controlled processes involving working memory are involved, but performance is unimpaired when a task can be executed largely automatically.

Acknowledgements

This research is supported by a grant from the Ontario Mental Health Foundation. Brian Conrod, Genevieve Coulombe, Eleanor Liederman, and Pamela Wightman helped with data collection. Guy Proulx and Jill Rich commented on earlier versions of this paper.

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