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The influence of mild traumatic brain injury on the temporal distribution of attention

Received: 25 January 2006 / Accepted: 21 March 2006
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Abstract The purpose of this study was to examine whether the temporal dynamics of attention was deficient in participants who have recently experienced mild traumatic brain injury (mTBI). For this purpose the rapid serial visual presentation (RSVP) task was used and the performance of participants with mTBI was compared to that of controls matched for age, gender, education, and activity type. In the RSVP task a stream of rapidly presented letters is displayed with target and probe letters separated by varying durations. The participant is required to identify the target letter and determine whether the probe letter was present or not. Previous research has shown that healthy participants display an attentional blink: they fail to detect the probe letter when it appears within ~500 ms of the target letter. We found that participants with mTBI had a normal attentional blink—it was neither greater in magnitude nor longer in duration than that displayed by the control participants. However, the participants with mTBI did show evidence of attentional competition—making more errors in identifying the target letter when the probe letter was presented—that was not present in the control participants. Taken together, these results suggest that the temporal constraints of attention are subtly but systematically affected by mTBI.

Introduction

Mild traumatic brain injury (mTBI) is a common neurological impairment caused by a blow to the head. Even

mild head injuries may cause neural damage consisting of focal lesions or diffuse axonal injury with mild to severe effects (Heitger et al. 2004; van Donkelaar et al. 2005; Halterman et al. 2006). Deficits in visuospatial attention are often observed in individuals that have recently suffered an mTBI. In particular, this population tends to have difficulty maintaining or allocating attention appropriately during task performance (Ponsford and Kinsella 1992; Stuss et al. 1989; Felmington et al. 2004; Spikman et al. 1996; Cicerone 1996; Chan 2002; Chan et al. 2003). We have recently demonstrated using the attentional network test (ANT) that specific components of visuospatial attention are affected by mTBI (van Donkelaar et al. 2005; Halterman et al. 2006). In particular, the orienting and executive components tend to be disrupted whereas the alerting component remains unaffected.

In addition to measuring the orienting of attention across different locations in space, it is also possible to characterize the temporal limits of attention at a single location. The RSVP task is designed to specifically probe the temporal dynamics of attention. During the RSVP task, stimuli are presented to the participant at the same location at a rate of 6–20 items/s (Shapiro et al. 1994). The task is to identify an initial target stimulus (T1) within the stream as well as whether or not a second target stimulus (T2) was present. Previous studies using the RSVP task have shown that for normal, healthy, young participants the presence of T2 can be accurately detected if it appears at least 500 ms after T1 but not if it appears before this time (Shapiro et al. 1994; Armstrong and Munoz 2003). This failure to accurately report T2 has been termed the attentional blink (AB).

Attention is defined as a resource that improves or limits performance depending on whether it is applied or withdrawn from a task (Armstrong and Munoz 2003). The RSVP task is resource demanding because the stimuli are only present for a short time and the participants have to split attention between identifying T1 and T2. Thus, it seems likely that any attentional dysfunction would exaggerate the AB. Previous studies on participants

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with attention-deficit hyperactivity disorder (ADHD) (Armstrong and Munoz 2003; Hollingsworth et al. 2001), Alzheimer's disease (AD) (Kavcic and Duffy 2003), and visual neglect (Rizzo et al. 2001; Husain et al. 1997) have shown evidence of a larger and more prolonged AB. Moreover, participants with AD also show evidence of attentional competition or masking during the RSVP task: when they report T2 correctly, they tend to miss T1 more frequently (Kavcic and Duffy 2003).

Given the fact that mTBI disrupts certain aspects of visuospatial attention, we were interested in determining whether it also affects the temporal dynamics of attention. Thus, in this study, we used the RSVP task to directly examine this issue by comparing the performance of participants with mTBI with matched controls. We hypothesized that both the participants with mTBI and the controls would display evidence of the AB. However, due to their attentional deficits, we hypothesized that the participants with mTBI would have a larger, more prolonged AB.

Materials and methods

Participants

Seventeen participants with mTBI [9 males, 8 females; mean age 22 ± 4.19 years (age range 18–32 years); education 15 ± 2.96 years] were recruited from the University of Oregon community. The American Academy of Neurology classifies a concussion according to three grades: a grade 1 concussion is defined as disorientation of time and place for less than 15 min, a grade 2 concussion is defined as disorientation for at least 15 min and a grade 3 concussion includes loss of consciousness. All of our participants were classified as having a grade 1 or 2 concussion which is roughly equivalent to suffering an mTBI. Exclusion criteria included a grade 3 concussion or any concussion within the previous 12 months. The cause of mTBI varied between participants from impacts to the head during football and soccer games to falls and car accidents. Certified athletic trainers and/or physicians of the university intercollegiate athletic program and student health center identified the mTBI and referred the participants for testing within 2 days of injury. The range of times at which the participants were brought in for testing varied from 12 to 40 h after the injury. Control participants taken from the same population at the University of Oregon were individually matched for age [mean age 22 ± 3.97 years (age range 20–37 years)], gender (6 males, 11 females), education (15 ± 3.13 years), and sporting activity to the participants with mTBI. Activity was matched for the athletes by recruiting teammates who played the same position. For the non-athletes, controls were recruited who participated at the same general level of recreational sporting activity. Signed informed consent forms were obtained from all participants before the start of the experiment,

and the university human subjects committee approved all testing and the procedures.

Procedure

All participants performed the rapid serial visual presentation (RSVP) task, which examines the ability to distribute attention across time (Fig. 1). The participants sat facing a computer monitor located 57 cm away on which the visual stimuli were presented. Each trial started with a central fixation cross that was present until the participants pressed the spacebar, after which a stream of uppercase letters, subtending a visual angle of $\sim 0.5^\circ$ vertically, were rapidly presented. Each letter was displayed against a gray background for 66 ms, with an inter-stimulus interval of 49 ms. All of the letters were black except one (T1), which was white. After T1 appeared, a black X (T2) either did or did not appear. During trials in which it did appear, the number of intervening letters between T1 and T2 was varied from 0 to 9 corresponding to a delay ranging 115–1,150 ms. The participants' aim was to identify T1 and whether T2 was present. At the end of each trial, the participants were prompted to type the letter of T1 and either a Y (yes) or N (no) for whether T2 was present. They were also instructed that accuracy was the variable of interest and therefore that quick responses with short reaction times were to be avoided. Before the experimental data were collected, each participant completed a series of practice trials until they felt comfortable performing the task. Participants then completed 16 blocks of trials with 20 trials per block half in which T2 was present and half in which it was absent. This resulted in a total of 16 trials for each combination of delay and T2 presence for each participant.

Data analysis

The main dependent variable of interest was the identification rate for T1 and T2. Identification rate was defined

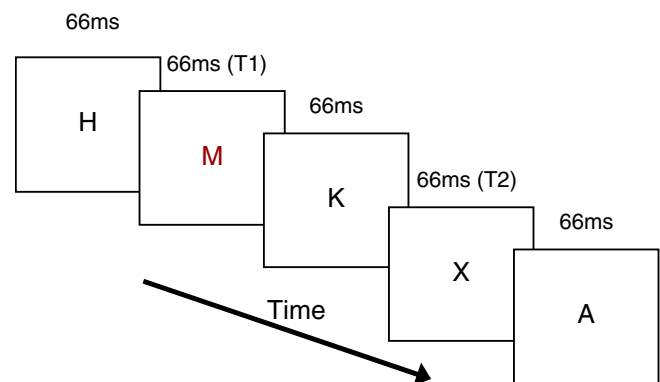


Fig. 1 Visual events occurring during the RSVP trials. A stream of uppercase letters was presented at the same location on a computer screen with an inter-stimulus interval of 49 ms. Each trial contained an initial target letter (T1). A black X (T2) may or may not have appeared 0–9 letters after T1. Participants typed responses for the identity of T1 and the presence of T2 on the keyboard at the end of each trial

as the percentage of trials in which the participant identified T1 or the presence of T2 correctly. To ensure that the analysis was from data in which participants were committing processing resources appropriately, the identification rate for T1 was calculated only from trials in which the presence of T2 was accurately reported and vice versa. In other words, the identification rates were conditional probabilities: the probability of detecting T2 given that T1 was reported correctly was our measure of the AB, whereas the probability of correctly reporting T1 given that T2 was detected was our measure of attentional competition or masking. A 2 (participant group) \times 10 (delay) mixed model analysis of variance was used to examine differences across conditions for both T1 and T2.

Results

Figure 2 shows the T2 identification rate when T1 was accurately identified at each T1–T2 delay for the participants with mTBI and the controls. Both groups demonstrated an increase in T2 accuracy as the delay between T1 and T2 increased. The T2 accuracy appeared to be similar for both groups across every delay as well. A 2 (participant group) \times 10 (delay condition) mixed model ANOVA revealed a significant delay effect ($F[1, 339] = 4.978$, $P < .0001$). However, there was not a significant group effect ($F[1, 339] = .026$) or a significant interaction between these two variables ($F[1, 339] = .071$). The significant delay effect shows that across both groups accuracy increased as the delay between T1 and T2 got longer. A post hoc Tukey's test showed that the T2 identification accuracy for the first two delays was significantly worse than for the last five delays. This failure to report the presence of T2 subsequent to accurate identification of T1 at the shorter delays is the attentional blink. The lack of a significant group effect indicates that the AB is the same duration and magnitude in both groups of participants. Thus, suffering an mTBI does not appear to alter the ability to distribute attention across time.

It is possible that there was no difference in the AB between the participant groups due to attentional competition by the participants with mTBI. If the participants with mTBI were reporting T2 accurately at the expense of reporting T1 accurately, then both groups would have the same AB. To test for attentional competition, we looked at the identification rate for T1 when T2 was present and accurately reported. Figure 3 displays T1 accuracy for both participant groups when the presence of T2 was accurately reported. T1 accuracy appeared to be lower for the participants with mTBI. A 2 (participant group) \times 10 (delay condition) mixed model ANOVA revealed a significant group effect ($F[1, 339] = 15.361$; $P < .0001$), but not a significant delay effect ($F[1, 339] = .359$) or significant interaction between these two variables ($F[1, 339] = .825$). These results indicate that the participants with mTBI were reporting T1 less

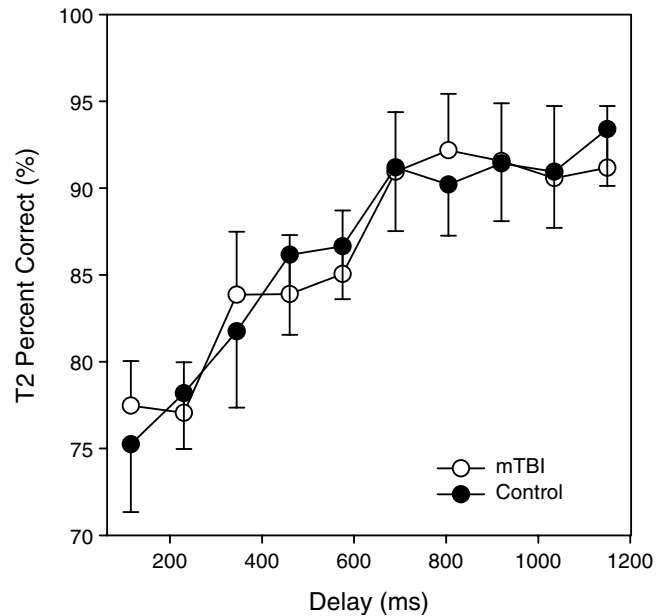


Fig. 2 Group means for T2 accuracy at each delay for the control participants (*filled circles*) and the participants with mTBI (*open circles*). Data are from trials in which T1 was correctly identified. Participants with mTBI showed a similar attentional blink to that of the control participants

accurately than the control participants when T2 was present and accurately reported. Thus, mTBI influences performance during the RSVP task by reducing the ability to overcome attentional competition induced by the presence of T2. Behaviorally, these results in normal appearing AB characteristics at the expense of accurately recalling T1 identity.

Discussion

In this report, the RSVP task was used to examine whether the temporal dynamics of attention were affected by mTBI. We demonstrated that the AB was neither larger in magnitude nor longer in duration in the participants with mTBI than it was in the controls. However, we did find that the participants with mTBI demonstrated a greater degree of attentional competition in this task than the controls. In the following, we discuss how our results compare to previous RSVP studies that have been carried out in other clinical populations with neurological deficits and to previous studies that have characterized other aspects of cognitive and attentional processing in participants with similar or more severe traumatic brain injury.

The RSVP task probes the temporal constraints of attention by measuring the AB. The AB is characterized by an increase in T2 accuracy as the delay between T1 and T2 increases, with the worst accuracy at delays earlier than 500 ms (Armstrong and Munoz 2003; Hollingsworth et al. 2001; Husain et al. 1997; Kavcic and

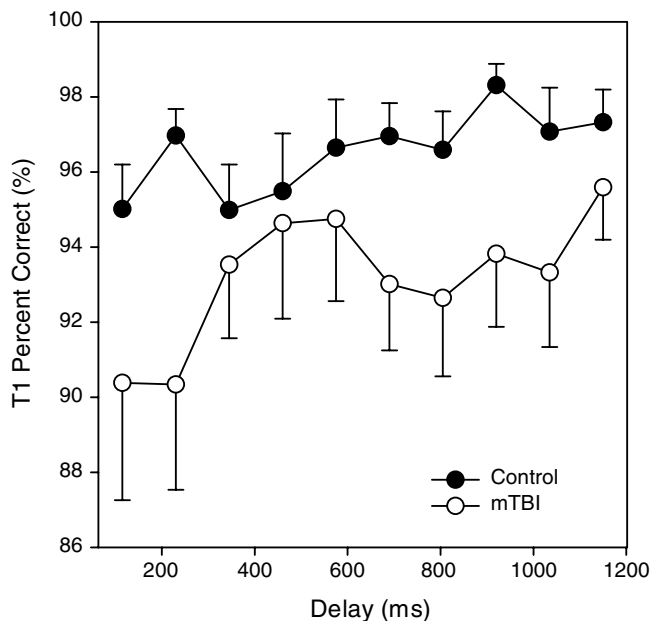


Fig. 3 Group means for T1 accuracy when T2 was present and accurately reported at each delay for the control participants (*filled circles*) and the participants with mTBI (*open circles*). Participants with mTBI had a lower T1 accuracy than the control participants

Duffy 2003; Raymond et al. 1992; Rizzo et al. 2001). The current finding that the AB was similar in participants with mTBI and controls suggests that suffering an mTBI does not affect the temporal dynamics of attention. This finding is inconsistent with previous RSVP studies that have found an exaggerated AB for participants with ADHD (Armstrong and Munoz 2003; Hollingsworth et al. 2001), AD (Kavcic and Duffy 2003), and visual neglect (Rizzo et al. 2001; Husain et al. 1997). This aspect of the current results suggests, therefore, that the processes that contribute to the temporal limits of attention and the corresponding areas of the brain that carry out these processes are not substantially influenced by mTBI.

Despite the similarity in the AB between our two subject groups, we did find evidence of exaggerated attentional competition in the participants with mTBI—when T2 was reported accurately participants with mTBI were markedly less likely to report T1 accurately than the controls. Such competition for attentional resources has been studied in detail in normal, healthy subjects and has been found to be present for very short delays between T1 and T2 (Potter et al. 2002a, b; Raymond et al. 1995). The fact that such competition is present across all the delays in the participants with mTBI in the present experiment is consistent with a general slowing of central processing speed and/or executive dysfunction (see below).

This finding is consistent with a report by Kavcic and Duffy (2003) who found that participants with AD showed evidence of attentional competition (they use the term “masking”) in the context of an RSVP task. In that paper the attentional competition dissipated in the participants with AD at the longest delays between T1 and

T2. This was not the case in the present study: there was no significant group by delay interaction indicating that the group difference was consistent across all the delays tested. However, we did not use delays as long as those used by Kavcic and Duffy (2003). It is possible that if we had used longer delays T1 accuracy in participants with mTBI would have returned to normal levels and a significant group by delay interaction would have been observed. Alternatively, because we did not measure T1 accuracy under single task conditions (i.e., when participants knew that T2 would not be presented), we cannot be absolutely sure that the T1 accuracy levels reached by the participants with mTBI at the longer delays were not already at their normal baseline levels. Unfortunately, this shortcoming cannot be addressed with the present data. However, the fact that a deficit was observed in participants with mTBI for T1 accuracy but not T2 accuracy suggests that there may not be a general deficit in attentional processing of rapidly presented visual stimuli in this population. In other words, the *pattern* of results for T1 and T2 is inconsistent with the possibility that mTBI leads to an overall deficit in the temporal dynamics of visuospatial attention. However, given the differences in task difficulty associated with T1 and T2 (see below), this possibility should be viewed cautiously.

Another difficulty for the interpretation of the current results is the disparity in the difficulty of T1 identification versus T2 detection. One could argue that differences in the AB between the participants with mTBI and controls would be more likely to be detected had we used a more difficult task for T2, like those used by Armstrong and Munoz (2003) and Kavcic and Duffy (2003). However, a very similar version of the RSVP task was used by Husain et al. (1997) to demonstrate AB deficits in patients with hemispatial visual neglect. Thus, it is not unprecedented for a version of the RSVP task like that used in the current study to reveal differences between a patient population and controls. With these caveats in mind, the present findings suggest that the normal appearing AB characteristics in participants with mTBI occur at the expense of accurately recalling T1 identity. Analogous visuospatial working memory deficits have been observed previously in participants with mTBI (Chuah et al. 2004; McAllistar et al. 2001).

Thus, when taken together, the results of the present study suggest that the processes that are involved in allocating attention over time and the areas of the brain that carry out these processes are subtly yet systematically affected by mTBI. Previous brain imaging studies have shown that cognitively demanding attentional tasks, such as the RSVP task, engage frontal–parietal areas including the anterior cingulate and intraparietal sulcus (Kranzioch et al. 2005; Marcontoni et al. 2003; Marois et al. 2000). For subjects with brain injury that affect the AB, there is evidence of altered activation in cortical areas associated with attentional tasks (Booth et al. 2005; Hao et al. 2005; Johannsen et al. 1999; Prvulovic et al. 2002; Vaidya et al. 1998). Thus, we would suggest that such areas were affected to a certain degree in our group

of participants with mTBI, but not the extent observed in other neurological conditions such as AD and ADHD.

Previous studies from our group have shown that mTBI affects the ability to orient attention in space and maintain executive control (van Donkelaar et al. 2005; Halterman et al. 2006). In addition, we have also shown that maintaining dynamic stability during gait is markedly compromised in participants with mTBI when attention is divided in a dual-task situation (Parker et al. 2005, 2006). Thus, not only does mTBI cause deficits in both spatial and temporal attention but also in motor control when attention must be divided between two tasks. There appears to be two general explanations for these types of deficits in traumatic brain injury. The first postulates that executive dysfunction limits the extent to which attention can be switched quickly and accurately between sets of task demands (Leclercq et al. 2000; Stablum et al. 1994). This could account for the present data if one assumes that reporting the presence of T2, being a simpler task that occurs closer to the end of each trial, automatically draws attention away from the complete processing of T1 because of deficient executive control processes in participants with mTBI. This would result in the normal T2 accuracy but reduced T1 accuracy that was observed in the current study. The second explanation suggests that a general slowing of central processing speed leads to difficulty in completing a given task prior to the requirement to initiate a subsequent task. Evidence for this sluggish central processing speed is clearly present in participants with more severe TBI when they attempt to perform dual tasks in a psychological refractory period (PRP) paradigm (Dell'Acqua et al. 2001, 2003, 2005; Hein et al. 2005). Reaction times for the first of two closely occurring tasks are relatively normal or slightly elevated in these patients, whereas those for the second are disproportionately greater than controls. The strict analogy for an RSVP task would be normal T1 and deficient T2 accuracy—that is, what is typically observed in the other neurological conditions discussed above. Clearly, we did not observe this pattern of results in the present study. One possible explanation for this discrepancy is that the PRP results are from participants with more severe TBI [i.e., patients who were in a coma and had marked post-traumatic amnesia (PTA)]; whereas the current data are from participants with very mild TBI (i.e., no loss of consciousness, no PTA). It would be interesting to test participants with mild TBI in a PRP paradigm to see whether the general slowing of central processing speed is still present in this population or whether it is restricted to more severely affected patients.

In conclusion, we have demonstrated that the ability to distribute attention over time is vulnerable to the effects of mTBI. Although the AB appeared to be normal in participants with mTBI, the presence of attentional competition suggested that the ability to distribute attention over time was subtly yet systematically affected by mTBI. Since this ability is required to successfully complete daily activities, it is important to know to what extent and duration it is affected by mTBI. Such

information could be used to improve treatment options and better inform guidelines for resuming normal activities after suffering an mTBI.

Acknowledgements This research was supported by CDC Grant# R49-CCR021735 awarded to Li-Shan Chou.

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