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Information processing difficulty long after self-reported concussion

DANIEL M. BERNSTEIN
Simon Fraser University, Burnaby, BC, Canada

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Abstract

Recovery of cognitive function after mild head injury (MHI) is thought to be relatively swift and complete. The present study replicates and extends previous work in which university students with self-reported concussion demonstrated reduced P300 amplitude on a set of easy and difficult attention tasks, in addition to performing more poorly than controls on demanding cognitive tasks many years after injury. In the present study, 13 students with self-reported concussion (MHI group: *M* time since injury = 8 years) and 10 controls were matched for age, sex, education, and a variety of cognitive, physical and emotional complaints. Controls outperformed the MHI group on the Digit Symbol substitution task and on a difficult dual task involving tone discrimination and visual working memory. Additionally, controls exhibited larger P300 amplitudes on both an easy and a difficult auditory discrimination task. A combination of electrophysiological, neuropsychological and self-report indices predicted group membership (MHI *vs.* control) with 88% accuracy. The present results, coupled with previous work, offer preliminary evidence that the combination of event-related potentials and demanding behavioral measures might reveal long-lasting, subtle cognitive problems associated with MHI. These findings may challenge existing notions of complete recovery after MHI. (*JINS*, 2002, *8*, 673–682.)

Keywords: Mild head injury, P300, Information processing

INTRODUCTION

So prevalent is mild head injury (MHI) that it has recently been described as an epidemic in the United States (Kushner, 1998). Despite this pervasiveness, there is much controversy surrounding the cognitive sequelae accompanying MHI. While it is virtually uncontested that MHI can produce transient disruptions to cognitive and behavioral functioning immediately after injury, the evidence for long-term impairment is mixed.

Most MHI research has typically focused on individuals who complain of cognitive and emotional difficulties in the acute stages of recovery after MHI. Relatively little is known about cognitive problems more than 1 year post injury. Gouvier and colleagues (Gouvier et al., 1988, 1992; Ryan et al., 1996) have demonstrated that university students with MHI many years post injury report no more frequent postconcussion symptoms than do non-head injured student controls. However, the students with MHI do report significant intensification of symptoms since their injury, and these symptoms seem to have an organic basis (Ryan et al., 1996). As for neuropsychological functioning long after MHI, there is some evidence for impaired information processing speed and difficulty with divided attention. Although some studies (e.g., Pinkston et al., 2000; Segalowitz et al., 2001) have failed to observe a difference between controls and individuals with MHI on the Digit Symbol substitution task, an index of processing speed, several studies have noted such a difference (Arcia & Gualtieri, 1995; Leininger et al., 1990; Macchiocchi et al., 1996). Cicerone (1996) has shown that dual task demands significantly slow information processing speed long after MHI. A recent review of this literature by Bernstein (1999) indicates that the neuropsychological tasks that are most likely to distinguish controls from those with MHI long after injury are those that place large demands on processing resources. Thus, task difficulty appears to moderate some of the inconsistency in the MHI literature.

Gronwall and Wrightson (1975) have speculated that cognitive deficits after MHI may be due to decreased attentional capacity. Therefore, tasks that require few atten-

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Reprint requests to: Daniel M. Bernstein, Department of Psychology, University of Washington, P.O. Box 351525, Seattle, WA 98105-1525. E-mail: db6@u.washington.edu

tional resources may not discriminate controls from individuals with MHI, because such tasks do not adequately tax one's available processing resources (cf. Kahneman, 1973). The present study sought to determine whether the manipulation of task demand, in addition to the combination of self-report, neuropsychological and electrophysiological measures, might reveal subtle long-term attentional problems associated with MHI.

It has been suggested recently that cognitive event-related potentials (ERPs) may prove valuable in the assessment of individuals with MHI (e.g., Potter & Barrett, 1999; Reinvang et al., 2000; Solbakk et al., 1999). In contrast to behavioral data, ERPs are believed to tap ongoing information processing without being subject to response strategies (McCarthy & Donchin, 1981). Two ERP components, the P300 and the contingent negative variation (CNV), were examined in the present study. The P300 has been linked to the allocation of attention to a stimulus (Polich, 1986), selective attention (Pritchard, 1981), and to mental effort (Wilson et al., 1998), and may reliably differentiate controls from individuals with MHI (e.g., Dupuis et al., 2000; Ford & Khalil, 1996; Gaetz et al., 2000; Gaetz & Weinberg, 2000; Granovsky et al., 1998; Pratap-Chand et al., 1988; Reinvang et al., 2000; Sangal & Sangal, 1996; Solbakk et al., 2000; see Gaetz & Bernstein, 2001, for review). The CNV has been linked to sustained attention (Teece & Cattanach, 1993), and has received relatively little work in MHI research.

Previously, Segalowitz et al. (2001) observed that, compared to matched controls, students with self-reported concussion (MHI) many years post injury demonstrated normal CNVs, but had reduced P300 amplitudes on a set of easy and difficult auditory attention tasks. The authors also noted that the P300 amplitude difference between groups was smallest on the most demanding task. This electrophysiological data pattern was different from that observed behaviorally: the two groups performed equally on easy attention tasks, but controls outscored those with MHI on the most demanding attention tasks. From these results, the authors concluded that MHI might be associated with subtle, long-term cognitive processing deficits.

The present study replicates and extends this work with an independent sample at a different university and in a different laboratory, using a more thorough battery of questionnaires and cognitive and electrophysiological measures (including a more complete montage of electrode sites, and the addition of visual evoked potentials). A second, relatively easy, dual task (*CNV distract*) was added to the present work to determine whether the CNV associated with this task might successfully discriminate the groups. Because the CNV typically increases with sustained attention and decreases with distraction (Teece & Cattanach, 1993), and because those with MHI typically have problems with divided attention (Bernstein, 1999; Cicerone, 1996), it is possible that the CNV distract will distinguish controls from those with MHI. Another reason for including this easy dual task in the present work was to determine whether the performance deficit observed previously on a demanding dual task represents a generalized difficulty with divided attention, or whether the previous deficit simply reflects task difficulty.

The distinction between task difficulty and a general divided attention deficit associated with MHI was tested in the present study by directly manipulating task demand between two different dual tasks. In the difficult dual task (*P3 distract*), a difficult visual working memory task was paired with a difficult tone discrimination task. In the easy dual task (*CNV distract*), the same visual working memory task was paired with an easy tone discrimination task. Thus, by changing the difficulty of the tone discrimination while holding the visual working memory task constant in the present work, it was possible to more carefully track the demands placed on processing resources. It has been suggested that, among healthy controls, a relatively easy task paired with a more demanding task will likely result in minimal interference, because the easy task requires few additional resources not already demanded by the more difficult task (Wingfield & Byrnes, 1981). If the MHI group's dual task performance deficit in Segalowitz et al. (2001) represents generalized difficulty with divided attention, then, in the present study, controls should outperform the MHI group on both the difficult and the easy dual task. If, however, the previous dual task difference was the result of task difficulty, then controls should outperform individuals with MHI on the difficult dual task but not on the easy dual task.

Based on Segalowitz et al. (2001), several predictions were made in the present study. With respect to electrophysiological task performance, the two groups were expected to perform similarly on the easy measures, but controls were expected to outperform the MHI group on the two difficult P300 tasks (*duration* and *P3 distract*). The CNV distract was not expected to distinguish the groups. This predicted data pattern favors task demand over divided attention deficit as the vital component responsible for long-term cognitive problems associated with MHI (see discussion above). As for electrophysiology, the MHI group was expected to have smaller CNVs on the CNV distract and reduced P300 amplitude on all auditory ERP tasks. No prediction was made regarding P300 amplitude on the easy visual discrimination task (*visual oddball*).

What is unique about the present study is that cognitive problems were sought in a group very unlikely to exhibit overt levels of dysfunction. The present study departs from most MHI investigations that focus on individuals' recovery within the first months after injury or among individuals who present with complaints of poor functioning after MHI. If, with the aid of a broad range of instruments including self-report, neuropsychological and electrophysiological measures, deficits are observed in a group of well-functioning university students many years after injury, then such findings might need to be reconciled with the prevailing wisdom that MHI results in relatively swift and complete recovery (e.g., Dikmen et al., 1995; Levin et al., 1987).

METHODS

Research Participants

Participants were selected from a sample of introductory psychology students ($N = 129$) who completed a battery of health and head injury questionnaires nine months prior for course credit. Of the original sample, 75 participants indicated that they might be interested in being in a follow-up study for pay. An attempt was then made to individually match students with self-reported MHI more than 1 year post-injury and controls on the basis of age and sex, cognitive, physical and emotional complaints, and a variety of problems for which the participants had been professionally diagnosed (e.g., depression, learning disability). Thirteen MHI participants (8 female; $M = 20.85$ years; $SD = 1.81$) and 10 controls (5 female; $M = 20.02$ years; $SD = 1.49$) were chosen for the present study, and received $25 for their participation. MHI was defined as any blow to the head forcing one to stop whatever one was doing because of brief unconsciousness (less than 20 min), dizziness, pain, or disorientation (Segalowitz et al., 2001; Segalowitz & Lawson, 1995). Participants reported on their most severe head injury. Average length of time since injury was 8 years (range = 1–16.5 years). Injuries were due to falls (6), bicycle accidents (4), motor vehicle accident (1), sports accident (1) and fighting (1). Seven of the 13 MHI participants reported unconsciousness (6 reported less than 1 min; one reported 5–20 min). Seven of the 13 MHI participants reported having had more than one MHI. Four MHI participants reported both unconsciousness and more than one MHI. Four MHI participants reported receiving medical attention for their injuries, and one of these participants was hospitalized over night. All participants were right handed.

Materials

Scales for cognitive, physical and emotional complaint were computed from five questionnaires, and these scales were used to match and compare participants. Measures included Broadbent et al.'s (1982) Cognitive Failures Questionnaire; Mateer et al.'s (1987) Memory Questionnaire; two versions of Gouvier et al.'s (1992) Post-Concussive Symptoms checklist; and a modified version of Segalowitz and Lawson's (1995) health and head injury questionnaire. Participants were unaware that the purpose of these measures was to tap a variety of factors commonly associated with head injury. Participants also completed a short neuropsychological battery including the Digit Span Forward and Backward, Vocabulary, Picture Completion, Block Design and Digit Symbol from the WAIS–R (Wechsler, 1981).

Electrophysiological Tasks

Four event-related potential (ERP) oddball tasks (two of which were easy and two difficult) were administered. In the first easy task (*auditory oddball*), participants pressed a button when a high tone (2012 Hz) sounded, but not when a low tone (1000 Hz) sounded. In the second easy task (*visual oddball*), participants responded to a visually presented square, subtending 6.0° of visual angle while ignoring a circle subtending 6.5° of visual angle. Target probability in both tasks was 15%. Stimuli were 100 ms in duration.

In the first difficult task (*duration*), participants responded to a 150 ms tone (15% probability) while ignoring a 100 ms tone, both of 400 Hz. The duration task is both subjectively and objectively more difficult for participants than are standard oddball tasks (Segalowitz et al., 2001). In the second difficult task (*P3 distract*), participants performed the duration task simultaneously with a visual working memory task: single digit numbers followed 800 ms after tones and were flashed for 150 ms. ERPs were collected only for the tone portion of the P3 distract task, as a means of directly comparing ERPs on the P3 distract and duration tasks. Participants responded whenever three odd numbers appeared consecutively (e.g., 3, 1, 9) or when three consecutive ascending or descending numbers appeared (e.g., 1, 2, 3; or 7, 6, 5, respectively). Target probability to the numbers was 30%.

Two contingent negative variation (CNV) tasks were given. In the first (go/no-go), participants responded whenever a double tone (1000 Hz tone followed immediately by a 2012 Hz tone) was preceded by a single, high (2012 Hz) tone (50% probability). All tones sounded for 100 ms with an interstimulus interval of 2000 ms. In the second task (CNV distract), participants performed the go/no-go task with the number counting task (described above). Digits followed 100 ms after single tones.

Participants also completed four pattern visual evoked potential (PVEP) tasks designed to detect possible disruptions to the visual pathways. There is little reason to suspect that MHI results in long-term PVEP abnormality (Gaetz & Bernstein, 2001). They were included here simply to ensure normal visual processing in both groups. In the first two tasks, participants wore a patch over their left and then their right eye while watching a black and white checkerboard pattern reversal on either the left or the right half of the computer screen, respectively (field size = 10° × 17°). Next, participants used both eyes to watch checkerboard reversals in the upper and then the lower half of the computer screen (field size = 8.6° × 20°). The checkerboard reversal rate was 1015 ms for each task.

Electrophysiological Recordings

Twenty-one disposable silver–silver chloride electrodes (Fp1, Fpz, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, Oz, O2) were attached to the scalp following the 10–20 system (Jasper, 1958). Linked ears served as reference and the right mastoid served as ground. Electrode impedances were maintained below 5 kΩ. EEG signals were amplified and recorded using a 21-channel Nihon-Kohden electroencephalograph with software developed by Kelly Jantzen. For both the ERP oddball and CNV tasks, only trials with correct behavioral responses were included in the averages. Single trials and averages were scored blind to participants' group.

For ERP oddball tasks, 1100 ms epochs including a 100 ms prestimulus baseline were digitized at a rate of 256 points per second, with a bandpass filter of .16–35 Hz and a sensitivity level of 10 μV/mm. Signals were sent to a 12-bit A to D converter and stored for off-line processing. Single trials were low pass filtered at 30 Hz and were visually inspected for ocular and/or movement artifact. Trials were removed from averaging if they contained signals exceeding ±75 μV between zero and 600 ms post stimulus. To further mitigate effects due to ocular artifact, single trials were omitted from averaging if the P300 amplitude at Fp1, Fpz, or Fp2 exceeded the amplitude at Pz. Topographic maps of the entire scalp distribution were visually inspected for each trial to ensure that the P300 was maximal either parietally or centrally. Average waveforms for the target trials were scored for components N100, P200, N200 and P300. N100 and P200 were scored at Fz, while N200 was scored at Cz and P300 was scored at Pz.

For the CNV tasks, EEG epochs were 4100 ms, including a 100 ms prestimulus baseline. The bandpass filter was .16 to 15 Hz with a sensitivity level of 10 μV/mm. Single trials with more than one peak exceeding ±75 μV between zero and 2500 ms post-stimulus were removed. A low pass filter of 5 Hz was used on the average waveform, and this average was then scored for the lowest negative point occurring at approximately 2000 ms using sites Fz, Cz and Pz. For the PVEPs, EEG epochs were 256 ms, including a 100 ms prestimulus baseline. The bandpass filter was .16 to 120 Hz with a sensitivity level of 10 μV/mm. All single trials were included in the average. Averages were scored for amplitude and latency using sites O1, Oz, and O2.

Recordings were made in a semi-darkened room with participants seated comfortably 1 m in front of a computer monitor. Each ERP and CNV task required 7 min to complete. Each PVEP task required 2 min.

Procedure

Participants completed questionnaires early in the year and left phone numbers if they wished to be contacted for follow-up. Those chosen for follow-up, and who agreed to participate, returned and completed the neuropsychological and then the electrophysiological measures. The CNV and P3 tasks were counterbalanced for order, with the exception that the P3 duration had to precede the P3 distract and the go/no-go had to precede the CNV distract. PVEPs were administered last. Participants practiced on all ERP and CNV tasks to ensure that they understood the directions. The neuropsychological and electrophysiological measures required up to 3.5 hr to complete, including electrode hookup. Participants were fully debriefed upon completing the study.

Data Analysis

The present sample size was similar to that used by Segalowitz et al. (2001), where large effect sizes were obtained. Significant performance differences were expected to emerge only on the most cognitively demanding measures, those tapping information processing speed and capacity, while P300 amplitude differences were expected on the easy and difficult measures. In no case was the MHI group expected to outperform controls, and this was confirmed in the analyses. To maintain balance between Type I and Type II error, alpha was set to .05 two-tailed without correction for multiple comparisons (see Cohen, 1992, for details). Two control participants were dropped from any analysis involving the duration and P3 distract tasks, because they were unable to distinguish the 100 ms and 150 ms tones. Their false alarm rates on both tasks exceeded two standard deviations above the mean for all participants combined. Further, during and after testing, these participants were the only ones to report an inability to distinguish the tones on each of these tasks. One MHI participant failed to complete the neuropsychological tasks.

Univariate comparisons were conducted using t-tests to determine whether the two groups were well matched in terms of subjective complaints and neuropsychological performance. Task difficulty was assessed by two separate MANOVAs using signal detection analysis of discrimination (d') as the dependent measure (Hochhaus, 1972; Tanner & Swets, 1954). Higher d' scores signify a greater ability to distinguish between targets and non-targets. In the first analysis, the three difficult tasks (duration, P3 distract, CNV distract) combined were compared to the three easy tasks (auditory oddball, visual oddball, go/no-go) combined, collapsing across groups (MHI and control). In the second analysis, again collapsing across groups, the two P3 distract sub-tasks (tones and numbers) were combined and compared to a composite score on the two CNV distract tasks.

To compare groups in terms of their performance on the electrophysiological tasks, *t* tests were conducted using d' as the dependent variable. To compare the groups in terms of electrophysiology (ERPs, CNVs and PVEPs), *t* tests again were performed. A prestimulus baseline was not collected for 1 MHI participant due to technical problems. Her ERP data were omitted. Four participants with excessive eye artifact on the auditory oddball and three participants with excessive eye artifact on the duration task were excluded from analyses involving these tasks.

Two separate exploratory analyses were performed to determine whether group membership could be predicted using a combination of electrophysiological, neuropsychological and self-report indices. Variables were chosen for the analyses based upon univariate differences observed. In the first analysis, a multiple regression was performed with group as the dependent variable, and auditory oddball P300 amplitude, digit symbol score and self-reported sleep difficulties as the independent variables. Next, a cross-validated discriminant function analysis, which is essentially a jack-

Table 1. Post-concussive symptoms

Symptom	Control	MHI
Sleep complaints	14.70 (1.89)	20.85** (1.68)
Memory problems	54.90 (3.08)	52.69 (2.15)
Cognitive failures	41.90 (1.98)	47.85* (2.29)
PCS–today	77.56 (5.93)	82.31 (8.67)
PCS–6 month	101.50 (4.81)	114.88 (5.97)

Note. PCS = Post-Concussive Symptoms Checklist.
*$p < .10$; **$p < .05$; standard error of mean in parentheses.

knife estimate (SPSS, Release 10.0), was performed using these same three predictor variables.

Finally, several variables that are believed to affect cognitive outcome after MHI were tested to determine whether they accounted for significant variance in the effects obtained. These analyses were conducted using Pearson correlation coefficients.

RESULTS

Questionnaires and Neuropsychological Tests

The two groups were similar in terms of their subjective complaints (see Table 1). The only significant differences to emerge involved more overall reported sleep problems among the MHI group [$t(21) = 2.43$, $p < .05$, effect size $(d) = 1.02$], and a tendency for the MHI group to report more problems on the Cognitive Failures Questionnaire [$t(21) = 1.90$, $p < .1$, effect size $(d) = .80$]. The former difference was expected from previous research (e.g., Segalowitz et al., 2001; Segalowitz & Lawson, 1995). Despite the statistical trend on the Cognitive Failures Questionnaire, the two groups reported similar cognitive complaints on all remaining questionnaires. The two groups were also similar in terms of self-reported problems for which they had been professionally diagnosed (e.g., depression, anxiety, learning, reading and speech difficulties), and their use of alcohol, caffeine and cigarettes ($p > .1$ for each). Thus, the groups were well matched.

In terms of neuropsychological performance, the only measure to distinguish the groups was the Digit Symbol [$t(20) = 2.82$, $p = .01$, effect size $(d) = 1.21$]. Here, controls outperformed the MHI group, a result consistent with the notion of reduced processing speed after MHI (see Table 1).

Table 2. WAIS–R test performance

Subtest	Control	MHI
Digit Span Forward	8.90 (.80)	9.31 (.59)
Digit Span Backward	7.60 (.72)	7.31 (.44)
Vocabulary	42.80 (5.39)	52.92 (3.94)
Picture Completion	14.70 (.58)	13.77 (.55)
Block Design	40.60 (2.50)	36.23 (1.83)
Digit Symbol	77.60 (2.83)	66.54** (3.29)

**$p < .05$; standard error of mean in parentheses.

Table 3. Performance (d') on discrimination tasks

Discrimination task	Control	MHI
Go/no-go	4.86 (.25)	4.91 (.24)
Auditory oddball	5.31 (.19)	5.11 (.21)
Visual oddball	5.33 (.16)	5.40 (.10)
Duration	3.64 (.42)	3.65 (.32)
P3 distract (tones)	3.51 (.32)	2.77** (.15)
P3 distract (numbers)	2.06 (.15)	2.18 (.11)
CNV distract (tones)	4.02 (.25)	4.19 (.23)
CNV distract (numbers)	3.15 (.38)	2.66 (.31)

**$p < .05$; standard error of mean in parentheses.

Electrophysiological Tasks (Performance)

As predicted, the difficult tasks received a lower overall d' score ($M = 3.21$) than did the easy tasks [$M = 5.19$; $F(1,17) = 176.40$, $p < .01$]. Further, the P3 distract task received a lower combined d' score ($M = 2.60$) than did the CNV distract task [$M = 3.57$; $F(1,19) = 30.42$, $p < .01$]. Task difficulty was, therefore, successfully manipulated.

With respect to group comparisons, contrary to prediction, controls ($M = 3.64$) and those with MHI ($M = 3.65$) performed equally on the duration task. However, when this task was performed with the number counting task in the P3 distract, as predicted, controls ($M = 3.51$) outperformed the MHI group ($M = 2.77$) on the tone portion of this dual task [$t(18) = 2.38$, $p < .05$, effect size $(d) = 1.09$; see Table 3]. The two groups performed similarly on the number counting portion of the P3 distract ($p > .1$). As predicted, no difference emerged on the tone or number counting portions of the CNV distract task ($p > .1$ for both tests). Thus, the two groups performed equally on an easy dual task and on a difficult tone discrimination task (duration) when it was performed alone; however, controls outperformed the MHI group on the most demanding measure of all—a difficult dual task.

Electrophysiological Measures (ERPs, CNVs, and PVEPs)

As expected, there were no amplitude differences between groups on N100, P200 or N200 ($p > .1$ for all tests). However, the MHI group demonstrated reduced P300 amplitude on two of three predicted measures, the auditory oddball and duration tasks [$t(16) = 3.01$, $p < .01$, effect size $(d) = 1.43$; and $t(15) = 1.97$, $p < .1$, effect size $(d) = .96$, respectively; see Figures 1 and 2]. There was no P300 amplitude difference on the visual oddball ($p > .1$). As expected, there were no significant latency differences, and no differences on the go/no-go or PVEPs ($p > .1$ for all tests).

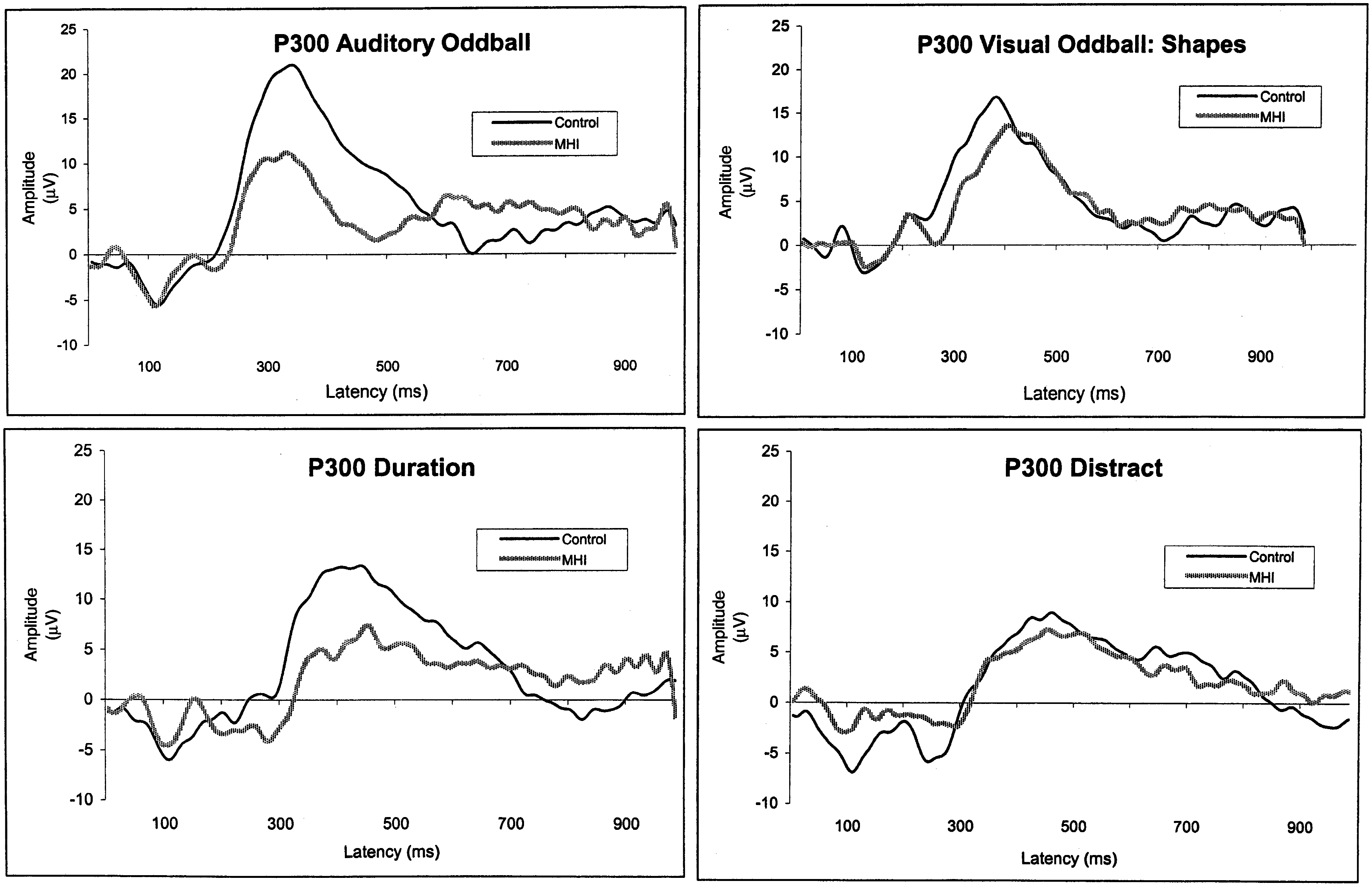

Fig. 1. Average ERPs to targets at Pz for each group for the auditory oddball, visual oddball, duration and P3 distract tasks. Positive voltages are plotted up. The control group average is indicated in thin lines, and thick lines represent the MHI group average.

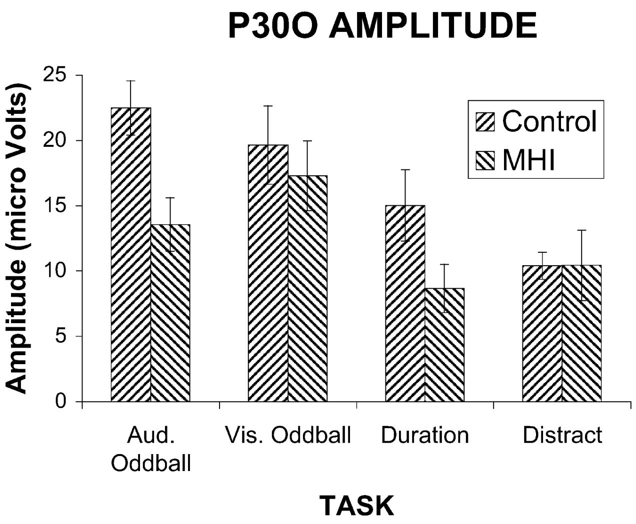

Fig. 2. P300 amplitudes for each group for the auditory oddball, visual oddball, duration and P3 distract tasks.

Contrary to expectation, there was no difference on the CNV distract ($p > .1$).

Discriminant Function Analysis

Together, auditory oddball P300 amplitude, digit symbol score and self-reported sleep difficulties accounted for nearly 70% of the variance in group membership ($R^2 = .695$). Moreover, 15/17 participants (88%) were correctly classified as belonging to their respective group (Kappa = .76). One participant was misclassified in each group, respectively.

Possible Moderator Variables?

In the MHI group, length of unconsciousness, number of MHIs, and time since injury all failed to correlate significantly with P300 amplitude, and with cognitive, physical and emotional complaints ($p > .1$ for all tests). Further, diagnosed problems (e.g., depression, learning and reading disabilities) and subjective complaint, including sleep difficulties and cognitive problems, did not correlate with each other or with performance and P300 amplitude in either group. Thus, the performance and electrophysiological differences observed were unlikely due to subjective complaints, diagnosed problems, injury severity, number of injuries or time since injury.

DISCUSSION

These results partially replicate and extend previous work on well-functioning university students with self-reported concussion (MHI) (Segalowitz et al., 2001). In both studies, participants with MHI exhibited subtle, long-term cognitive problems compared to controls matched for age, sex, education and cognitive, physical and emotional complaints. In the present study, individuals with MHI an average of 8 years post injury performed more poorly on a highly demanding divided attention task and on the Digit Symbol substitution task, a measure of processing speed. Moreover, individuals with MHI had reduced P300 amplitude relative to controls on two out of three measures previously shown by Segalowitz et al. to distinguish controls from those with MHI. These findings, though preliminary, suggest that self-reported concussion may be associated with subtle, long-term information processing difficulty.

In the present study, contrary to prediction, controls and individuals with MHI performed equally on a difficult tone discrimination task (duration) when it was performed alone; however, as predicted, controls outperformed the MHI group on this task when it was paired with a visual working memory distractor task (P3 distract). When this same working memory distractor task was paired with an easy tone discrimination task in the present study, as predicted, the two groups performed similarly. Thus, controls and individuals with MHI performed equally well on two of three difficult tasks in the present study (confirming two of three predictions), indicating that the extent to which processing demand is manipulated may be critical in MHI research.

The three difficult tasks in the present study require varying numbers of processing resources, and this may explain why only one of these measures distinguished the two groups. The duration task involves sustained attention to subtle differences in tone length, where even momentary inattention likely results in failure to register tones. The MHI group had little trouble on this task. However, in the P3 distract task, this same duration task was performed simultaneously with a visual number counting task requiring continuous updating of working memory. Here, the MHI group performed more poorly than controls, suggesting that the duration tone discrimination was more difficult for the MHI participants in the presence of an additional, demanding task. The CNV distract task, like the P3 distract, involves working memory for visually presented numbers. However, unlike the P3 distract, the CNV distract involves only brief episodes of sustained attention, where lapses rarely cause tone misdetection. Park et al. (1999) have recently reported that individuals with severe traumatic brain injury perform poorly on divided attention tasks requiring working memory, but these same patients perform well on tasks that can be executed relatively automatically. The tone portion of the CNV distract task can be performed with very little effort, thus freeing up resources for the number counting task, and the MHI group had no difficulty on either measure. The present findings indicate that individuals with MHI do not possess a generalized difficulty with divided attention. Rather, the degree to which processing resources are taxed seems vital for elucidating enduring changes in information processing after MHI.

Gronwall and Wrightson (1975) have argued that MHI may be associated with reduced processing capacity. Another possibility is that individuals with MHI have normal processing capacity, but have trouble allocating resources (cf. Baddeley, 1998). Thus, when performing a task requiring relatively few resources, individuals with MHI have little difficulty. However, when task demands require more resources than are available or when task demands exceed one's ability to allocate resources, performance may decline. The fact that the MHI group in the present study performed more poorly than controls on the Digit Symbol, an index of information processing speed, supports the view that MHI may be associated with impaired resource allocation (Potter & Barrett, 1999).

In addition to resource allocation deficits, the P300 amplitude decrements observed in the MHI group in the present work and in that of Segalowitz et al. (2001) also argue for deficits in processing capacity (see Segalowitz et al. for discussion). In the present study, participants with MHI demonstrated reduced P300 amplitude on both an easy and a difficult auditory discrimination task (auditory oddball and duration, respectively), but not on the most difficult task (P3 distract). This might seem inconsistent with the behavioral performance, where significant group differences emerged only on the P3 distract; however, as shown previously, P300 amplitude declines with increasing task difficulty (Polich, 1987), raising the possibility of a floor effect. Moreover, Segalowitz et al. (2001) observed that the P300 amplitude difference between groups was smallest on the P3 distract, consistent with the floor effect assumption. Thus, the present data pattern replicates that of Segalowitz et al., and lends further support to the notion that P300 amplitude may be a useful marker of information processing difficulty after MHI (e.g., Dupuis et al., 2000; Ford & Khalil, 1996; Granovsky et al., 1998; Reinvang et al., 2000; Sangal & Sangal, 1996; Solbakk et al., 2000). Together, the neuropsychological and electrophysiological findings in the present work point to long-term deficits in both resource allocation and information processing capacity after MHI.

Distinguishing Controls from MHI

Despite the P300 differences observed in the present study, no pattern visual evoked potential (PVEP) or contingent negative variation (CNV) differences emerged. This suggests that the MHI group had normal visual pathways and had no difficulty sustaining attention for the brief intervals required by the CNV tasks. These results also indicate that the PVEP and CNV may have less clinical utility than does the P300 in distinguishing controls from those with MHI long after injury (cf. Gaetz & Bernstein, 2001).

One of the many challenges facing MHI researchers is how to accurately distinguish controls from individuals with MHI. In the present study, group membership was predicted with 88% accuracy using a combination of electrophysiological, neuropsychological and self-report indices. Although this is a high level of accuracy, it must be noted that choosing predictor variables based on univariate differences obtained, as was done in the present work, might bias a result in favor of detecting a difference. Replication of this particular set of predictor variables, therefore, is warranted.

Implications and Limitations

The fact that MHI participants in the present study were well-functioning university students with self-reported concussion and with no major subjective complaints makes these data all the more intriguing. Admittedly, these results are hard to reconcile with recent meta-analytic work showing scant evidence for cognitive impairment long after MHI (Binder et al., 1997). As has been argued elsewhere (Bernstein, 1999; Stuss et al., 1985), cognitive deficits after MHI may be highly select and subtle in nature. If so, many of the tests included in Binder et al.'s calculations may be insensitive to subtle deficits. Perhaps a more demanding and comprehensive array of indices, including the specific combination of self-report, neuropsychological and electrophysiological measures, might reveal long-term, subtle cognitive problems associated with MHI.

What do these results mean for the late recovery process following MHI? It appears that MHI may result in enduring cognitive changes; however, these changes are highly subtle in nature, and will likely only surface when processing demands exceed either one's processing capacity or one's resource allocation ability. As the auditory oddball task in the present study suggests, individuals with MHI can perform at ceiling on an easy task, despite having reduced P300 amplitude (a possible index of reduced processing capacity). Thus, people with MHI will be largely indistinguishable from controls on the majority of behavioral tasks, unless these tasks unduly tax processing resources or unless more sensitive measures such as electrophysiological recordings are obtained.

One variable that may account, in part, for the present findings and that is often overlooked in MHI research is testing duration. Most participants in this study and in that of Segalowitz et al. (2001) underwent several hours of continuous assessment. It is, therefore, possible that the observed deficits in both studies were partially due to decreased arousal in the MHI group (Bernstein & de Ruiter, 2000; cf. Parasuraman et al., 1991).

A potential drawback of the present study and that of Segalowitz et al. (2001) is that the methodology does not rule out pre-morbid differences. A longitudinal, prospective design, preferably using an additional control group of individuals with traumatic injuries other than MHI (cf. Dikmen et al., 1995; Satz et al., 1999), would strengthen the results reported here. In sum, the present findings suggest that university students with self-reported concussion may demonstrate subtle problems with information processing many years after injury. Further work is clearly needed to confirm the existence, nature and potential repercussions of such problems.

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