

# P300 Event-Related Potential Decrements in Well-Functioning University Students with Mild Head Injury

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Published online January 29, 2001

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We compared the performance of 10 well-functioning university students who had experienced a mild head injury (MHI) an average of 6.4 years previously and 12 controls on a series of standard psychometric tests of attention, memory, and thinking and on a series of auditory oddball vigilance tasks to which we also took event-related potentials (ERPs). The MHI and Control groups performed equivalently on all the psychometric tasks and on self-report questionnaires of everyday memory and attention difficulties. The MHI group performed more slowly and with lower accuracy on only the most difficult of the oddball tasks, yet they showed substantially and significantly reduced P300 amplitudes and subsequent attenuation on all the oddball tasks, both easy and difficult. There were no alterations of N1, P2, and N2 components. These data suggest that despite excellent behavioral recovery, subtle information processing deficits involving attention nevertheless may persist long after the original injury and may not be apparent on a variety of standard psychometric measures. © 2001 Academic Press

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Individuals who have sustained a mild head injury (MHI) have been shown to demonstrate slower information processing, problems on tasks involving divided attention, impaired focused attention, and overall inconsistency in performance up to 3 months postinjury (Hugenholtz, Stuss, Stethen, & Richard, 1988) in addition to visuospatial attention deficits a year postinjury (Cremona-Meteyard & Geffen, 1994). Indeed, in a large study of MHI with normal Glasgow Coma Scale scores, 6.5% of participants nonetheless have positive CT scan abnormalities related to the injury (Haydel, Preston, Mills, Luber, Blaudeau, & DeBlieux, 2000), while individuals with MHI and no CT scan indications show significantly reduced cortical excitability (Chistyakov, Soustiel, Hafner, Elron, & Feinsod, 1998). These deficits as well as others involving subjective complaints of attention and concentration often mitigate over time. Thus, MHI is generally considered to have an outcome of “good” or “excellent” recovery (Levin, Mattis, Ruff, Eisenberg, Marshall, Tabaddor, High, & Frankowski, 1987), although the subjective complaints may persist a year postinjury (Rutherford et al., 1979) and often longer. Unfortunately, the effects of mild head injury on cognitive performance many years after injury have not been well ex-

We thank Drs. Kim Kerns and Catherine Mateer for their comments on an earlier draft of this article and Imaging Research, Inc. for the use of their MQE digitizing software. This research was funded by grants from the Natural Sciences and Engineering Research Council of Canada and the Ontario Neurotrauma Foundation to the first author. Daniel M. Bernstein is now at the Department of Psychology, Simon Fraser University, Burnaby, British Columbia, Canada.

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plored (see Bernstein, 1999, for a review). We chose to study these effects in a relatively high-functioning group—1st-year university students—on a series of standard cognitive assessment measures and auditory vigilance tasks. We also collected event-related potentials (ERPs) on these vigilance tasks to determine whether individuals who have sustained a mild head injury differ electrophysiologically from controls.

The majority of work involving ERPs and head injury has concentrated on severe head injury (Curry, 1980; Heinze et al., 1992; Rugg et al., 1993; Unsal & Segalowitz, 1995). Most of the ERP work on MHI comes from clinical studies involving the brain stem auditory evoked response (Rowe & Carlson, 1980; Schoenhuber & Gentilini, 1986) and middle-latency responses (Ford & Khalil, 1996; Soustiel et al., 1995), with less work done on the later components of the ERP. Some of this work has demonstrated that P300 may be used to differentiate the mild head injured from controls within a short period after the injury (Papanicolaou et al., 1984; Pratap-Chand, Sinniah, & Salem, 1988; also see Solbakk et al., 2000, and Granovsky, Sprecher, Hemli, & Yarnitsky, 1998). However, the “good recovery” associated with most cases of MHI may really represent a behavioral adaptation rather than a return to preinjury levels of functioning. In many cases, persons with an MHI complain of persisting attentional problems (Marshall & Ruff, 1989), although it is difficult to demonstrate this with standard psychological measures. The current study represents an attempt to objectively quantify these subtle attentional difficulties by means of ERPs collected to stimuli in focused attention tasks (auditory ERPs) and sustained attention tasks (contingent negative variation).

### *The Auditory ERP and Information Processing*

ERPs to simple auditory stimuli have a characteristic set of major components ranging from about 100 to 600 ms following stimulus presentation. The first is a negative peak 50 to 150 ms after the stimulus (N1), which reflects stimulus detection (Parasuraman, Richer, & Beatty, 1984), followed by a positive P2, usually 150 to 250 ms poststimulus, which reflects perceptual elaboration in secondary sensory cortex (Braun, Miltner, & Scherg, 1990). The N2 follows the P2 at 250–400 ms and reflects some automatic aspects of stimulus classification (Ritter, Simpson, Vaughan, & Macht, 1982).

The P300 component of the ERP is the next major positive peak following the N2 and is associated with evaluation of a stimulus as being salient in the task, usually because it is a target which demands a response. Paradoxically, the P300 amplitude is usually reduced if the processing required for the stimulus evaluation is more complex, probably because complex processing involves more subprocesses each with a P300 of different timing (e.g., Houlihan, Stelmack, & Campbell, 1998). This P300 component is also referred to as the P3b. There can also be a P300 response to a nontarget stimulus if it stands out to the subject because it is perceptually salient, such as some novel stimulus. This “novels” P3 is associated with a more automatic response compared to the P3b, which is associated with more effortful information processing; the novels P3 is of greater amplitude at more central and frontal midline electrode sites while the P3b is maximal at posterior sites (Knight, 1984). The novels P3 is associated with frontal lobe generator sites (Knight, 1984) rather than more posterior generators as for the P3b (Knight, 1990).

In contrast to behavioral tasks, ERP measures tap into ongoing processing of information without being influenced by response strategies and compensations (e.g., McCarthy & Donchin, 1981). Thus, while subjects with good recovery have by definition few lingering behavioral deficits from the injury, it may be that ERP measures are

sensitive to subtle decrements in attentional processes for which the person cannot compensate.

We predicted that in a group of well-functioning university students who had sustained a mild head injury at some time in their life, if performance deficits persisted, they would be demonstrated on difficult attentional tasks, especially those requiring divided attention. Furthermore, we hypothesized that if there is a general decrement of attentional capacity (Gronwall & Wrightson, 1975), then the P300 components would be smaller in the mild head injured group than in the controls, especially in a dual-task situation. Such a performance deficit and P300 attenuation, if present many years following mild head injury, would argue for a model of long-lasting cognitive deficit. In contrast to the P300 components, we predicted that the earlier N1, P2, and N2 components would be relatively normal in an MHI group of individuals who claim no sensory or perceptual difficulties.

A second ERP paradigm, the Contingent Negative Variation (CNV), examines electrophysiological responses leading up to an anticipated stimulus after a warning and thus reflects orienting to the first warning stimulus and subsequent expectation of the second stimulus (the "response" or "imperative" stimulus). The ERP during the interstimulus period typically is a growing negativity that reflects orienting to the warning stimulus (the O-wave) while the latter portion reflects the expectation of the response stimulus (the E-wave) (Gaillard, 1977). In a Go/NoGo paradigm where the warning stimulus is also a signal as to whether the subject should respond to the imperative stimulus, the Go trials are associated with a full CNV negativity while the NoGo trials are associated with an O-wave and a much attenuated E-wave (Campbell, Suffield, & Deacon, 1990). Thus, this paradigm allows us to examine orienting and sustained attention at an electrophysiological level.

## METHOD

### *Participants*

Ten participants (six female, four male) ( $M = 20.1$  years;  $SD = 1.52$ , range = 19–23) were recruited for the present study if they had reported a mild head injury on a questionnaire given to an introductory psychology class. Mild head injury was defined as any blow to the head forcing one to stop whatever one was doing. Unconsciousness was reported in 8 of the 10 cases ( $M = 5.3$  minutes,  $SD = 6.43$ ; 2 reported no unconsciousness, 3 reported 1 min, 2 reported 5 min, 2 reported 10 min, and 1 reported 20 min of unconsciousness). Average length of time since injury was 6.4 years ( $SD = 4.3$ ; range = 1–13 years). Three participants were hospitalized overnight for their injury. Causes of injury were sports accidents (4), vehicle accidents (3), falls (2), and fighting (1). Seven people reported having had more than one head injury, but indicated that the most severe was the one we classified as mild.

There were 12 healthy controls (eight female, four male) ( $M = 20.67$  years;  $SD = 3.63$ ; range = 19–32), all but one currently attending university, with no history of head injury. All participants (controls and MHI) had normal hearing in that they all could easily detect tones 20 db above ambient room noise level.

### *Materials*

Participants completed the Vocabulary, Digits Span Forward and Backward, Block Design, and Digit Symbol from the WAIS-R (Wechsler, 1981) and Concept Formation from the Woodcock Johnson Psycho-Educational Battery: Tests of Cognitive Ability (Woodcock & Johnson, 1977). Participants also completed the following questionnaires and underwent an interview where they were asked to provide details about their injury. The Cognitive Failures Questionnaire (CFQ, Broadbent, Cooper, Fitzgerald, & Parkes, 1982) contains 25 questions about self-reported failures in perception, memory, and motor function rated on a 5-point scale. Mateer, Sohlberg, and Crinean's (1987) Memory Questionnaire contains 30 items tapping attention/prospective memory, retrograde memory, anterograde memory, and historic/overlearned memory. Items are rated on a 5-point scale. A modified version of Segalowitz and Lawson's

(1995) questionnaire was used, including items regarding head injury, sleep disturbances, and psychosocial behavior.

### *Electrophysiological Tasks*

Participants completed four auditory ERP oddball tasks, two easy and two difficult. In the first easy one (Regular Oddball), the task was to press a key when the target high tone (1500 Hz) sounded and not when the nontarget low tone (800 Hz) sounded. In the second task (Novels Oddball), another "novel" nontarget sound (a sliding tone that was different on each presentation) was added to distract the participants and to produce a novel P3 ERP component. The target tones in both of these easy conditions and the novel tones in the Novels Oddball appeared on 15% of trials, while the nontarget tones appeared on the remaining trials. All stimulus tones were of 100 ms duration and the stimulus onset asynchrony (SOA) for all oddball paradigms was randomly varied between 1200 and 1800 ms, with a mean of 1500 ms. (We have found in the past that subjects are much less likely to become bored or sleepy with this slight variation in SOA.)

The difficult tasks (Duration and Duration with Distraction) involved responding to 100-ms target tones (15% occurrence frequency) and not to 150-ms nontarget tones, all of which were of 400 Hz. Subjects report that this duration judgment is more difficult than the pitch oddball, presumably because echoic memory serves to carry the pitch after presentation while duration judgment must be made online, i.e., the duration discrimination requires constant attention to the task while the pitch discrimination permits more lax attending. The Duration with Distraction condition was the same as the Duration condition except that subjects simultaneously performed a visual working memory distractor task: Single-digit numbers between 1 and 9 were flashed every 2 s for .5 s on a second computer screen. Participants responded by pressing a mouse button with their dominant hand whenever they saw either three consecutive odd numbers (e.g., 3, 7, 1) or three consecutive ascending or descending numbers (e.g., 4, 5, 6 or 8, 7, 6). Meanwhile, participants responded with the other hand on the computer keyboard whenever the 100-ms target tone sounded. Practice was given until participants understood directions perfectly (usually within 2 min).

We used two CNV tasks. In the Standard CNV task, subjects responded to a 100-ms 1500-Hz imperative tone 2.3 s after hearing a 100-ms 800-Hz warning tone. Intertrial interval varied randomly between 5 and 9 s. There were 30 trials, of which the first 5 counted as practice to familiarize the subject with the 2.3-s interstimulus interval.

The second CNV paradigm—a Go/NoGo task—required the participant to respond to the imperative tone only when the warning tone was 800 Hz (Go trials) and to withhold a response when the warning tone was 400 Hz (NoGo trials). The imperative tone and interstimulus interval were the same as those used in the Standard CNV task. There were 60 trials (50% Go and 50% NoGo), counterbalanced within subject every 10 trials. The first 4 trials served as practice.

### *Electrophysiological Measurements*

Gold electrodes were placed with electrode cream and surgical tape to midline sites Fz, FCz (midway between Fz and Cz), Cz, and Pz using the 10-20 electrode placement system (Jasper, 1958). The FCz site was used to help identify novel P3 components which are expected to be maximal over the more frontal sites (Knight, 1984). Eye movement artifact was monitored by a vertical and a horizontal EOG channel attached to the supraorbital and outer canthus of one eye, except for one control subject for whom we had only a horizontal EOG. All EEG and EOG electrodes were referenced to linked ears, with the right mastoid serving as ground. Electrode impedances were maintained below 5 k $\Omega$ . For both oddball and CNV tasks, only trials with correct responses with RTs between 50 and 1000 ms were used in the averaging.

For the oddball tasks, EEG was digitized at a rate of 2.5 ms per point, with a 12-bit A-D window for  $\pm 250$   $\mu$ V, gain of 10,000 and band pass of .5 to 30 Hz. Rejection for movement artifact was set at  $\pm 100$   $\mu$ V on any channel. ERPs were averaged offline over 1100 ms of EEG per trial including a prestimulus baseline period of 100 ms before the tone onset, and amplitudes for each component were calculated relative to this baseline. ERP components of N1, P2, N2, and novels P3 and P3b were visually identified on the averaged waveforms for each subject in each condition separately. The following criteria were used in scoring component latencies and amplitudes: N1 = most negative point in the interval 50–150 ms; P2 = first major positive peak after N1; N2 = most negative peak in the interval 175–400 ms; P300 = highest positive peak between 250 and 600 ms. The novel P3 was the P300 component derived from the novel stimulus trials in the Novels condition and had to be of greater amplitude at the Fz or FCz sites than at the Pz site. The P3b component was the P300 from the target trials in each condition and had to be of greater magnitude at the Cz or Pz sites than at the FCz or Fz sites.

For the CNV tasks, the amplifier band pass was .01–30 Hz with a time constant of 10 s and a sampling rate of 10 ms per point. All other EEG characteristics were the same as for the oddball tasks. For the two CNV tasks, the ERP between 600 ms after the warning stimulus until the onset of the imperative stimulus was divided into five equal time frames of 340 ms (see Segalowitz, Unsal, & Dywan, 1992; Dywan, Segalowitz, & Williamson, 1994). The initial two time frames were grouped to form the O-wave, and the latter three time frames were grouped to form the E-wave (Gaillard, 1977).

### Procedure

Participants completed the questionnaires and neuropsychological measures and then completed the electrophysiological measures. Most participants completed testing in 3 consecutive h, except for one person, who completed the questionnaires and neuropsychological measures and then the ERP measures on 2 consecutive days. The order in which the electrophysiological tests were administered was as follows: (1) the two CNV tasks (counterbalanced within groups), (2) the two easy ERP tasks (counterbalanced within groups), (3) the difficult Duration task without the visual distractor counting task, and (4) the difficult Duration task with the visual distractor. All testing was done between 11 A.M. and 6 P.M. Participants were asked to refrain from caffeine and nicotine for at least 3 h before testing and from excessive alcohol use on the night prior to testing.

## RESULTS

### Psychometric Measures

*Neuropsychological measures and questionnaires.* There were no differences between Controls and MHI subjects on Digit Span, Digit Symbol, Block Design, or Vocabulary from the WAIS-R, on the Concept Formation from the Woodcock Johnson Psycho-Educational Battery: Tests of Cognitive Ability, or on the CFQ or Mateer memory questionnaires ( $p > .1$  for all tests). On our own survey, the MHI and Control groups self-scored similarly [all  $t(20) < 1.25$ ] on their use of alcohol (3.1 vs 2.9 drinks per week),<sup>1</sup> cigarettes (2.1 vs 1.75 per day),<sup>1</sup> and caffeine (1.7 vs 1.0 drinks per day). There was a statistical trend for the MHI group to report more sleep-related complaints than the controls [ $t(20) = 1.99, p = .06$ ]. All  $t$  tests were two-tailed.

### ERP Auditory Discrimination Tasks

*Reaction time performance.* If we consider reaction time (RT) as an indicator of task difficulty, the four tasks differed as predicted, with the Duration task and Duration with Distraction task requiring longer median RTs than the Regular and Novels Oddball tasks [see Fig. 1;  $F(3, 60) = 174.8, p < .001$ ].<sup>2</sup> We predicted that the MHI group would have particular difficulty with the more demanding tasks. While neither the Group [ $F(1, 20) = 2.65, ns$ ] nor Group  $\times$  Task interaction [ $F(3, 60) = 2.21, p < .12$ ] was significant, the difference in RTs between the two groups gradually increased and reached significance for the Duration with Distraction task [ $t(20) = 3.30, p < .005$ ]. The RTs on the distractor task itself were not different for the two groups [ $t(18) = .78$ ; for one subject in each group, the RTs to the distractors were not recorded].

<sup>1</sup> The MHI and Control groups scored 2.30 vs 2.25 on a 5-point scale of alcoholic consumption (from less than 1, 1–3, 4–7, 8–10, to more than 10 drinks per week), 1.7 vs 1.25 on a 5-point scale of cigarette consumption (from 0, 1–5, 6–10, 11–20, to 20+ per day), and 2.7 vs 2.0 on a 5-point scale of consumption of caffeinated drinks (from 0, 1, 2, 3, to 4+ per day).

<sup>2</sup> For all repeated-measures ANOVA designs, we report the  $p$  value associated with the Greenhouse–Geisser correction for sphericity, but maintain the degrees of freedom associated with the research design. The sample size varies for some analyses because one MHI and two control subjects occasionally had some unreliable components in some conditions.



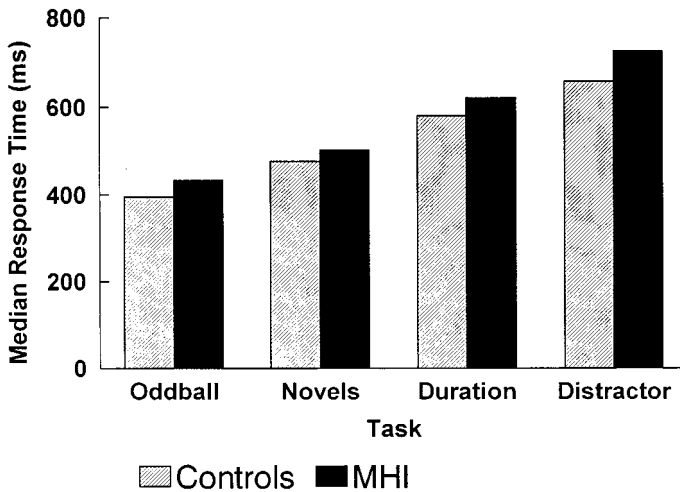
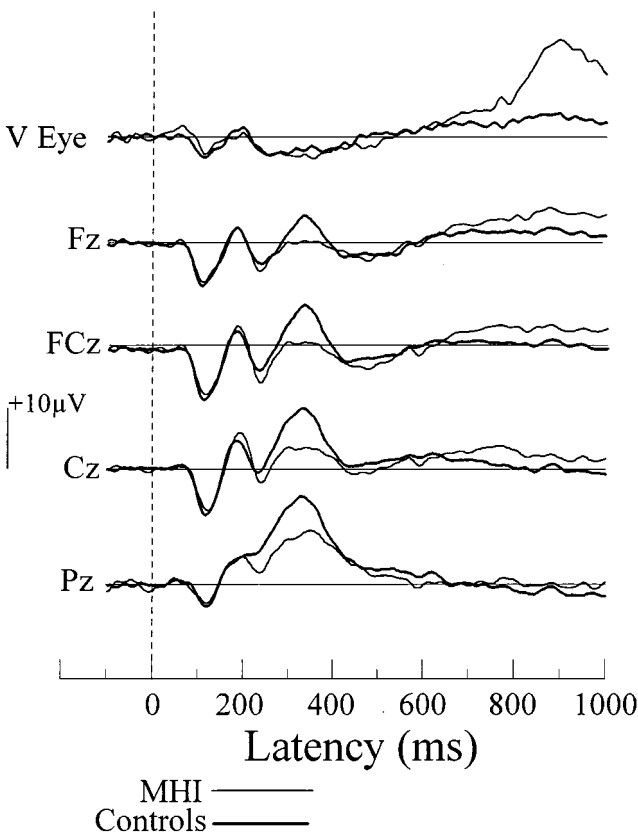


FIG. 1. Response times (in milliseconds) to the four ERP tasks for each group.

*Oddball task performance.* Signal detection analysis of the performance on the oddball tasks revealed that the groups did not differ on the Regular and Novels Oddball tasks, but the controls had higher discrimination ( $d'$ ) than the MHI group on both Duration tasks, i.e., with and without the distractor component [ $t(20) = 2.36$  and  $2.37$ , respectively,  $p < .05$ ]. Finally, the MHI participants demonstrated a lower threshold to respond (lower  $\beta$ ) on the distractor task ( $Z = 2.43$ ,  $p < .02$ , Mann-Whitney  $U$  test with correction for ties), although the  $d'$  did not differ on this task between groups. That is, on the auditory portion of the dual task, the MHI group performed significantly worse (lower  $d'$  and slower reaction time) than controls, while on the distractor portion, the MHI group responded less cautiously than controls despite equal  $d'$  values and comparable RTs.

*ERP components.* The target trials for the four oddball tasks were scored for each of the four ERP components. The two earlier components (N1 and P2) were statistically analyzed at Fz and Cz, where they were maximal, and the latter two (N2 and P3) at Cz and Pz (see Fig. 2 for an illustration of the pitch oddball task for each group). Site did not affect the results, so we present details for the Pz scoring of P3b. The four components were entered separately into  $2$  (Group)  $\times$   $4$  (Task) repeated-measures ANOVAs with Group as a between-subject factor and Task as a within-subject factor. There were no significant effects of Group, Task, or Group  $\times$  Task interactions on either the amplitudes or latencies of the N1, P2, and N2 components, except for a significant Group  $\times$  Task interaction for N1 amplitude. Here the Control group had similar N1 amplitudes for the four tasks (see Fig. 3), but the MHI group had greater negativity for the two Duration tasks [ $F(3, 57) = 2.87$ ,  $p < .05$  at Cz;  $F(3, 57) = 3.22$ ,  $p < .05$  at Fz].

As expected, P3b amplitude decreased from the simple to complex tasks [ $F(3, 60) = 14.95$ ,  $p < .001$ ] (see Fig. 4). In addition, the MHI group had reduced P3b amplitude on all four tasks compared to that of the Control group [11.5, 11.0, 7.7, and 5.5 vs 17.5, 15.1, 15.1 and 9.6;  $F(1, 20) = 13.7$ ,  $p < .001$ ] (see Table 1); one control subject had an unscorable P3b in the Novels paradigm and was omitted from this analysis, but including this person for the other conditions did not alter the results. Pairwise comparisons between the two groups on each task revealed that controls had a significantly higher P3b amplitude than did the MHI group on all four tasks [ $t(20) = 3.05$ ,  $p < .01$ ;  $t(20) = 2.29$ ,  $p < .05$ ;  $t(20) = 3.03$ ,  $p < .01$ ;  $t(20) = 2.52$ ,

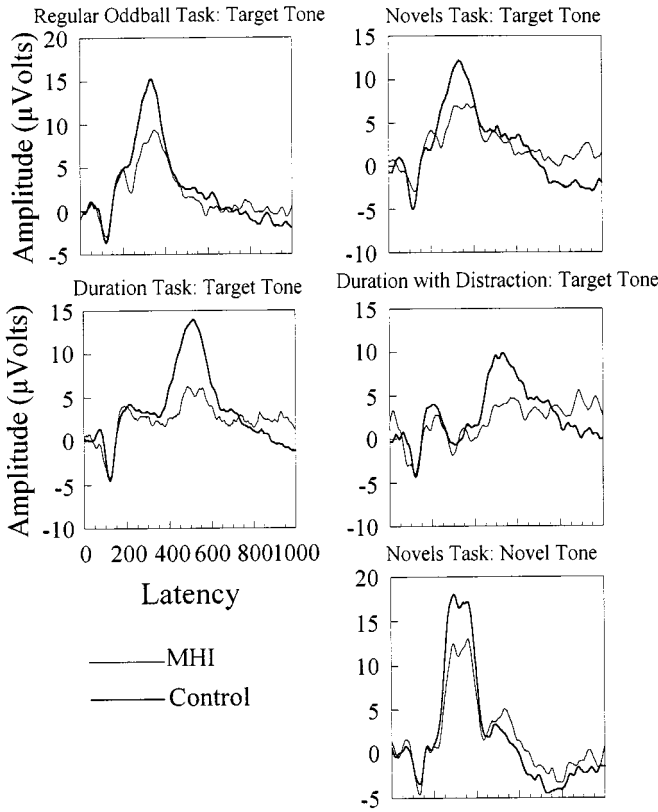


**FIG. 2.** Averaged ERPs for each group for the simple pitch oddball task. Note that the N2 and the P3b are maximal more posteriorly than are the N1 and P2 components. The MHI group average is indicated in thin lines and the Control group average is indicated in thick lines.

$p < .025$ ]. Contrary to prediction, the interaction was not significant [ $F(3, 60) = 1.10, ns$ ]. That is, the distract condition did not augment the P300 amplitude difference between the controls and participants with MHI and in fact reduced it somewhat.

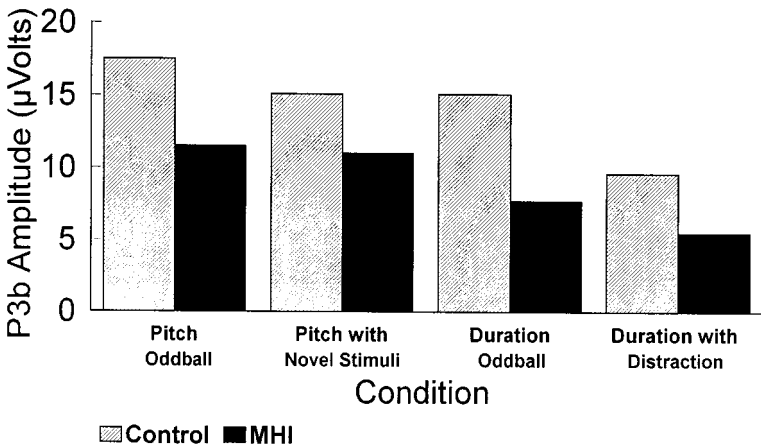
Novel P3 analyses produced the same results as those for P3b in the Novels condition. Novels P3 was maximal at Cz and was scored there (see Fig. 5). When novels P3 and P3b are entered into the same  $2$  (Group)  $\times$   $2$  (novels P3 vs P3b) ANOVA, we find a Group effect of Controls' amplitudes being larger [ $F(1, 20) = 8.08, p < .01$ ], and the novels P3 being larger than P3b [ $F(1, 20) = 18.76, p < .001$ ; see Fig. 3 and Table 1], but no interaction [ $F(1, 20) = .89$ ]. A simple comparison of novels P3 between the two groups was also significant [ $t(20) = 2.50, p < .025$ ].

Although scoring the P3b peak amplitude gives an unambiguous group effect, the result allows several potential interpretations (for further discussion, see Ford et al., 1994, and Unsal & Segalowitz, 1995). For example, it could be that while the Control group has greater P3b peak amplitudes, the MHI group may be able to allocate attention to an equal extent when measured over a longer period of time. That is, it may be that the MHI group may have similar waveform area but smaller peaks, indicating an overall flattening of the P3b waveform. Examination of the group averages can be misleading because latency variation across subjects can obscure differences in wave shape (Unsal & Segalowitz, 1995). One strategy to examine this possibility is to utilize the area under the curve during the P3b component rather than the single maximal point as the dependent measure. To do this, we calculated the degree of



**FIG. 3.** Average ERPs for each task for each group. The MHI group average is indicated in thin lines and the Control group average is indicated in thick lines. The target tones waveforms are taken at Pz; the novel tone waveforms are taken at Cz.

positive fluctuation from baseline during four time windows surrounding the P3b peak amplitude: durations of 50, 100, 150, and 200 ms. The more difficult tasks had a smaller area under the curve for all window sizes (all  $p < .001$ ), with the attenuation especially evident in the Duration with Distraction task (see Table 2). The MHI group had a significantly smaller area under the curve than the Control group, with the



**FIG. 4.** P300 (P3b) amplitudes for the four tasks for each group.



TABLE 1  
ERP Amplitudes (in Microvolts) and Standard Deviations by Task and Group

Task	Group	Component				
		N1	P2	N2	P3b	Novels P3
Oddball	Control	-7.70 (2.4)	5.07 (4.2)	3.80 (3.9)	17.53 (4.6)	
	MHI	-7.51 (2.8)	6.43 (4.3)	.70 (2.9)	10.41 (4.7)	
Novels	Control	-8.21 (2.7)	4.04 (4.4)	2.01 (4.9)	15.06 (4.1)	21.42 (7.2)
	MHI	-8.45 (3.9)	5.56 (1.3)	1.66 (2.0)	10.98 (4.2)	15.07 (3.8)
Duration	Control	-7.91 (1.4)	5.33 (2.9)	.82 (3.4)	15.13 (6.3)	
	MHI	-9.29 (2.7)	6.76 (3.1)	-.16 (4.8)	7.72 (4.9)	
Distract	Control	-7.27 (2.4)	5.98 (2.9)	-2.17 (2.3)	9.56 (3.6)	
	MHI	-10.02 (3.3)	5.40 (4.4)	-3.38 (3.9)	5.47 (4.0)	
<i>F</i> (Condition)		1.53	.86	7.17***	14.95***	18.76***
<i>F</i> (Group)		1.09	.58	2.41	13.74***	8.08**
<i>F</i> (Cond × Group)		2.87*	.76	.48	1.10	.89

Note. The N1, P2, N2, and P3b components are to the target stimuli in each of the conditions. The novels P3 component is scored only for the novel stimuli in the Novel oddball condition. The Condition factor is significant for the N2 and P3b components, and the Group factor is significant for the P3b component. The *F* statistics for the novels P3 column refer to a novels P3/P3b × Group analysis, with “Condition” referring to the novels P3 versus P3b factor.

- \* *p* < .05.
- \*\* *p* < .01.
- \*\*\* *p* < .001.

significance of the difference between groups diminishing slightly as the window enlarged. Thus, the difference between groups was evident at various window sizes but the possibility remains that further study would indicate a broadening of the peak.

Examining Fig. 3, we noticed that the MHI group, in addition to having smaller P300 amplitudes and P300 area measurements, also has more positive waveforms in the 800- to 1000-ms period. It is as if the rise in positivity associated with the P300 is not only diminished among the MHI subjects but also takes longer to return to baseline after the event. We examined this statistically by entering the P3b area measurements for the four tasks along with an area measurement in the 800- to 1000-ms range into a mixed 2 (Group) × 4 (Conditions) × 2 (Areas) ANOVA. Whether we use the 50-, 100-, 150-, or 200-ms window for the P300 area, the Group × Area

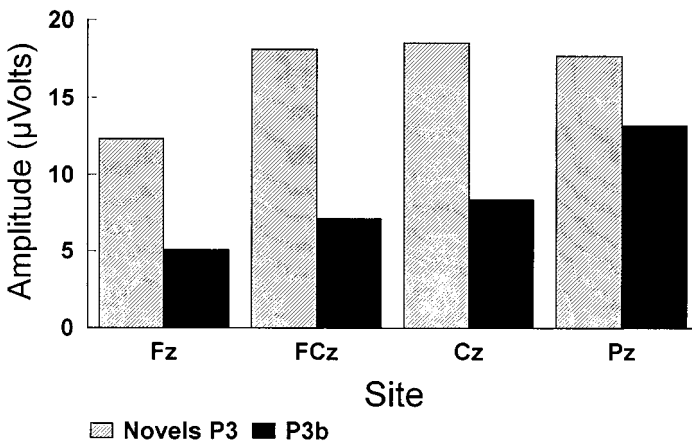


FIG. 5. Novels P3 (P300 to novel sounds) versus P3b at each site of the midline sites. FCz is midway between Fz and Cz. Novels P3 is maximal at Cz and P3b is maximal at Pz.

TABLE 2  
P3b Area under the Curve to Targets

Task	Group	Window size			
		50	100	150	200
Oddball	Control	4.95	4.25	3.66	3.22
	MHI	2.97	2.35	1.99	1.91
Novels	Control	4.37	3.80	3.32	2.93
	MHI	2.99	2.47	2.17	1.98
Duration	Control	4.34	3.93	3.53	3.16
	MHI	2.27	1.91	1.68	1.53
Distract	Control	2.68	2.32	1.98	1.70
	MHI	.42	-.15	-.34	-.38
$F(\text{Condition})$		12.61***	12.09***	11.50***	11.03***
$F(\text{Group})$		6.08*	5.79*	4.69*	3.57
$F(\text{Cond} \times \text{Group})$		.38	.63	.73	.77

*Note.* Window size refers to the number of milliseconds in the window around the P3b peak over which the areas are taken. Figures are the mean amplitude per sampling point in the indicated window.

\*  $p < .05$ .

\*\*  $p < .01$ .

\*\*\*  $p < .001$ .

crossover interaction apparent in Fig. 3 is always statistically significant [ $F(1, 19) = 9.37, 10.14, 8.39, \text{ and } 6.39$ , respectively,  $p < .01, < .005, < .01, \text{ and } < .025$ , for the four area windows].

Latencies for N1 did not differ for either task or group, but P2, N2, and novels P3 and P3b all showed Task effects and no Group or Task  $\times$  Group interactions (see Table 3). However, novel P3 latency was, as expected, significantly shorter than that for P3b, with no interaction with Group.

TABLE 3  
ERP Latency in Milliseconds by Task and Group

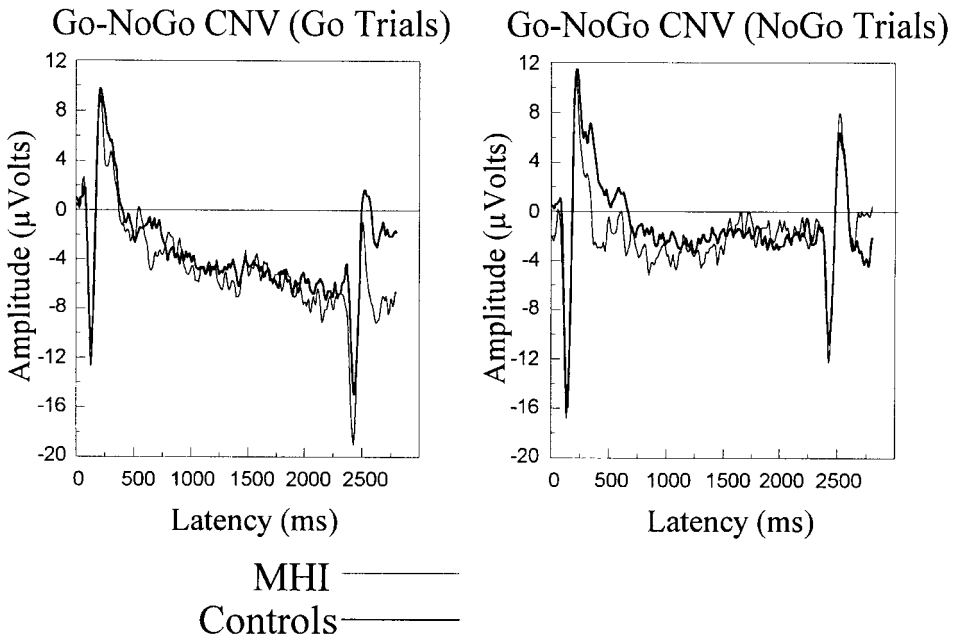
Task	Group	Component				
		N1	P2	N2	P3b	Novels P3
Oddball	Control	121.46	184.17	229.50	326.67	
	MHI	121.67	190.83	239.38	320.28	
Novels	Control	119.38	187.08	235.25	344.58	312.50
	MHI	118.89	187.78	249.38	329.72	308.25
Duration	Control	121.46	207.71	312.00	488.54	
	MHI	120.28	202.50	304.06	481.11	
Distract	Control	120.83	197.08	306.25	531.67	
	MHI	117.22	201.67	329.06	535.28	
$F(\text{Condition})$		1.46	5.63**	21.69***	95.74***	7.14*
$F(\text{Group})$		.16	.07	.94	.28	.25
$F(\text{Cond} \times \text{Group})$		.63	.49	.48	.12	.06

*Note.* In the novels P3 comparison, "Condition" refers to the novels P3/P3b comparison. N1, P2, N2, and P3b are taken to the target stimuli, while novels P3 figures are taken to the novel stimulus in the Novel Oddball paradigm.

\*  $p < .05$ .

\*\*  $p < .01$ .

\*\*\*  $p < .001$ .



**FIG. 6.** Average Contingent Negative Variation ERPs for the Go and the NoGo trials of the Go/NoGo CNV tasks for each group. The MHI group average is indicated in the thin line and the Control group average is indicated in the thick line.

*CNV tasks.* The Standard CNVs for the two groups did not differ either as a whole [ $F(1, 19) = 3.43, ns$ ] or when divided into early [O-wave;  $F(1, 18) = 1.1, ns$ ] or later [E-wave;  $F(1, 18) = .51, ns$ ] components. Similarly, there was no Group difference on either the Go or the NoGo trials of the Go/NoGo task [ $F(1, 18) = .09$  and  $.03$ , respectively; see Fig. 6].

## DISCUSSION

We have shown that a well-functioning university sample with a prior history of mild head injury demonstrates a drop in attentional performance when examined in a demanding context even many years after the injury. This is so despite normal functioning on basic standard neuropsychological measures and no long-term self-reported problems with memory and attention different from control subjects. We should note, however, that they did have some complaint about adequacy of sleep.

This performance deficit is confirmed by our electrophysiological data, which indicate that the MHI group exhibits smaller novel P3 and P3b amplitudes on four different auditory discrimination tasks compared to controls. The P3b component of the evoked potential is believed to reflect stimulus evaluation (Donchin & Coles, 1988) and the allocation of attention to the stimulus (Polich, 1986). This P300 amplitude difference between groups may offer a physiological reflection of decreased attentional capacity in individuals with MHI (Gronwall & Wrightson, 1975) or decreased attentional control (Ford et al., 1994; Stuss et al., 1989; Unsal & Segalowitz, 1995). We interpret the fact that the P300 latencies were not different between groups in the present study, as it was in previous work (Papanicolaou et al., 1984; Pratap-Chand et al., 1988) to suggest that the two groups demonstrate comparable information processing speed but that the MHI group possesses less overall information pro-

cessing capacity (indicated by the P300 amplitude differences). It is also important to note that there is no indication of a generalized difficulty with information processing in that the N1, P2, and N2 components, which reflect detection and automatic categorization of the stimuli, do not differ between groups (Picton & Hillyard, 1988; Ritter et al., 1982). In addition, there were no differences on the CNVs in a simple sustained attention paradigm.

### *Effects of Task Difficulty*

Tasks of greater difficulty are associated with decreased P300 amplitude (Donchin & Coles, 1988; Polich, 1987). The exact reason for this is unclear, but it may be that the averaged ERP reflects a more complex amalgam of cognitive processes in difficult tasks, with the complexity reflected in a series of late positivities and negativities that serve somewhat to cancel each other out. In any case, the controls' data serve to illustrate the relationship between P300s and the relative difficulty of the tasks (see Fig. 4).

It is useful to note that the MHI subjects performed at ceiling on the two easy oddball tasks, despite the dramatically reduced amplitudes. We conclude from this that the easy oddball tasks need little effort so that even the attentional allocation reflected in a dramatically reduced P300 is adequate to do the task at ceiling.

The Duration tasks, however, require constant focused attention, i.e., a sustained attention, since there can be no echoic replay of the stimulus as is possible with the pitch discriminations in the Regular and Novels Oddball tasks. The Duration tasks are much more difficult and here the lower attentional allocation becomes problematic for performance in that the MHI subjects performed significantly worse than controls. The fact that the MHI group performed more poorly than the controls on the difficult evoked potential tasks involving sustained and divided attention lends support to prior findings (Stuss et al., 1985, 1989; Hugenholtz et al., 1988).

There is some argument in the literature surrounding the length and extent of neurobehavioral recovery from a mild head injury (Levine, 1988). Though there is evidence that uncomplicated mild head injury rarely elicits overt chronic cognitive impairment (Levin et al., 1987; Dikman, McLean, & Temkin, 1986), the precise length and extent of recovery from mild head injury are still largely unknown (Bernstein, 1999; Bohnen & Jolles, 1992). Our results suggest that given a sophisticated enough paradigm, mild head injury with excellent recovery may still be associated with subtle deficits in attentional processes.

### *Focused versus Sustained Attention*

We would have expected that if MHI subjects had difficulty with the focused attention tasks presented in the oddball paradigm that they would also have difficulty with sustaining attention in the CNV tasks compared to controls. This did not arise, suggesting that when the task is explicitly structured so that attention need only be sustained for 2-s periods, the MHI subjects are equally capable of doing this. It may be that had we used a dual-task paradigm, thus taxing the subjects more, we may have found a group difference. There are practical problems with this, however, since introducing new information during the CNV task eliminates the negative variation (Tecce, Savignano-Bowman, & Meinbresse, 1976).

### *Cause or Effect?*

A major difficulty in post hoc studies of characteristics associated with MHI is the potential for premorbid traits appearing and being interpreted as resulting from

the MHI (Segalowitz & Brown, 1991; Segalowitz & Lawson, 1995). It could be, for instance, that whatever attentional deficits led to the attenuated P300 amplitudes, they were present before the head injury incident and perhaps even played a causal role in it. We think that this is unlikely for several reasons. First of all, the MHI and control subjects were highly comparable on a variety of measures. The subjects with MHI performed equally well as controls on a set of standard psychometric tasks. They were all university students who must have overcome any major intellectual handicap to reach postsecondary education, although university students with MHI have been reported elsewhere to experience cognitive deficits and lower grades (Beers, Goldstein, & Katz, 1994). In addition, the MHI group had no more subjective complaints of difficulty with memory or attention than the control group. Thus, the MHI subjects did not have a different self-concept surrounding issues of memory and attention as one might expect if they had grown up with seriously inferior attentional skills (although see Segalowitz & Lawson, 1995, for other social differences found in a much larger cohort). However, we acknowledge that the problem of disentangling cause and effect persists, and there always remains the possibility that our sample was self-selective with respect to sleep disturbance and arousal symptoms, a problem commonly but not universally associated with both mild and nonmild head injury (Segalowitz & Lawson, 1995). Whatever the resolution of this difficulty, it appears that well-functioning university students who experienced an MHI at some time in the past may perform equivalently to peers without an MHI on psychometric measures, but perform significantly more poorly on some demanding vigilance tasks and display distinctly reduced amplitudes of the P300 but not other components of the auditory ERP. While they may show poor performance on a more demanding neuropsychological battery, the lack of obvious symptoms or self-report of symptoms contrasts with their ERP P3b abnormality.

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