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# Effect of mild head injury on event-related potential correlates of Stroop task performance

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## Abstract

The effect of mild head injury on event-related potential (ERP) correlates of Stroop task performance was explored with the aim of further elucidating the basis of processing impairments after mild head injury. Computer- and card-based Stroop tasks were employed to assess attention function. A sequence of incongruent color words were presented followed by a sequence of congruent color words (printed in congruent colors). Control performance was equivalent on computer- and card-based versions of the incongruent task and faster on the congruent card task than the preceding congruent computer task. The mild head injury group were as fast as controls on the computer-based task but made more errors. However, they were relatively slower on both the congruent and incongruent parts of the card-based task and made more errors in the incongruent task. ERP correlates of computer-based Stroop task performance suggested a greater allocation of attention resources in the incongruent condition in both groups in the form of relatively greater negativity in the latency range 350 to 450 ms with a distribution consistent with the activation of the anterior cingulate gyrus. In addition the mild head injured group showed relatively greater enhancement than the control group in this latency range in both congruent and incongruent conditions. There was, however no evidence of reduced amplitude P1, N1, N2, or P3b deflections. Trails, digit symbol, digit span and auditory verbal learning tests (AVLT) were also administered. Mild head injured participants were impaired only on the AVLT. The finding of greater ERP negativity in the mild head injured group is consistent with greater allocation of attention resources to achieve equivalent performance in the computer-based Stroop task. (*JINS*, 2002, *8*, 828–837.)

**Keywords:** ERP, Traumatic brain injury, Memory, P3, CHI, Closed head injury

## INTRODUCTION

Mild head injury can produce a wide range of symptoms and can result in a significant number of individuals experiencing difficulties in coping with the normal demands of daily life (Bernstein, 1999; King, 1997). There are several possible underlying causes for these impairments which include predisposing psychological factors, the nature of the incident in which the injury occurred, as well as possible organic damage (Barrett et al., 1994; Evans, 1992; Fisher & Williams, 1994; Newcombe et al., 1994). Closed head injury can cause diffuse damage in the orbitofrontal, ventral frontal, and anterior temporal regions and, to a lesser degree, the dorsolateral frontal cortex. This is in part due to more frequent occurrence of impacts to the front of the head and partly due to greater forces being exerted on the front of the brain as a result of the internal shape of the brain case. In addition, white matter shearing and focal brain stem damage may occur. This pattern of damage can have a number of functional consequences: Orbitofrontal regions are important in implicit modification of behavioral and affective responses to objects and individuals (Rolls, 1998). Lateral ventral frontal cortex is implicated in temporal order memory (Petrides, 1998). Dorsolateral and polar frontal regions are implicated in planning and dual task performance (Robbins, 1998). In addition, anterior temporal lobe structures are important in the operation of long-term memory and are involved in coding the recency, familiarity and novelty of objects or individuals in the environment (Aggle-

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ton & Brown, 1999). Central to the normal function of these systems is the integrative role of attention mechanisms and it is hypothesized that closed head injury reduces the efficiency of these systems as a result of diffuse damage and consequent loss of long fiber connections (in the millimeter to centimeter range). The coping hypothesis (van Zomeren et al., 1984) suggests that head injured individuals can, to some extent, overcome this reduced efficiency of operation and achieve normal levels of performance by the (conscious and effortful) allocation of additional attention resources. Previous studies of mild head injured individuals using electrophysiological measures have produced some evidence of decreased allocation of attention resources at early or peripheral stages in processing in the form of reduced N1 and Nd amplitudes (Jory et al., 2000; Potter & Barrett, 1999; Solbakk et al., 1999). In some studies of mild and severe head injured individuals there is evidence of enhanced central allocation of attention resources in the form of enhanced N2 amplitudes (Jory et al., 2000; Potter et al., 2001b; Rugg et al., 1988). The aim of this study is to determine if there is electrophysiological evidence of increased allocation of central attention resources during the performance of the Stroop task, a task that has been shown to be sensitive to the consequences of mild (Bohnen et al., 1992a; 1993) and severe head injury (Vakil et al., 1995).

## Theories of the Basis of Stroop Task Effects

The Stroop phenomenon, originally reported by Stroop in 1935, has been the subject of considerable research in recent decades (Macleod, 1991; Macleod & Macdonald, 2000). In this task color names are printed in conflicting ink colors and the participant must name the ink color and inhibit the tendency to say the conflicting color word. When compared to naming color blobs or color words printed in black ink, performance is much slower and more error prone. An influential account of the Stroop effect was based on the distinction between controlled and automatic processing (Posner & Snyder, 1975). In this framework words are processed automatically but the unfamiliar task of color naming was dependent on the use of a slow, limited capacity central attention resource. The highly automated word reading process would thus always tend to interfere with the consciously controlled color naming task. Macleod and Dunbar (1988) provided empirical evidence to support an alternative model that is based on the assumption of a continuum of automaticity. In this framework word reading and color naming pathways compete for the same response resources and the interference exists because of the great difference in skill levels between color naming and word naming. This theoretical approach has been formalized in connectionist models of Stroop performance in which interference occurs because of crosstalk between shared subsystems used in reading and color identification (Cohen et al., 1990; Zhang & Kornblum, 1998).

An important part of Stroop task performance appears to be the establishment of temporary cognitive structures or "task sets." The existence of these task sets can be demonstrated by requiring subjects to switch between two tasks every few trials (e.g., Wylie & Allport, 2000). A large increase in reaction time and error rates is seen on the trials immediately after the task switch. A potentially useful theoretical framework for accounting for these switching costs is the "global workspace" framework that assumes the presence of a widely distributed network of connections that allow for the rapid development of novel patterns of integration between long-term memory, perceptual, evaluative, and attention systems (Dehaene et al., 1998). This approach is of particular interest from the perspective of understanding the possible effects of closed head injury. Such models depend on long distance connections between systems as well as diffuse modulatory input that is transmitted from distant locations. Diffuse damage to the brain may compromise these distant connections to the greatest extent. While there is some possibility of local adaptation to the consequences of damage it seems far less likely that these long distance connections will recover after damage as they were specified during development. It is therefore assumed that brain injured individuals are less able to establish efficient solutions to deal with novel or changing processing demands and, as a result, they have to maintain effortful processing strategies for longer.

## Functional Imaging Studies of Stroop Task Performance

A consistent finding in functional imaging studies of the Stroop task is the activation of anterior regions of the cingulate gyrus. This is sometimes associated with reduced activation in left temporal lobe regions, consistent with inhibition of color word naming, but enhanced activation in prestriate color areas, consistent with deriving color names from the stimulus color (George et al., 1994; Larrue et al., 1994; McKeown et al., 1998; Pardo et al., 1990; Smith & Jonides, 1999; Taylor et al., 1997). Connections from frontal and posterior regions of the cortex interdigitate in the anterior cingulate gyrus and this region is seen as a key structure in attention control mechanisms involved in selection of targets from competing inputs (Peterson et al., 1999; Posner & Dehaene, 1994). If head injured individuals have to utilize conscious and effortful strategies more than controls then one would expect to see greater activation of anterior cingulate regions in the head injured.

## ERP Studies of Mild Head Injury

Current evidence supports the view that individuals who have experienced a closed head injury are often able to perform as well as control groups but that they have to expend additional effort, or in other words allocate additional central attention resources, to achieve normal levels of performance. ERP findings, to date, have produced mixed results (see Potter & Barrett, 1999, for review). For example Rugg et al. (1988), using an auditory oddball paradigm and Jory et al. (2000) using an auditory selective attention paradigm provide evidence of enhanced N2b deflections (after severe and mild head injury respectively) that suggests increased allocation of attention resources. However Rugg et al. (1993) did not observe an enhanced N2b in a subsequent study of severe head injured individuals in a three-stimulus auditory oddball paradigm. They did, however, observe sustained differences in this group in the form of relatively more negative ERP deflections in all conditions and these were interpreted as evidence of greater allocation of attention resources. The presence or absence of N2b differences appears to be influenced by working memory load. An important distinction between the Rugg et al. (1988) and Rugg et al. (1993) studies was that the first study involved counting targets and the second involved a button press to each target. In an auditory selective attention study comparing button pressing and counting it was evident that N2b differences between controls and mild head injured are most prominent in the counting task (Potter et al., 2001b).

### ERP Studies of Stroop Task

A limited number of ERP studies have explored the electrophysiological correlates of Stroop task performance although a number of other studies have explored variants of the Stroop task (e.g., Czigler & Csibra, 1991; Duncan-Johnson & Kopell, 1981; Kaiser et al., 1997). The two studies of most relevance to the present study are that of Grapperon et al. (1998) and that of West and Alain (1999). In both cases the original interference task was used. They both identified an enhanced level of negativity in the waveforms associated with the incongruent task at the midline central location in the 400 to 500 ms latency range. This would be consistent with increased allocation of attention resources. In addition West and Alain observed a reduced level of negativity associated with poorer performance in the elderly. However, a difficulty with this latter finding is that there were large behavioral response latency differences between the control and elderly but the same ERP latency range was used for the voltage measurements.

### Rationale for Present Study

In this study ERPs were recorded during the performance of a computer-based Stroop task to determine if mild head injury would result in increased allocation of attention resources. It was hypothesized, based on previous findings (Grapperon et al., 1998; Jory et al., 2000; Rugg et al., 1988; West & Alain, 1999) that this would take the form of relatively more negative ERP deflections in the mild head injury group at the central (Cz) electrode location. A simplified Stroop task was used which consisted of a block of incongruent ink color/color name combinations followed by a block of congruent ink color/color name combinations. These were presented one word at a time in central fixation on a computer screen. The incongruent task was presented before the congruent task to allow the visualization of the brain activity evoked by incongruence without the presence of possible overlapping priming effects from prior color- or word-naming tasks.

Shortly after the ERP recordings a brief series of neuropsychological tests was carried out to independently demonstrate the existence of memory and attention impairments in this population. This included a card-based version of the Stroop task. The incongruent condition was performed before the congruent condition to allow comparison with the computer-based Stroop task. It was hypothesized that the higher attention demands of the card-based Stroop task would result in a greater performance decrement in the mild head injured group.

A further goal of this research was to determine the sensitivity of the P3 deflection to the effects of mild head injury. Previous research on the effects of closed head injury on parietal P3 amplitude has produced mixed results. Some studies report no effects of mild head injury on P3 amplitude (Jory et al., 2000; Potter et al., 2001a) while one study reports changes in latency and amplitude (Pratap-Chand et al., 1988). It was therefore of interest to find out whether the parietal P3 deflection was affected in the mild head injured group.

## METHODS

### Research Participants

Controls included 10 females and 14 males; mean age 31.4 years (range 18–46). The mild head injured group comprised 8 females and 16 males; mean age 32 years (range 16–54). All participants were right-handed. Mild head injury was defined as trauma to the head that led to unconsciousness or confusion for a period of less than 60 min, including injury that led to confusion with no loss of consciousness, a Glasgow Coma Score of between 13 and 15 and absence of focal neurological deficits or neurosurgical pathology (Evans, 1992). The mild head injured group had all been knocked unconscious at some point in the last 3 years (*MDN* time since injury 6 months). All individuals who sustained a mild to moderate head injury were invited to attend a head injury clinic 6 weeks after their accident if they felt they had symptoms that still concerned them. Participants were recruited sequentially from this population on a voluntary basis. Individual details of severity of injury are given in Table 1. All participants were requested not to consume alcohol or other drugs on the day before testing, to ensure that they were well rested and that they had eaten prior to the testing session. Time of day of testing was matched across the groups.

### Initial Screening Tests

Participants filled out the Eysenck Personality Inventory (EPI), Becks Depression Inventory (BDI) and the State Trait Anxiety Inventory (STAI) prior to ERP testing (to

**Table 1.** Mild head injured participant details

| ID | Age | Sex | Time since injury: Months | Nature of injury | Estimated time unconscious | PTA estimate | Persistent memory problems | Persistent attention problems |
|---|---|---|---|---|---|---|---|---|
| 16 | 38 | F | 24 | Sledgehammer (accident) | None | None | No | No |
| 17 | 47 | M | 6 | Bike RTA | 30 s | None | No | No |
| 18 | 18 | M | 12 | Car RTA | 5 min | 15 min | No | No |
| 20 | 20 | M | 12 | Baseball bat | 3 min | 30 min | Yes | Yes |
| 21 | 44 | M | 12 | Bike RTA | 5 min | None | Yes | Yes |
| 22 | 40 | F | 9 | Pedestrian RTA | 60 min | 1 min | Yes | Yes |
| 23 | 50 | F | 36 | Banged head | None | None | No | No |
| 24 | 16 | F | 3 | Horse riding accident | None | None | No | No |
| 25 | 36 | M | 36 | Fell, banged back of head | 1 min | None | Yes | No |
| 27 | 27 | M | 3 | Accident at work, left side of head | 15 min | 1 min | No | No |
| 29 | 41 | F | 3 | Fainted, struck head | 2 min | 20 s | No | No |
| 33 | 22 | M | 3 | Assault—front of head | 10 min | None | Yes | Yes |
| 35 | 26 | F | 6 | Hit head on wall | None | None | Yes | Yes |
| 40 | 42 | M | 18 | Hit head diving into pool | None | None | No | No |
| 41 | 28 | M | 3 | Pedestrian RTA | 60 min | 1 min | Yes | No |
| 43 | 19 | F | 3 | Horse riding | None | 20 s | No | No |
| 44 | 43 | M | 6 | Motorbike RTA | 20 min | 30 s | No | No |
| 45 | 54 | M | 3 | Fainted and banged back of head | 15 min | 1 min | Yes | No |
| 47 | 20 | M | 6 | Fainted, banged head | 3 min | 30 s | No | No |
| 50 | 34 | M | 3 | Hit head on pavement | 4 min | 20 s | No | No |
| 52 | 17 | F | 4 | Banged head | 1 min | 20 s | No | No |
| 62 | 26 | M | 12 | Banged head | None | None | No | No |
| 65 | 33 | M | 6 | Car RTA | None | 30 s | No | Yes |
| 66 | 28 | M | 6 | Motorbike RTA | 60 min | 5 s | No | No |

control for other possible factors that might influence cognitive performance).

## Computer-Based Stroop Task

Participants sat in front of a computer monitor at a distance of 800 mm. The words *green*, *red*, *yellow*, and *blue* were displayed in lower case in either congruent or incongruent ink colors. Word size was approximately 22 mm × 5 mm. The words appeared at a rate of one every 2000 ms and were displayed for 2000 ms. Participants were instructed to say the color used to display the word as quickly as possible in the incongruent and congruent conditions. There were 84 items in the incongruent and congruent blocks. Each color word appeared in three incongruent display colors seven times. The order of presentation of color words was randomly determined with the constraint that no display color/word name combination should occur on more than two consecutive occasions. Voice output was sampled at 1000 Hz and voice reaction times for each trial were determined from these data. Error trials were recorded manually.

## Neuropsychological Tests

The following neuropsychological tests were administered 15 min after the ERP recordings. Participants first completed a card-based Stroop task. They were instructed to read a 10 × 10 array of color words, printed in landscape format on a sheet of A4 card, as quickly as possible. They first read a card in which the words *red*, *green*, *yellow*, and *blue* were printed in incongruent colors and then they read a card on which the ink colors were congruent with each word. Time taken to read each card was measured and errors recorded. The Auditory Verbal Learning Task (AVLT) was used to assess verbal memory function (Lezak, 1995; Rey, 1964). A Digit Span task was used to assess verbal short-term memory (Kaplan et al., 1991) and the Trails A and B (Spreen & Strauss, 1991) and Digit Symbol (Wechsler, 1981) were used to assess ability to rapidly shift attention. The National Adult Reading Test (Nelson, 1982) was used to estimate IQ.

## ERP Recording

ERPs were recorded, with respect to an impedance balanced linked mastoid reference from three midline scalp sites; Fz, Cz, Pz, and from lateral electrodes over the left and right frontal (midway between F3/F4 and F7/F8), temporal (midway between T3/T4 and C3/C4) and inferior parietal (midway between T5/T6 and P3/P4) regions. Vertical and horizontal electro-occulograms (EOG) were recorded from bipolar electrode pairs placed above and below the right eye (vertical) and on the outer canthus of each eye (horizontal). EEG and EOG were recorded with bandwidths of 0.03 to 30 Hz (3 dB points). EEG and EOG were digitized and stored for off-line analysis. Sampling rate was 200 Hz. Trials on which errors or artifacts occurred were excluded from the averages. Trials containing signal drift greater than 50 $\mu$V were excluded from the averages. An eye-blink artifact correction procedure, similar to that advocated by O'Toole and Iacano (1987) and Semlitsch et al. (1986) was used in all subjects.

## Electromyograph (EMG) Recording

EMG was recorded from linked zygomatic arch electrodes using the same mastoid reference as the ERP measures and the same sampling parameters. This gave only a limited picture of the EMG signal but provided an accurate measure of the effect that the EMG was likely to have on the scalp recordings.

## Analysis Design

Univariate analysis of variance was used for both behavioral and ERP measures. Both peak amplitude measures and mean area amplitude measures were made relative to a 100 ms prestimulus baseline.

# RESULTS

## Neuropsychological Tests

Results of the neuropsychological tests are summarized in Table 2. Mild head injured participants were impaired on the AVLT in both immediate and delayed recall. There was, however, no evidence of impairment on either the Trails, Digit Symbol or Digit Span tasks. IQ estimates did not differ between groups. There was no evidence of differences on the EPI, BDI or STAI measures other than a significantly greater score on the lie scale of the EPI and a nonsignificant trend for the state anxiety measure to be slightly higher in the head injured group.

## Behavioral Performance on Computer and Card-Based Stroop Task

Reaction times for the computer-based Stroop task were measured offline from records of the vocal responses on each trial. Reaction times for each item in the card-based Stroop task were estimated from the overall time taken to complete 100 items to allow comparison with the computer-based Stroop task. The results, presented in the order in which the participants carried out the tasks are illustrated in Figure 1. Reaction times on the computer and card-based tasks were compared in a three-way repeated measures

**Table 2.** Performance on neuropsychological tests

| Neuropsychological test | Control *M* (*SD*) | Mild head injured *M* (*SD*) | *T* test significance |
|---|---|---|---|
| BDI | 4.3 (5.9) | 7.7 (8.1) | n.s |
| STAI–State | 33.2 (9.0) | 38.3 (12.4) | n.s. |
| STAI–Trait | 38.0 (9.4) | 39.8 (11.1) | n.s. |
| EPI–Neuroticism | 9.9 (4.5) | 11.0 (4.7) | n.s. |
| EPI–Extroversion | 11.6 (4.7) | 10.9 (4.5) | n.s. |
| EPI–Lie | 1.6 (1.3) | 2.8 (2.0) | $p = 0.018$ |
| AVLT | | | |
| A1 to A5 | 58.8 (7.9) | 50.8 (10.3) | $p = .004$ |
| A6 | 12.3 (2.4) | 10.3 (2.8) | $p = .014$ |
| A7 | 13.7 (1.5) | 12.2 (2.3) | $p = .012$ |
| A30 | 12.5 (2.3) | 10.5 (2.7) | $p = .009$ |
| B30 | 4.8 (3.3) | 2.8 (2.3) | $p = .019$ |
| Trails B–A (s) | 28.8 (14.6) | 27.0 (16.3) | n.s. |
| Digit Symbol (s) | 98.2 (17.7) | 98.4 (17.4) | n.s. |
| Digit Span–forward | 9.9 (2.1) | 9.4 (1.9) | n.s. |
| Digit Span–backward | 7.3 (2.2) | 7.6 (2.3) | n.s. |
| PC Stroop–incong (RT) | 890 (190) | 890 (173) | n.s. |
| PC Stroop–cong (RT) | 507 (120) | 560 (120) | n.s. ($p = .10$) |
| PC Stroop–incong (% Err) | 0.5 (0.8) | 1.3 (2.7) | n.s. ($p = .15$) |
| Card Stroop–incong (RT) | 886 (200) | 1025 (293) | $p = .061$ |
| Card Stroop–cong (RT) | 407 (71) | 535 (152) | $p < .001$ |
| Card Stroop–incong (% Err) | 1.0 (1.2) | 2.3 (2.1) | $p = .010$ |
| NART errors | 12 (6.6) | 15.8 (9.2) | n.s. |
| (IQ Estimate) | 118 | 114 | |

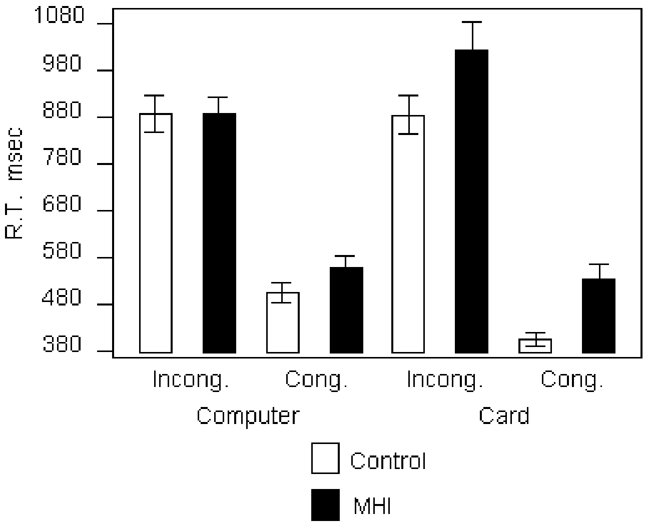

**Fig. 1.** Mean reaction times in each of the four Stroop task conditions. Incong. = Incongruent, Cong. = congruent.

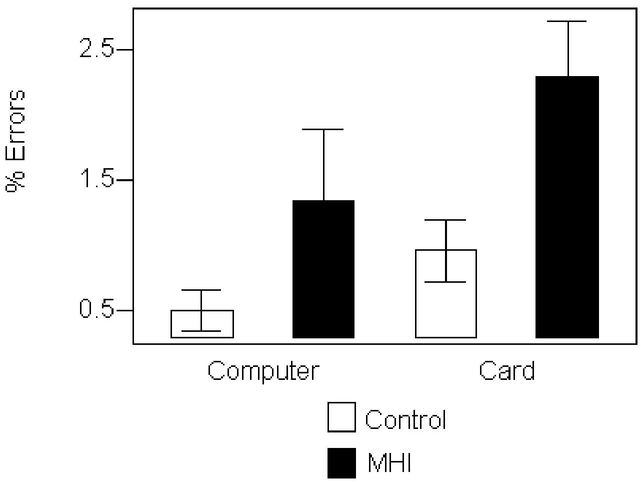

**Fig. 2.** Percentage errors made in the incongruent block of the computer and card tasks.

ANOVA with factors of group, task type, and task difficulty. Reaction times were slower in the incongruent task than the congruent task [$F(1,46) = 332.4$, $p < .001$]. Reaction times were also, on average, slower in the mild head injured group [$F(1,46) = 4.3$, $p = .044$]. Mild head injury affected performance more in the card-based task than in the computer-based task, resulting in a significant Group × Task Type interaction [$F(1,46) = 9.1$, $p = .004$]. Differences between performance on the congruent and incongruent tasks were larger in the card-based task than the computer-based task; that is, a significant interaction of Task Type × Task Difficulty [$F(1,46) = 20.9$, $p < .001$]. Although there is evidence in the pattern of results of a three-way interaction between Group × Task Type × Task Difficulty, this was not significant [$F(1,46) = 1.3$, $p = .258$]. However, exploratory *t* tests of congruent performance indicated that control performance was faster in the card than computer task ($t = 4.67$, $p < .001$) and also faster than mild head injured in the card task ($t = 3.74$, $p < .001$).

Error rates for incongruent task performance are illustrated in Figure 2. Congruent errors are not plotted as only 1 subject made 1 error. Error rates on the incongruent computer and card-based tasks were compared in a two-way repeated measures ANOVA with factors of group and task type. More errors were made in the card-based task than the computer-based task [$F(1,46) = 4.2$, $p = .046$] and the mild head injured group made more errors than the controls [$F(1,46) = 7.2$, $p = .010$].

These behavioral data were reanalyzed by dividing the mild head injury group into symptomatic and asymptomatic on the basis of reported persistent symptoms (Table 1). There were no significant differences between the symptomatic and asymptomatic mild head injured groups and both of these groups were significantly impaired when compared to the control group.

## Event-Related Potential Correlates of the Computer-Based Stroop Task

The grand averaged ERPs for controls and mild head injured are illustrated in Figure 3. The waveforms illustrate the pattern of electrical activity observed in the first 980 ms after stimulus onset. Prominent P1, N2, P2, and N2 deflections can be observed at posterior electrodes. The large positive deflection at Pz that reaches maximum amplitude at 400 ms is the visual P3.

Repeated measures ANOVA of mean amplitudes in the latency range 350 to 450 ms at Pz with factors of group and task difficulty revealed that P3 was of lower amplitude in the incongruent condition than the congruent condition [$F(1,46) = 35.7$, $p < .001$] but there was no evidence of reduced amplitude in the mild head injured group [$F(1,46) = 0.8$, $p = .386$]. ANOVA of mean amplitude measures in the same latency range at Cz revealed that the ERP deflections were relatively more negative in the incongruent condition than in the congruent condition in both groups [$F(1,46) = 36.45$, $p < .001$]. In addition mild head injured ERP deflections were relatively more negative than the control group in both incongruent and congruent conditions [$F(1,46) = 3.65$, $p = .063$].

A prominent feature of these waveforms is the large frontally distributed speech artifact. The linked zygomatic arch electrode recording, labelled EMG, illustrates the pattern of this artifact. ANOVA of mean amplitudes in the latency range 350 to 450 ms provide little evidence that the more negative going deflections at Cz can be attributed to the presence of this artifact [$F(1,46) = 0.10$, $p = .758$].

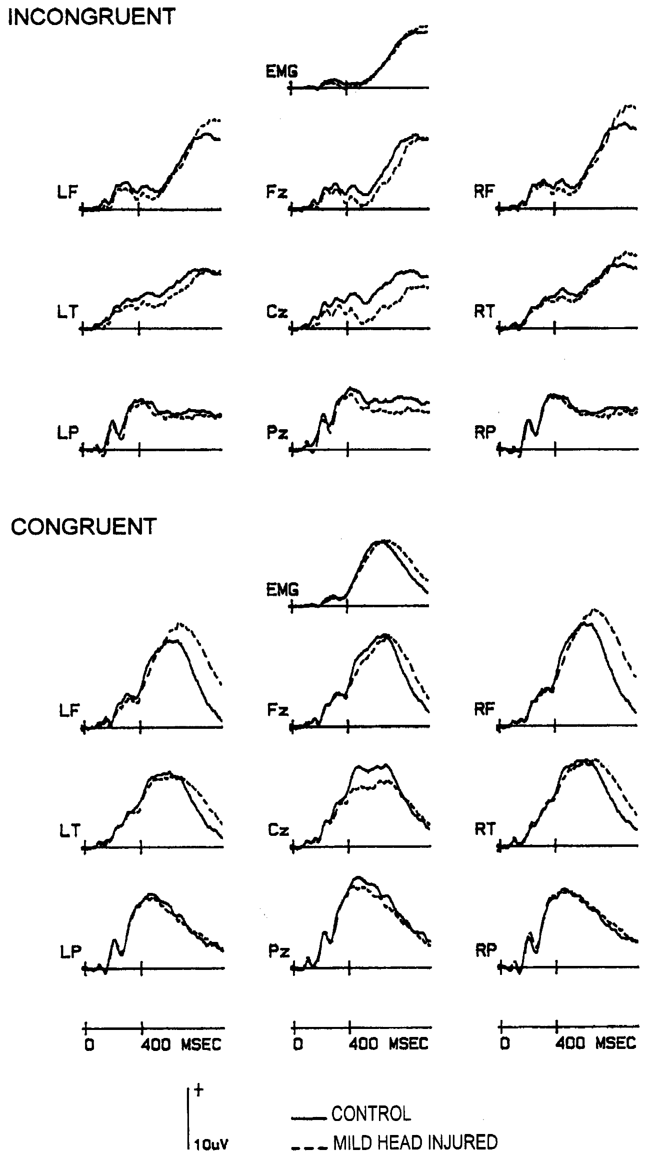

**Fig. 3.** Grand average ERPs associated with naming congruent and incongruent color words. Incongruent ERPs are relatively more negative than congruent ERPs. This effect is most pronounced at Cz. Mild head injured ERPs are relatively more negative than control subjects at both posterior and central sites in the incongruent task and at the central site in the congruent task. L = left, R = right, F = front, T = temporal, P = parietal.

It can be seen in Figure 3 that there is some evidence in the incongruent condition of enhanced P1, N1, and N2 deflections in the head injured group. These effects were, however, not significant.

## DISCUSSION

The neuropsychological tests carried out in the present study provide evidence of impairment of attention and memory function in this group of mild head injured individuals. The ERP data at the central electrode location provides evidence of enhanced allocation of attention resources in the mild head injured group in the form of relatively larger negative ERP deflections with no evidence of reduction of P1, N1, P2, N2, or parietal P3 deflections.

### Stroop Behavioral Findings

In the computer-based Stroop task the mild head injured group responded as quickly as the controls but made more errors. This observation is consistent with the view that reduced capacity to inhibit prepotent responses is a component of cognitive impairment after mild head injury. The control group performed the card-based incongruent task as quickly as the computer-based task and took significantly less time to complete the card-based congruent task. In contrast the mild head injured group took significantly longer in both congruent and incongruent conditions of the card-based task and produced more errors in the incongruent condition. The differences in performance on the card-based Stroop task are consistent with previous findings in groups of mild head injured who are complaining of persistent symptoms 3 to 6 months after injury (Bohnen et al., 1992a, 1992b). The significant impairment observed in the mild head injured group in the card-based task suggests problems with eye movement control or the ability to ignore flanking distractor stimuli. There is certainly evidence to suggest that severe closed head injury can lead to abnormal patterns of orienting responses, consistent with increased distractibility (Kaipio et al., 1999, 2000; Rugg et al., 1989). There is also evidence that similar but milder abnormalities can be detected in some cases of mild head injury (Potter & Barrett, 1999; Potter et al., 2001a). In addition, a large overlap exists between the structures involved in attention and eye movements in frontal, parietal and cerebellar regions (Corbetta et al., 1998; Nobre et al., 2000). The present contrasting findings in the computer and card-based tasks suggest the possibility of a significant deficit in the operation of these systems.

### ERP Correlates of Stroop Task Performance

The ERPs in both groups were relatively more negative in the 350 to 450 ms latency range in the incongruent task in comparison to the congruent task. This finding is consistent with previous studies of Grapperon (1998) and West (1999) suggesting greater allocation of attention resources in the performance of the incongruent task. This difference in ERP measures is consistent with reported activation of the anterior cingulate gyrus in the incongruent condition of the Stroop task (George et al., 1994; Larrue et al., 1994; McKeown et al., 1998; Pardo et al., 1990; Smith & Jonides, 1999; Taylor et al., 1997). The centrally distributed relatively greater ERP negativity observed in the head injured group in both congruent and incongruent conditions suggests they had to engage in more effortful processing to achieve the same speed of performance. It is unlikely that the waveforms were more negative going as a result of greater variability in either latency or amplitude in the mild head injured group as there was little evidence of reduction in P3 amplitude in the same latency range. There was also no evidence of reduction in amplitude of earlier deflections in the ERP. It remains to be determined whether the relative increase in negativity observed in the present task is analogous to previously reported enhancements of N2 in closed head injury (Jory et al., 2000; Potter et al., 2001b; Rugg et al., 1988).

### Are the ERP Differences an EMG Artifact?

Several pieces of evidence suggest that this is unlikely to be the case. The timing and distribution of the EMG artifact does not correspond to the observed ERP differences. The pattern of ERP differences is consistent with previous studies of Stroop task performance (Grapperon et al., 1998; West & Alain, 1999). In addition, area measures in the latency range of the central electrode differences did not approach significance at the EMG electrode.

### Other Measures of Memory and Attention Performance

Clear evidence of memory impairment and abnormal allocation of attention was provided by the AVLT and Stroop tasks respectively. No evidence was found of impairment on the Trails, Digit Symbol or Digit Span tasks. Previous studies have reported impairments on both Digit Symbol and Trails as well as paired associate memory tasks in mild head injured, for example, Potter and Barrett (1999) and in cases of more severe head injury, for example, Rugg et al. (1993). The main difference between the present study and the previous mild head injury study is that the mean age of the sample was 10 years younger and the age range was much narrower. The variability in performance on these two tasks was correspondingly smaller in the study using the younger population. One possible reason for poorer performance on the AVLT and Stroop tasks could be that the head injured were depressed or anxious. There was a small amount of evidence of greater anxiety in the head injured and it is possible that the differences in performance and brain activity were related to this. However, these measures were not significantly correlated.

### Conclusions

The findings of this study support the view that mild head injury can, in some cases, lead to measurable impairments of episodic memory and abnormal attention function. The mild head injured group showed evidence of impaired attention function in the incongruent card-based Stroop task in terms of their ability to scan a sequence of stimuli and inhibit prepotent responses. ERP data suggested enhanced allocation of attention resources in the performance of the simpler computer-based Stroop task. These results are consistent with previous findings in that they suggest that people with head injuries may have to allocate additional resources to achieve normal levels of performance. One would predict that this can result in a reduced capacity to deal with high information processing loads as well as more rapid onset of fatigue. It is, of course, important to maintain an appropriate perspective on these findings. This is the lower end of the spectrum of head injury and the majority of these individuals *may* adapt to these changes in capacity, given time. This does not however mean that these minor impairments have no real short- or long-term consequences for these individuals.

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