

The Persistent Effects of Concussion on Neuroelectric Indices of Attention

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Abstract

Mild traumatic brain injuries (mTBIs) that result from participation in sports are a major public health issue affecting 1.6–3.8 million individuals annually. The injury has been postulated as transient and void of long-term consequences when rapidly diagnosed and properly managed. Emerging evidence, however, has suggested an increased risk for late life cognitive dysfunction in those with previous injuries. The purpose of this investigation was to evaluate young adults with and without a history of concussion using a standard clinical assessment and highly sensitive electrophysiological measures for persistent changes in cognitive functioning. Ninety participants (19.7 ± 1.3 years; 44 without mTBI and 46 with previous mTBI) were evaluated using the ImPACT and event-related brain potentials (ERPs) that were recorded during a three-stimulus oddball task. Those with a history of concussion reported an average of 3.4 years post-injury. No significant differences were found between groups on the ImPACT. Significant decrements in the N2 and P3b amplitudes of the stimulus-locked ERP were noted for those with a history relative to those without a history of concussion. Although the previously concussed participants performed equal to those without injury on the clinical cognitive assessment, these findings support the notion that sport mTBI can no longer be thought of as a transient injury resulting in short-lived neurological impairment. It is not clear if these persistent deficits will manifest into clinical pathologies later in life.

Key words: electroencephalogram (EEG); event-related potentials (ERP); mild traumatic brain injury; N2; novelty oddball; P3

Introduction

MILD TRAUMATIC BRAIN INJURY (mTBI), or concussion, has been defined as “a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces” (Aubry et al., 2002). In the acute stage of injury, decrements in cognitive functioning, postural control, and increases in concussion-related symptoms are clearly evident (Broglio and Puetz, 2008). In most individuals, these impairments resolve spontaneously within 7–10 days of injury (Aubry et al., 2002; Delaney et al., 2002; McCrea et al., 2003). The athletic environment offers the unique advantage for evaluating mTBI because it affords the opportunity to collect pre-injury evaluation (i.e., a baseline) information on a group with a known injury rate. In most instances, several measures of post-concussion injury rapidly return to normal operative levels in the post-morbid state, with concussed individuals returning to the pre-morbid level of functioning within a few days of the injury. For instance, 95% of concussed collegiate-level soccer and football athletes no longer report concussion-related symptoms within 7 days of injury (Dela-

ney et al., 2002). Similarly, McCrea et al. (2003) reported a return to baseline levels of postural control and cognitive functioning in a comparable cohort within 5 and 7 days of concussion diagnosis, respectively.

Despite the rapid resolution from concussion on functional performance measures, the potential for persistent effects has yet to be fully elucidated. In young adults reporting zero, one, two, or two or more previous injuries, a pencil and paper evaluation of cognitive functioning indicated no difference between those with and without an injury history (Guskiewicz et al., 2002). Furthermore, computer-based assessments of cognitive functioning have demonstrated no measurable differences in previously concussed and non-concussed high school and university athletes reporting one or two previous concussions (Iverson et al., 2006b). Similarly, Australian rules football players with up to four injuries demonstrated no measurable deficits in cognition (Collie et al., 2006). These findings may be limited by the testing instruments, which might lack the necessary sensitivity to detect subtle cognitive decrements in the post-acute stage of injury (Broglio et al., 2006). Further, concussion-related cognitive dysfunction may

occur on a covert level relative to overt behavioral measures (i.e., RT, response accuracy), or may not be apparent until later in life.

A recent investigation evaluated the persistent effects of concussion in a group of retired athletes reporting multiple injuries across their careers. In a sample of former professional football athletes, those reporting at least three concussions during their athletic career displayed a fivefold increase in diagnosed mild cognitive impairment and a threefold increase in self-reported memory problems compared to a subset of non-concussed former athletes (Guskiewicz et al., 2005). These findings suggest a disconnect between the apparent transient nature of concussive injuries in young adults and the presence of cognitive dysfunction in later life.

Accordingly, implementing sensitive instrumentation with the ability to detect subtle, covert changes in cognitive functioning may clarify this apparent discrepancy. Specifically, electroencephalograms (EEG) have been extensively used to examine electrical activity associated with brain function; however, their use to investigate the impact of concussion on cognition has been limited. One particular aspect of EEG, known as event-related brain potentials (ERPs), has been useful in providing insight into the underlying neural processes involved in cognitive function beyond that of overt behavioral measures. ERPs reflect patterns of voltage change in ongoing neuroelectric activity that occurs in response to, or in preparation for, a stimulus or response.

The P3 component of a stimulus-locked ERP has been especially well studied with regard to alterations in cognitive function related to development (Ridderinkhof and van der Stelt, 2000), aging (Polich, 1996), health behaviors (Hillman et al., 2005), and clinical pathology (Knight, 1984). The P3 is a large positive-going component that appears approximately 300–800 ms following stimulus onset and reflects attentional processes, which are indexed by the P3a and P3b subcomponents, each of which has a unique scalp distribution. These components represent related but distinct neuroelectric processes that are distinguished based upon the context in which they occur. That is, different stimulus environments elicit activation of the P3a and P3b leading to modulation of the component amplitude. The P3a is typically elicited by an infrequent and uninstructed novel stimulus. This component is characterized by a fronto-central topographic maximum and relatively short latency. Alternatively, an instructed yet infrequently presented target stimulus elicits the P3b component that is reflected by topographic maximum amplitude over the parietal cortex (Donchin et al., 1986; Johnson, 1993).

Accordingly, the cognitive functions required to process the various stimuli provide a basis for inferring the meaning of the appearance and modulation of the various subcomponents. Specifically, the P3a is thought to reflect the selection of stimulus information associated with attentional orienting to a change in the environment (Knight, 1984; Kok, 2001), such that this component reflects the disengagement of attentional focus from one aspect of the stimulus environment and the reengagement toward another aspect of the environment (Squires et al., 1975). As such, P3a amplitude is thought to represent attentional orienting with larger amplitude indicative of greater focal attention (Polich, 2007). Alternatively, the P3b is theorized to index processes associated with the allocation of attentional resources during cognitive operations involved in the updating of working memory (Donchin, 1981;

Donchin and Coles, 1988). Thus, P3b amplitude is sensitive to the amount of attentional resources allocated toward a stimulus (Polich, 1987; Polich and Heine, 1996). P3b latency is sensitive to stimulus classification speed (Duncan-Johnson, 1981; Kutas et al., 1977). Accordingly, P3b latency is thought to reflect stimulus detection and evaluation time (Ilan and Polich, 1999; Magliero et al., 1984), independent of response selection and behavioral action (Verleger, 1997).

Emerging just prior to the P3 is a smaller negative-going component known as the N2. Relative to P3, the meaning of this component is somewhat tenuous, as multiple N2 components have been identified in the literature (Folstein and Van Petten, 2008), some of which have unique topographies and others of which overlap in their topography. With regard to the P3, a discernable N2 with a fronto-central maximum occurs just prior to the P3a, and a disparate N2 with a parietal maximum precedes a P3b. In response to uninstructed, novel stimuli, the fronto-central N2 has been linked to deviance or mismatch of a stimulus from a mental template, or an increase in cognitive control over response inhibition (Folstein and Van Petten, 2008). In response to infrequent, target stimuli the parietally occurring N2 has been associated with the amount of attention required to process stimuli in the visual cortex (during visual tasks).

Changes in the neuroelectric system have been documented in the acute and immediate post-acute stages of mTBI. For example, following a sport-related concussion diagnosis, deficits in P3 (i.e., P3b) amplitude were noted in symptomatic (1.7 months post-injury) athletes when compared to asymptomatic (9.75 months post-injury) and a non-concussed group (Dupuis et al., 2000). Others have reported a delayed P3 response in both symptomatic and asymptomatic athletes when compared to control participants despite all groups performing normally on a clinical cognitive evaluation (Gosselin et al., 2006). Further, Gaetz et al. (2000) reported a linear relationship between the number of concussions sustained (up to three) and P3 latency approximately 1 year post-injury. Taken together, these investigations provide evidence indicating that mTBI sustained from athletic endeavors may have a persistent effect on cognitive functioning up to 1 year post-injury. The persistence of these deficits beyond 1 year is not clear.

As such, we hypothesize that young adults reporting a history of concussion would demonstrate persistent changes in cognitive functioning detectable through highly sensitive measures of brain functioning such as ERPs, but not on standard clinical measures of functional cognitive performance. Specifically, we predicted a decrease in the amplitude and an increase in the latency of the P3a and P3b components, indicating prolonged deficits in the orienting of focal attention, the allocation of attentional resources, and cognitive processing speed, respectively. We further predicted that N2 amplitude would be sensitive to concussion history, with decreased amplitude of N2 indicating prolonged deficits in the attentional system. Given the intended design of the ImPACT to assess acute deficits in concussion-induced cognition, we predicted no such differences based on concussion history.

Methods

Male and female young adults aged 18–25 years participating in organized ice hockey, rugby, soccer, judo, and track participated in the study. Each subject provided written in-

formed consent prior to testing. Testing consisted of a single 3-h session in which the participant completed the following evaluations: health history and demographics screening indicating no neurological disorders, cardiovascular disease, or any medications that influence central nervous system function. All participants had normal or corrected vision based on the minimal 20/20 standard. Each participant completed the Edinburgh Handedness Inventory (Oldfield, 1971) and had their body mass index calculated from their height and weight measured using a stadiometer and a Tanita BWB-600 digital scale, respectively. The Kaufman Brief Intelligence Test (K-BIT) (Kaufman et al., 1990) was then administered to estimate intelligence quotient. Functional cognitive performance was evaluated using the ImPACT inventory. The participant was then fitted with a 64-channel Quik-cap (Compumedics Neuroscan, El Paso, TX), provided instructions for completing the novelty oddball task and given 20 practice trials. Upon completion of the task, participants were informed of the purpose of the experiment and received \$30 remuneration for their participation.

ImPACT

The ImPACT (version 5.6.724; ImPACT Applications, Pittsburgh, PA) consists of two segments. The first is a brief demographic questionnaire and symptom report, which is followed by six modules that evaluate functional cognitive performance indexed by scores of verbal memory, visual memory, processing speed, and reaction time. The test has been widely applied in a number of sports settings to evaluate for cognitive dysfunction following mTBI (Iverson et al., 2006a; Lovell et al., 2003; McClincy et al., 2006; Pellman et al., 2006). The verbal memory score is the average percent correct for a word recognition task, a symbol-number matching task, and a letter recall task. The visual memory score is the average percent correct scores for two tasks; an abstract line drawings memory task and a memory task requiring the identification of a series of Xs and/or Os after an interference task (counting down from 25 to 1 on a random grid). The reaction time score is the average response time (in milliseconds) on a choice reaction time task, a go/no-go task, and the symbol-number matching task. The processing speed composite represents the weighted average of three interference tasks for the memory paradigms.

Novelty oddball task

A visual three-stimulus oddball task had participants respond as quickly and accurately as possible with a right hand thumb press only to a randomly occurring, infrequent target stimulus while ignoring all other stimuli (Knight, 1997). Target stimuli were 5-cm-tall white triangles that occurred with a probability of 0.12, and non-target stimuli were 5-cm-tall inverted white triangles that occurred with a probability of 0.76. In addition to the target and non-target stimuli, novel stimuli (e.g., dog, airplane, coffee mug) comprised of simple white line drawings were also presented with a probability of 0.12. Three counterbalanced blocks of 300 trials were presented focally on a computer monitor at a distance of 1 m. All stimuli were presented on a black background for a 100-ms duration, with a 1000-ms response window and a 2000-ms inter-trial interval.

ERP recording

Data collection. EEG activity was recorded from 64 electrode sites (FPz, Fz, FCz, Cz, CPz, Pz, POz, Oz, FP1/2, F7/5/3/1/2/4/6/8, FT7/8, FC3/1/2/4, T7/8, C5/3/1/2/4/6, M1/2, TP7/8, CB1/2, P7/5/3/1/2/4/6/8, PO7/5/3/4/6/8, O1/2) of the International 10–20 system (Jasper, 1958), using a Neuroscan Quik-cap, referenced to averaged mastoids (M1, M2), with AFz serving as the ground electrode, and impedance of <10 k Ω . Additional electrodes were placed above and below the left orbit and on the outer canthus of each eye to monitor electro-oculographic (EOG) activity with a bipolar recording. Cognizant that eye movement artifacts may confound interpretation of the data, our analyses yielded an average of 68.6 (SE = 6.4) blinks per task in the concussion history group and 73.8 (SE = 8.25) blinks per task in the non-concussed group [$t(64) = 4.23$, $p = 0.423$]. The finding of no difference between group eye movements led us to conclude this variable did not skew data interpretation.

Continuous data were digitized at a sampling rate of 500 Hz, amplified 500 times with a DC to 70-Hz filter, and a 60-Hz notch filter using a Neuroscan Synamps 2 amplifier (2003).

Data reduction. Reduction of the EEG data was completed with Neuroscan Edit software (2003). Averaged mastoid-referenced continuous data were corrected for eye movement artifacts using spatial filtering. Epochs from 100 ms pre-stimulus to 1000 ms post-stimulus were created, and baseline corrected using the 100 ms pre-stimulus period. Data were filtered using a 30-Hz (24 dB/octave) low-pass filter, and artifact detection excluded trials containing amplitude excursions of $\pm 75 \mu\text{V}$. The N2 component was defined as the largest negative-going peak occurring at 150–300 ms. The P3 components were defined as the largest positive-going peaks occurring within 300–700 ms. Amplitude was measured as the difference between the mean pre-stimulus baseline and maximum peak amplitude; peak latency was defined as the time point corresponding to the maximum amplitude. Trials were then averaged for each participant based on task condition. Each participant's condition-averaged data was outputted in ASCII format for statistical analysis.

Statistical analysis

All statistical analyses were completed using SPSS version 14.0 (SPSS Inc., Chicago, IL) and statistical significance was noted when $p < 0.05$. Between-group differences in demographic variables (e.g., age, IQ, and years of education) were evaluated using independent samples t -tests.

ImPACT. Output variables (verbal memory, visual memory, processing speed, and reaction time) were generated through automated algorithms embedded within the program. Box's test was implemented to evaluate violations to the assumption of covariance matrix homogeneity. Group performance differences in cognitive variables were then evaluated using a multivariate analysis of variance (MANOVA). This statistical technique was selected because the ImPACT output variables are thought to collectively represent cognitive functioning (Broglia et al., 2006). An independent samples t -test was conducted to evaluate differences in the total number of symptoms endorsed by the participants.

ERPs. Statistical analyses were performed using four midline electrode sites (Fz, Cz, Pz, Oz). ERP component values (i.e., amplitude, latency) for each participant were submitted to a 2 (Group: concussed and non-concussed) \times 4 (Site: Fz, Cz, Pz, Oz) repeated-measures MANOVA for each condition (i.e., target, novel). RT and response accuracy data were analyzed using independent *t*-tests for group. Post hoc comparisons were conducted using Tukey's honestly significant difference (HSD) tests.

Results

A total of 90 young adults (65 male, 25 female: 19.71 ± 1.27 years, 26.1 ± 3.6 BMI) free from injury at the time of testing completed this investigation. Participants were separated into groups (0 and 1+) based on their self-report of physician-diagnosed concussions.

ImPACT assessment

Group demographics and ImPACT scores are provided in Table 1. Non-significant differences were noted between groups for demographic measures ($p > 0.05$), with the exception of age [$t(88) = 2.43, p = 0.02$], as those with a history of concussion were slightly older than those without previous injury. This single demographic difference was deemed negligible in our homogenous, young adult population and was therefore not considered further. Analysis of the ImPACT scores indicated homogeneity of the covariance matrix [$M = 13.82, F(10, 36850.86) = 1.31, p = 0.22$] and no difference in functional cognitive performance between groups [$\Lambda = 0.994, F(4,85) = 0.118, p = 0.976$]. No significant differences were found between the number of symptoms reported [$t(88) = 0.59, p = 0.56$].

Novelty oddball

Task performance. Table 2 presents the RT and response accuracy data for the novelty oddball task based on concussion history. Results indicated non-significant group differences for either RT, $t's (88) < 0.08, p \geq 0.94$, or response accuracy, $t's (88) < 1.8, p \geq 0.08$, indicating that behavioral indices of cognitive performance on this task was not influenced by concussion history.

TABLE 2. TASK PERFORMANCE (MEAN [STANDARD DEVIATION]) ACROSS CONCUSSION HISTORY GROUPING

	No concussion history	Concussion history
Non-target response accuracy (%)	99.8 (0.3)	99.8 (0.3)
Novelty response accuracy (%)	99.6 (1.2)	99.4 (1.5)
Target response accuracy (%)	97.2 (5.2)	95.0 (6.2)
Target reaction time (msec)	417.4 (43.1)	418.1 (39.2)

N2 amplitude. The omnibus analysis for N2 amplitude during the novel condition indicated significant main effects of Group, $F(1, 88) = 4.2, p < 0.05, \epsilon = 0.05$, and Site, $F(3, 86) = 32.1, p < 0.001, \epsilon = 0.53$, which were superseded by a Group \times Site interaction, $F(3, 86) = 3.4, p = 0.02; \epsilon = 0.11$. Decomposition of this interaction indicated larger N2 amplitude for the group without a history of concussion relative to the group with a history of concussion at the Fz (Concussion group: $-4.7 \pm 4.0 \mu V$; Non-concussion group: $-7.5 \pm 4.4 \mu V$) and Cz (Concussion group: $-4.5 \pm 4.9 \mu V$; Non-concussion group: $-7.0 \pm 5.4 \mu V$) electrode sites, $t's (88) \geq 2.2, p \leq 0.03$ (Fig. 1). No such effect was evident at the Pz or Oz electrode sites ($p > 0.6$). Analyses of the target condition indicated only a Site effect with the N2 maxima occurring over the Fz site, with significantly smaller amplitude at the Pz and Oz sites, $t's (90) \geq 2.5, p \leq 0.01$.

N2 latency. Omnibus analyses for the novel and target condition revealed non-significant group differences. The only significant effect was for electrode site during the target condition, $F(3, 86) = 9.2, p < 0.001; \epsilon = 0.24$, with follow-up analyses indicating significantly longer latency at the Fz site relative to the Cz, Pz, and Oz sites, and at the Cz site relative to the Pz site, $t's (89) \geq 2.5, p \leq 0.01$.

P3 amplitude. P3a amplitude analyses for the novel condition indicated a main effect of Site, $F(3, 86) = 61.5, p < 0.001; \epsilon = 0.68$, which was superseded by a Group \times Site interaction, $F(3, 86) = 3.3, p < 0.025; \epsilon = 0.10$. However, decomposition of this interaction did not reveal any significant group differences, $t's (88) \leq 1.2, p \geq 0.24$. Analyses of the tar-

TABLE 1. PARTICIPANT DEMOGRAPHICS AND IMPACT SCORES (MEAN [STANDARD DEVIATION]) ACROSS CONCUSSION HISTORY GROUPING

	No concussion history (n = 44)	Concussion history (n = 46)
Age (years)	19.4 (1.3)	20.0 (1.2) ^a
Body Mass Index	25.9 (3.3)	26.3 (3.9)
K-Bit (IQ)	107.7 (8.0)	105.5 (6.1)
Previous concussions	0.0 (0.0)	1.7 (1.1)
Concussion with loss of consciousness	—	0.8 (1.0)
Concussion with amnesia	—	0.7 (1.1)
Time from last concussion (years)	—	3.4 (3.0)
ImPACT scores		
Composite Verbal Memory	89.56 (10.29)	90.36 (8.67)
Composite Visual Memory	82.95 (9.45)	82.16 (9.82)
Composite Motor Speed	43.92 (9.76)	44.08 (6.95)
Composite Reaction Time	0.53 (0.07)	0.53 (0.06)
Total Symptom Score	8.08 (8.77)	6.91 (9.79)

^aSignificantly greater than the no concussion group.

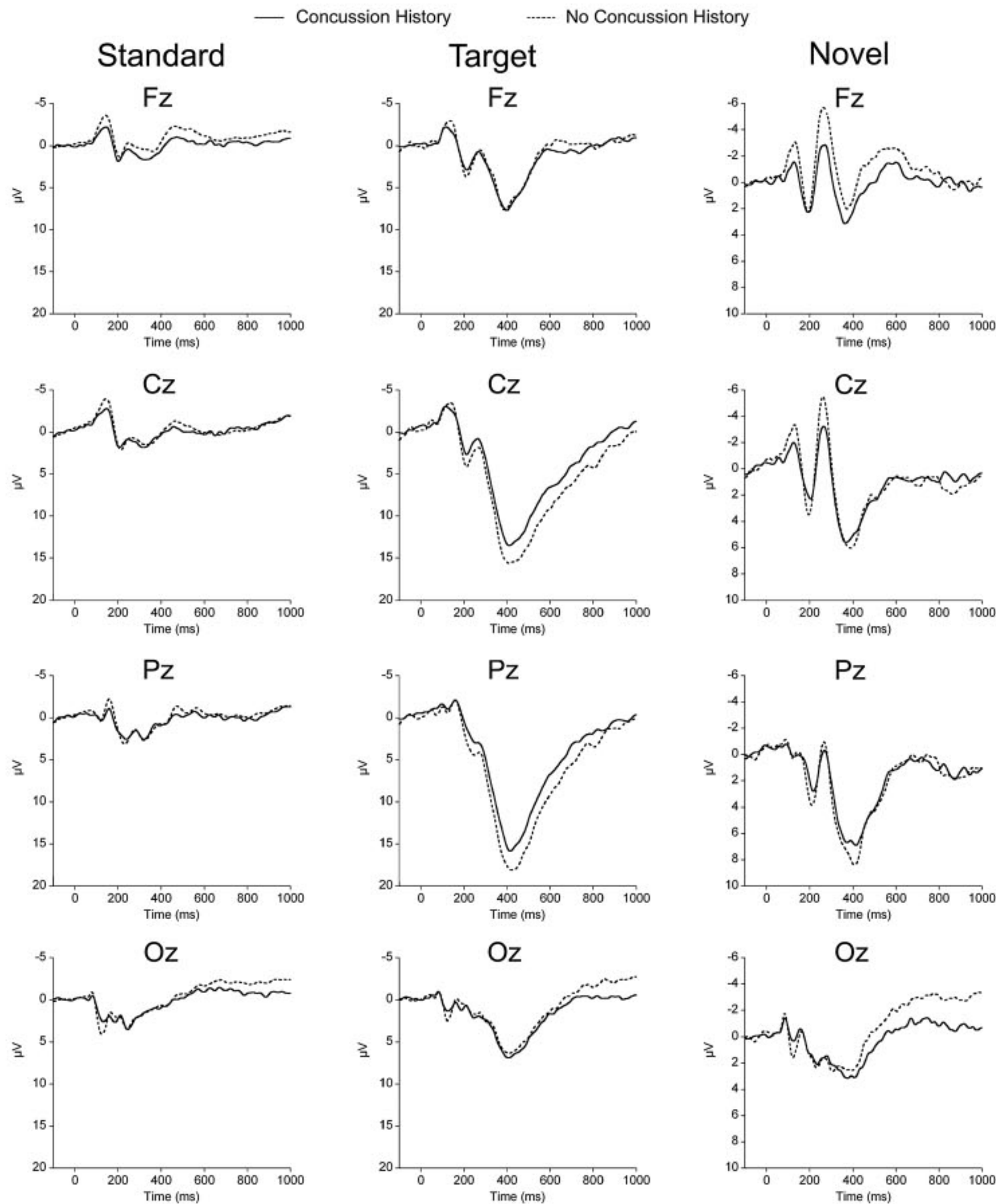


FIG. 1. Grand averaged ERP waveforms for each concussion group and task condition.

get condition (i.e., P3b) also yielded a main effect of Site, $F(3, 86) = 192.7, p < 0.001; \epsilon = 0.87$, which was superseded by a Group \times Site interaction, $F(3, 86) = 4.5, p < .01; \epsilon = 0.13$. Decomposition of the interaction revealed significantly larger P3b amplitude at the Pz electrode site for the group without a history of concussion ($20.4 \pm .96 \mu V$) relative to the group with a history of concussion ($17.6 \pm 1.1 \mu V$), $t(88) = 2.0, p < 0.05$ (Fig. 1).

P3 latency. Analyses for P3 latency revealed no significant group effects. Site effects were observed for both the novel and target conditions, F 's $(3, 86) = 5.1, p < 0.005; \epsilon = 0.15$, with follow-up analyses indicating short P3 latency at the Oz site relative to the Cz and Pz sites for the novel condition, t 's $(89) \geq 2.2, p \leq 0.03$, and shorter latency at the Fz and Oz sites relative to the Cz and Pz sites for the target condition, t 's $(89) \geq 2.1, p \leq 0.04$.

Discussion

Our findings fail to support the supposition that concussion is a transient injury, void of long-term consequences (Aubry et al, 2002). We found that persistent deficits in the neuroelectric system are present following concussion in young adults at 3 years post-injury, despite normal cognitive performance on a standard clinical assessment. The neuroelectric deficits were noted in the P3b and N2 components during the target and novelty conditions of the three-stimulus oddball task, respectively. These findings indicate that specific deficits in component cognitive processes occurring between stimulus engagement and response execution in the information processing stream persist following trauma.

Specifically, the P3b is thought to correspond with the allocation of attentional resources in the service of working memory operations once a stimulus has been presented

(Donchin, 1981; Polich, 2007). P3b amplitude is modulated by target stimuli that are expected, but presented infrequently (Polich, 2007). The suppressed P3b amplitude in the concussed group may therefore reflect a decreased capacity to allocate attentional resources (Polich, 1987) compared to the non-concussed group. Recent research by Polich (2007) has theorized that P3 generation might reflect neural inhibition. That is, the amplitude of this component indexes the suppression of extraneous neuronal activity, which is relevant to the engagement of focal attention (P3a) and the allocation of attentional resources towards working memory (P3b). Accordingly, the differential P3b amplitude exhibited by the concussion history group would suggest a failure to inhibit extraneous neuronal activity in the service of attentional resource allocation necessary for processing the target stimulus. Given that group differences were not evident for the P3a component, the current findings suggest that prolonged deficits in the attentional system are selective to attentional processing. Specifically, reductions in attentional orienting were not observed for the concussion history group, as measured via P3a amplitude, suggesting that not all attentional systems exhibit long-term deficits.

However, deficits in the neuroelectric system were noted during conditions requiring attentional orienting, as N2 amplitude was smaller in the concussion history group. Based on contemporary theories of the N2 during novel conditions requiring attentional orienting, the current findings suggest that the reduced N2 component for the concussion history group might reflect a deficit in a general alerting system or the mismatch of a novel stimulus with the mental template (based on task instructions). It is also possible that the decreased N2 for the concussion history group reflects a decrease in cognitive control over response inhibition. That is, the N2 during certain tasks (i.e., Go/NoGo and flanker tasks) has been linked to the inhibition of a prepotent response. In the novelty condition of the three-stimulus task implemented here, the N2 may reflect motor inhibition, which has traditionally been considered a component of the orienting response to ongoing environmental changes (Ohman et al., 2000). Based on this interpretation, the current findings indicate prolonged deficits in the cognitive control of motor inhibition. Clearly, future research will need to elucidate whether any of these inferences regarding concussion history and novelty N2 are most probable. Lastly, the N2 to target stimuli has been previously linked to visual processing. Given that group differences were not observed during the target condition, the findings suggest no prolonged deficits in visual processing following concussion.

Other investigations have also reported suppressed neuroelectric activation using shorter intervals following mTBI. For example, persistent deficits were demonstrated in concussed athletes who were asymptomatic 15 weeks post-injury and symptomatic athletes 5 weeks post-injury relative to non-concussed control athletes during performance of a stimulus discrimination task. Specifically, both concussed groups exhibited increased P3b latency compared to controls, suggesting that concussion resulted in delays in cognitive processing speed regardless of the presence of post-concussion symptoms and normal performance on standard clinical measures of cognitive functioning (Gosselin et al., 2006). Other research has corroborated these findings as longer P3b latency to a stimulus discrimination task was observed in individuals a minimum of 6 months post-injury who have sustained up to

three concussions (394.5 ms) relative to those that had never been injured (354.3 ms) (Gaetz et al., 2000). The relationship between increased latency and concussion history appears linear as those that had sustained one (375.8 ms) or two (375.5 ms) concussions exhibited P3b latencies that fell between those with three concussions and those that had never been concussed. In combination with our results, these findings highlight the sensitivity of ERP measurement to persistent concussion-induced changes in cognition and the inadequacy of standard clinical evaluations to detect subtle changes in cognitive functioning beyond the acute phase of injury.

Our lack of significant findings of chronic functional deficits is not unprecedented and may be related to the clinical test we employed. The sensitivity of the computer based assessment employed here and in other investigations (Broglia et al., 2006; Collie et al., 2006; Iverson et al., 2006b) does not seem adequate to detect chronic cognitive deficits. In part, these tests were not developed to detect subtle persistent changes, but rather to be sensitive to the gross changes in cognition that are present immediately following mTBI. We speculate that other cognitive measures may provide greater sensitivity to persistent decrements associated with mTBI. For example, Ellemburg et al. (2007) reported prolonged cognitive decrements in concussed soccer athletes 6–8 months post-injury on the Stroop Color Word Test and the Tower of London DX, whereas Collins et al. (1999) reported deficits in previously concussed collegiate athletes on the Trail Making Test–Part B. Each of these pencil and paper tests are well-established evaluative measures of various aspects of executive function that are not indexed by the ImpACT battery used here.

Whether or not the suppressed neuroelectric profile reported here and elsewhere is related to increased reports of mild cognitive impairment and depression (Guskiewicz et al., 2005) is not clear. The underlying mechanism of those impairments cannot be fully elucidated by this investigation, although similarly suppressed P3 amplitude and scalp distribution has been tied to non-pathological aging (Polich, 1997). Consequently, we speculate that the reported late life clinical pathologies reported in retired athletes might reflect some form of accelerated aging resulting from mTBI. Abated pyramidal cell structure is a well-known effect associated with aging (Peters, 2002) and cellular death in the CA3 region of the hippocampus has been reported in mice 72 h following mTBI (Tashlykov et al., 2007). Similarly, TBI has been linked to pyramidal neuron atrophy and death in the CA1 and CA4 hippocampal subfields in the months following injury (Maxwell et al., 2003). Cellular death following mTBI may also occur with the collective cell loss subsequent to mTBI and aging resulting in a neuropathological manifestation (Omalu et al., 2005, 2006).

Pathological changes may not be apparent until later in life, as young adults with a history of mTBI, like those in this investigation, benefit from cognitive reserve (Katzman et al., 1988). That is, these individuals likely demonstrated normal functional cognitive performance by recruiting other cortical networks and regions to aid in accomplishing the cognitive task at hand. For example, one investigation found concussed young adults performed normally on functional cognitive evaluations by recruiting additional cortical areas as evidenced by increased blood oxygen level-dependent (BOLD) signals (Jantzen et al., 2004). Cognitive reserve is known to

decrease with age (Fratiglioni and Wang, 2007), but coupled with increased cell death resulting from mTBI, cognitive decline may be exacerbated and ultimately develop into clinical signs and symptoms.

Although significant differences were demonstrated between our concussed and non-concussed groups, the use of participant-report concussion diagnoses limits the strength of the investigation. We find it unlikely that our participants over-reported the number of injuries they sustained as many mTBI go unreported (Langlois et al., 2006). In addition, the cross-sectional nature of the study limits our ability to draw conclusions of how these injuries may affect the participants later in life. Lastly, the cross-sectional nature of the study compromises our ability to indicate causation regarding the effect of concussion history on cognition. It is possible, although unlikely, that a secondary factor or set of factors may be responsible for the group differences that were attributed to concussion history. Future investigations should adopt a longitudinal design to better elucidate these effects.

Conclusion

In the final analysis, we demonstrated persistent deficits in the neuroelectric system of young adults reporting at least one mTBI over the 3 years prior to this investigation. Although the changes occurred in absence of functional cognitive declines, these findings support and extend a growing body of literature suggesting that cerebral concussion can no longer be thought of as a transient injury without long-term threats to cognitive health. It is not clear if or how these deficits will manifest into clinical pathologies with age, but clearly a conservative approach to mTBI is warranted. At the least, those suspected of sustaining a concussion should be withheld from activity until they perform at or above a pre-morbid level of functioning (Guskiewicz et al, 2004; McCrory et al., 2005). Using these guidelines, many athletes will return within 1 week following injury, but in light of these findings and those presented elsewhere, others have speculated that a longer rest period is necessary (Mayers, 2008).

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Author Disclosure Statement

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