International Journal of Psychophysiology 99 (2016) 85–95

Contents lists available at ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

The persistent influence of concussion on attention, executive control and neuroelectric function in preadolescent children

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A R T I C L E   I N F O

Article history:
Received 18 August 2015
Received in revised form 2 November 2015
Accepted 18 November 2015
Available online 26 November 2015

Keywords:
Sport-concussion
Children
Brain function
Event related potentials
Cognition

A B S T R A C T

The aim of this investigation was to examine the influence of pediatric sport-related concussion on brain and cognitive function. To do so, we used a between-participants design, measures of executive control, and event-related potentials (ERPs). The findings demonstrate that children with a history of concussion exhibit behavioral deficits in attention, working memory and impulse control, as well as neuroelectric alterations in ERP indices of visual attention (N1), conflict resolution (N2) and attentional resource allocation (P3). Furthermore, the age at injury related to the magnitude of several concussion-related deficits. Accordingly, a single sports-related concussive incident during childhood (m = 2.1 years prior to testing) may lead to subtle, yet pervasive alterations in the behavioral and neural indices of attention and executive control, and age at injury may moderate injury outcomes.

1. Introduction

Although the field of concussion research is growing rapidly, the majority of research has focused on injured adults, with children receiving less attention. More than a million brain injuries are treated annually in the United States (Yeates et al., 1999), with an estimated 75% of these injuries classified as mild or concussion (Faul et al., 2010). Further, children are disproportionately affected by sport-related injuries, with approximately 65% of all pediatric concussions occurring during sport and recreation (Control and Prevention, 1997). The outcomes of pediatric concussion remain debated, as several large-scale studies and reviews suggest that the prognosis of pediatric concussion is relatively good with only a small portion of children exhibiting persistent developmental deficits (Babikian and Asarnow, 2009; Hung et al., 2014; McKinlay et al., 2010; Yeates and Taylor, 2005). However, even if only a small portion of children experience adverse outcomes in neurobehavioral development, these injuries represent a serious public health concern, warranting further investigation (McKinlay et al., 2010; Yeates, 2010).

Indeed, contrary to the above findings, several pediatric studies examining concussive injuries of various etiologies observed persistent behavioral deficits in aspects of attention and executive functions (i.e. working memory, inhibition, cognitive flexibility), which are essential to academic and vocational success, as well as overall effective functioning (Catale et al., 2009; Hessen and Nestvold, 2009; Hessen et al., 2007; Moore et al., 2015; Nolin and Mathieu, 2000; Ornstein et al., 2013). For example, Catale et al. (2009) reported deficits in divided attention and working memory during the Test of Attentional Performance in children 1-year post-injury. Nolin and Mathieu (2000) noted deficits in processing speed and mental flexibility during the Comprehensive Trail-Making Test in children three years from injury. Employing a modified flanker task, Moore et al. (2015) observed deficits in sustaining and modulating attention and executive control in children more than two-years following a sports-related concussion. Furthermore, children who were injured earlier in life exhibited the largest deficits. Perhaps the most compelling evidence, however, comes from a series of longitudinal studies examining patients from childhood to adulthood. Using a comprehensive neuropsychological battery, Hessen et al. (2006) reported deficits in measures of attention and memory in young adults who had sustained a concussion on average of 25 years prior to testing. In a follow-up study, Hessen et al. (2007) observed that children who sustained a concussion before ten years of age were much more likely than non-injured controls to display chronic mild deficits in attention

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http://dx.doi.org/10.1016/j.ijpsycho.2015.11.010
0167-8760/

and cognitive flexibility. Together these results indicate that irrespective of etiology, a concussive injury can indeed lead to developmental deficits in attention and executive functions, with younger children experiencing worse outcomes.

Given these divergent findings and the potential for concussive injuries to alter functions essential to everyday functioning, it is critical to further delineate the long-term outcomes of pediatric concussion. Indeed, few pediatric studies have actually measured brain function to evaluate the outcomes of concussive brain injuries, and although a small literature evaluating brain function following non-sport/mixed etiology injuries is emerging (for review see Keightley et al., 2012), to the best of our knowledge only two pediatric studies evaluated the long-term outcomes (6 + months) of sport-specific injures by assessing brain function. Both studies employed electroencephalography (EEG) to evaluate event-related brain potentials (ERPs) during experimental task performance. For example, Baillargeon et al. (2012) evaluated children, adolescents, and adults by employing a battery of neuropsychological tests as well as a simple visual discrimination task during which ERPs were recorded. Standard neuropsychological tests failed to differentiate children with and without a history of concussion; however, irrespective of age, participants with a history of concussion exhibited smaller P3 ERP amplitude, which is a neural index of attentional resource allocation during working memory (Polich, 2007). Thus, a single sports-related concussion can lead to persistent alterations in the neurophysiology underlying attention during visual discrimination.

Beyond simple visual discrimination, Moore et al. (2015)) evaluated ERPs during a modified flanker task, which modulates attention and executive control. The authors observed that children with a history of concussion exhibited pervasive alterations in the neuroelectric indices of cognition including: conflict monitoring (N2), attention/working memory (P3), action monitoring (ERN), and error awareness (Pe). Importantly, these alterations were directly related to behavioral deficits (commission errors—N2; lapses of attention—P3; post-error accuracy—Pe). Thus similar to adults (Broglio et al., 2009; Larson et al., 2012; Moore et al., 2014), concussion-related alterations in pediatric brain function may become more pervasive during conditions requiring the up-regulation and coordination of attention and executive control, resulting in behavioral deficits.

Accordingly, the first aim of our study was to evaluate neurocognition in preadolescent children with a history of sport-related concussion by employing experimental tasks that modulate attention and executive control demands. Specifically, we utilized an experimental *n*-back task to evaluate sustained attention and working memory, an experimental switch task to evaluate attention and cognitive flexibility, and an experimental Go–NoGo task to assess inhibition/impulse control.

Although valuable information is gained from behavioral assessments, understanding the neuropathological underpinnings of concussion is critical for aiding the diagnosis, prognosis, and remediation of concussive injuries (Bigler and Maxwell, 2012; Mayer et al., 2012). Measures of functional brain activity, and ERPs in particular, allow researchers to parse the stimulus–response relationship into its constituent cognitive components. Such an approach enables the identification of where in the processing stream groups or conditions differ, yielding a more precise and integrative understanding of neurocognition than behavioral measures alone. Thus, to gain greater understanding of the neurophysiological processes underlying attention and executive functions we measured ERPs during experimental task performance. We sought to evaluate both early (i.e., N1, N2) and late (P3) ERP components to gain a better understanding of the influence sport-related concussion across the information-processing stream.

The N1 component is believed to reflect neuronal activity associated with the discrimination, encoding, and integration of basic stimulus properties (Vogel and Luck, 2000), with amplitude reflecting sensory gains in the service of selective attention processes (Hillyard and Anllo-Vento, 1998; Hillyard and Munte, 1984). The fronto-central N2 is believed to reflect conflict-monitoring processes, with amplitude reflecting the magnitude of stimulus–response conflict experienced (Schmitt et al., 2000), and latency reflecting the duration of conflict resolution (Gajewski and Falkenstein, 2013). Lastly, the P3 component is believed to reflect the allocation of attentional resources during the updating of working memory (Polich, 2007). Accordingly, we evaluated ERP indices of perceptual attention (N1), stimulus–response conflict (N2), and attentional resource allocation (P3) in children with and without a history of concussion.

We predicted that relative to children in the control group, children with a history of concussion would exhibit deficits in behavioral performance during more difficult task conditions, which require the up-regulation and coordination of multiple aspects of attention and executive function (2-back, heterogeneous condition of the switch task, NoGo condition). We expected these behavioral deficits to be paralleled by changes in brain function at multiple points in the information processing stream. Specifically, we predicted that children would exhibit reduced N1 amplitude, increased N2 amplitude and latency, and reduced P3 amplitude. Lastly, as previous research evaluating non-sport related injuries observed a correlation between the age at injury and cognitive function (Hessen et al., 2007; Moore et al., 2015), we predicted a negative correlation between the age of injury and the magnitude of observed deficits.

2. Methods

2.1. Sample and participant selection

Participants included thirty (15 concussion, 15 control) 8–10 year-olds who were recruited through university recruitment services via an online community bulletin and Central Illinois youth athletic associations (YMCA, hockey, football, soccer). Specifically, athletic associations referred athletes who had been removed from the game for a concussion. All participants had their injuries diagnosed by healthcare providers of the same Central Illinois healthcare system. Further, all concussive injuries were confirmed by experimenters using the criteria established by the American Academy of Neurology (McCrea et al., 1997). Eight of the fifteen participants in the concussion group lost consciousness as a result of their injury, but no participant incurred a complicated injury requiring surgical intervention or hospital admittance. Furthermore, no participant reported any symptoms at time of testing according to a commonly used symptom checklist (McCrory et al., 2009). All participants were physically active on a regular basis and actively participating in one or more sports at time of testing.

2.2. Inclusion/exclusion criteria

To be included in the current study, all participants were required to be right handed, and to be free of a history of special educational services, attentional disorders, psychiatric or neurological disease/disorders, and physical disability. Further, all participants were required to be free of any medication/nutritional supplementation that may influence brain or cognitive function. Participants with a history of concussion had to have experienced a single, medically diagnosed concussion incurred during participation in organized/recreational sport (i.e. soccer, football, hockey, etc.). To assess long-term injury outcomes, participants were required to be 6 + months removed from injury (range = 0.5–4.2 years, age at injury 5.2–9). All participants were required to be free from a history of more complicated or severe brain injury. Demographic information is presented in Table 1.

2.3. Matching

Following their initial visits, participants with a history of concussion were matched with participants who had not sustained a concussion,

Table 1
Participant demographic values (±1 SD).

Measure	Concussed	Control
Age	9.2 (±0.6)	9.0 (±0.7)
Age at injury	7.1 (±2.2, range = 4.1–9)	N/A
Years since injury	2.1 (±1.9)	N/A
Loss of consciousness	8	N/A
Grade	3.6 (±0.7)	3.7 (±0.8)
Gender	10M/5F	10M/5F
Pubertal timing	1.2 (±0.4)	1.4 (±0.3)
K-BIT (IQ)	116.3 (±14.4)	118.8 (±13.4)
ADHD-concentration%	50.0 (±3.3)	47.4 (±3.7)
ADHD-impulsivity%	42.3 (±3.1)	39.2 (±3.7)
ADHD-hyperactivity%	52.6 (±2.7)	55.9 (±2.9)
SES	2 (±0.8)	2 (±0.9)
Fitness% (VO_2 rel.)	40.5 (±6.7)	42.9 (±8.7)
Physical activity per week	5.2 (±1.1)	5.4 (±1.8)
BMI	20.74 (±4.3)	18.7 (±4.6)
SSAP	3.3 (±1.0)	3.1 (±0.6)
SSAS	1.4 (±0.6)	1.5 (±0.9)

Note: K-BIT = Kauffman Brief Intelligence Test; ADHD-concentration, ADHD-impulsivity, ADHD-hyperactivity refer to the concentration, impulsivity and hyperactivity subscales of the Connors' Child ADHD Rating Scale; SES = socioeconomic status, Fitness% = relative cardiorespiratory fitness percentile based on age, height and weight. BMI refers to body mass index; SSAP and SSAS refer to social support for academics from parent and school teachers respectively.

but had a similar history of sport participation. Specifically, demographic factors were collected and participants were matched on a battery of demographic factors including: age, sex, pubertal timing, IQ, ADHD symptoms (concentration, hyperactivity, impulsivity, socioeconomic status (SES), social support for academics, cardiorespiratory fitness, weekly physical activity and BMI. These factors are known to influence brain and cognitive development (Anderson et al., 2011; Hillman et al., 2008) and to moderate the incidence and outcomes of pediatric brain injury (Anderson et al., 2011; Catroppa et al., 2012; Satz et al., 1997; Yeates and Taylor, 2005). Demographic information is listed in Table 1.

2.4. Testing

Cardiorespiratory fitness (VO_{2max}) was measured on a motor–driven treadmill using a modified Balke protocol and VO_{2max} was established when children met a minimum of two of the following four criteria: 1) a plateau in oxygen uptake corresponding to an increase of less than 2 $ml/kg \cdot min^{-1}$ despite an increase in exercise workload; 2) a peak heart rate ≥ 185 beats per minute; 3) heart rate plateau; 4) respiratory exchange ratio ≥ 1.0; and/or 5) ratings on the children's OMNI scale of perceived exertion ≥8, (Bar-Or, 1983; Freedson and Goodman, 1993; Utter et al., 2002); see Hillman et al. (2014) for more details.

2.5. Procedures

All participants completed a two-day test protocol, which lasted 1.5–2 h per visit. The protocol was approved by the Institutional Review Board at the University of Illinois, and previously used to evaluate hundreds of children as part of the NICHD funded FITKids clinical trial. Specifically, during the first visit guardians provided written informed consent, and participants provided written assent. Guardians then provided demographic information as described above. Pubertal timing was assessed via a modified Tanner Staging System questionnaire (Taylor et al., 2001), and SES was determined using a trichotomous index based on: (1) participation in free or reduced-price meal program at school, (2) the highest level of education obtained by the mother and father, and (3) number of parents who worked full-time (Birnbaum et al., 2002). ADHD symptoms (concentration, hyperactivity, impulsivity) were asses with the Conners' Child ADDH Rating Scales (Conners et al., 2001). Health issues exacerbated by physical exercise were screened via the PA Readiness Questionnaire (Thomas et al., 1992). While guardians completed demographic information, participants completed the Kaufman Brief Intelligence Test (Kaufman et al., 1990) to assess IQ. Participants then completed a social support for academics questionnaire, followed by an *n*-back task to assess working memory. Following neuropsychological testing, participants completed a maximal exercise test to assess aerobic fitness.

On the second visit, participants were outfitted with a high density EEG cap and sat in a sound and light attenuated room, 1 m from a monitor, and completed experimental switch and Go–NoGo tasks. Participants were given a brief break and encouragement after each testing block. All participants were paid $15 per hour for their participation.

2.6. Cognitive tasks

To investigate sustained attention and working memory, participants completed a serial *n*-back task during which they viewed a series of shapes (Gothe et al., 2013; Kamijo et al., 2011). Participants completed 0-, 1- and 2-back conditions. During the 0-back condition, participants were asked to respond with a right thumb press on a handheld response controller only when they saw a cross, and to respond with a left thumb press for all other shapes. During the 1-back condition participants were asked to respond with a right thumb press only when the shape was the same as the previously presented shape, and respond with a left thumb press if the current shape differed from the previously presented shape. During the 2-back condition participants were asked to respond with a right thumb press only when the current shape was the same as the shape presented on the trial two shapes earlier, and respond with a left thumb press if the current shape differed from the shape presented two shapes prior. Participants completed 24 practice trials and 100 trials for each of the three conditions of the task. All stimuli were presented foveally on a black background for 200 ms with an inter-stimulus interval of 2000 ms and a response window of 1950 ms (Fig. 1).

To investigate behavioral inhibition, participants completed a Go–NoGo task (Hillman et al., 2012; Kamijo et al., 2012) during which they viewed a series of cartoon stimuli (i.e., tigers and lions) and were asked to respond to one stimulus (i.e., Go-stimuli), but to refrain from responding to the other stimulus (i.e., NoGo-stimuli). During the first block (Go condition), participants were asked to respond with a right thumb press to an infrequently occurring (20%) lion stimulus, but to refrain from responding to a frequently occurring (80%) tiger stimulus. During the second block (NoGo condition) participants were asked to respond with a right thumb press to a frequently occurring (80%) tiger stimulus, but not to respond to the infrequently occurring (20%) lion stimulus. Participants were given 24 practice trials and then completed two counterbalanced blocks of 200 trials. All stimuli were presented foveally on a black background for 200 ms with a 2000 ms inter-stimulus interval and a 950 ms response window.

To investigate mental flexibility, participants completed a switch task (Chaddock et al., 2012; Hillman et al., 2014). Participants first completed two single-item tasks referred to as the homogeneous conditions during which a series of cartoon shapes were presented. In the first task, participants were asked to press the left button on the response controller if the shape was a circle, and the right button if the shape was a square. Participants then completed a different homogeneous task during which they were asked to press the left button on the response controller if the shape was blue, and the right button if the shape was green. These two homogenous conditions were counterbalanced across participants and groups. Following the homogenous conditions, participants completed the heterogeneous (i.e., mixed rule set) condition of the task, which required participants to switch between the two previously learned rule sets depending on whether the cartoon stimuli were holding their arms up or down. The arms up direction cued participants to respond according to the shape rule and the arms down direction cued participants to respond according to the color rule. During the

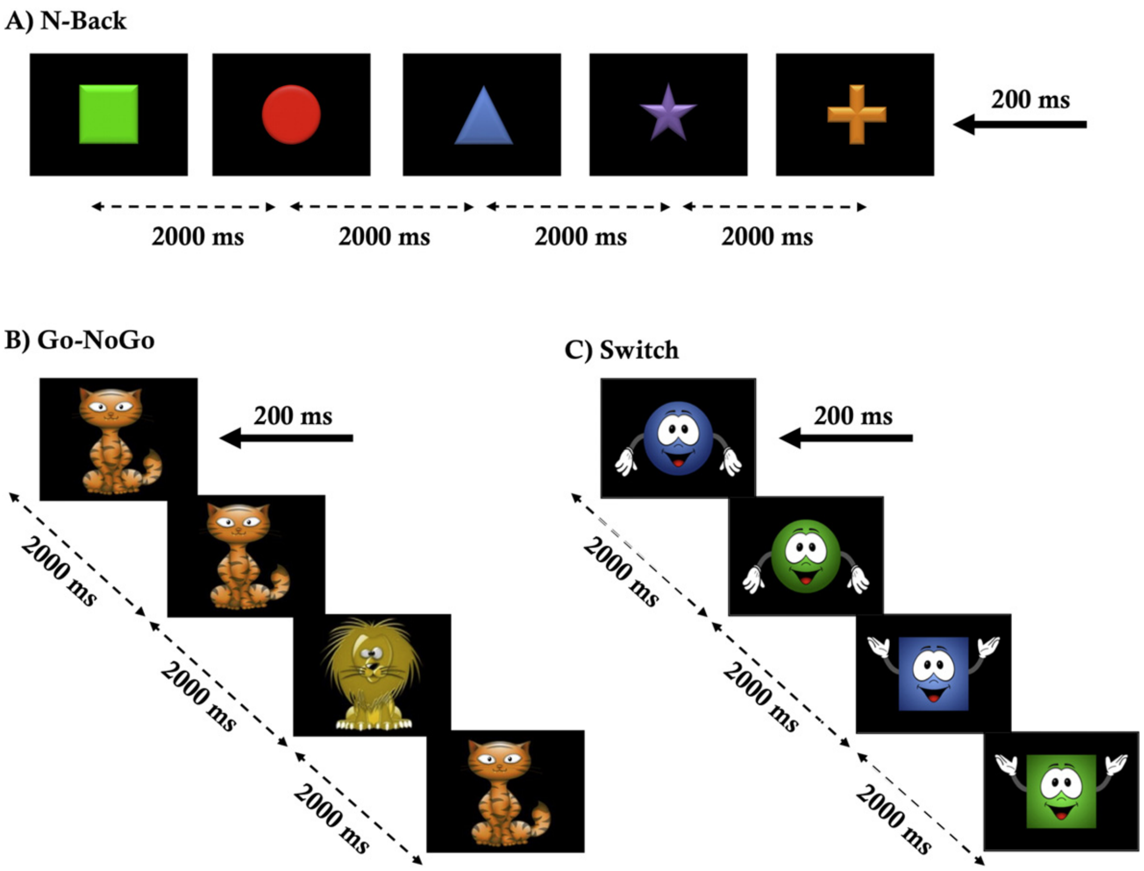

Fig. 1. Task stimuli and parameters for the n-back, Go–NoGo and switch tasks.

heterogeneous task the two rule sets alternated in an equiprobable and random fashion with seven consecutive trials serving as the maximum number presented repeatedly for each rule set. Participants were given 24 practice trials prior to performing each homogeneous condition, which consisted of 64 trials each. Next, participants were given 48 practice trials prior to performing the heterogeneous condition, which consisted three blocks of 82 trials. All stimuli were presented foveally on a black background for 200 ms with a 2000 ms interstimulus interval, and a 1950 ms response window.

Mean reaction time, response accuracy, errors of omission (misses) and errors of commission (false alarms) were computed for each condition of each cognitive task. d' (Z(hit rate) $-$ Z(false alarm rate)) scores were also calculated for each condition of the *n*-back and Go–NoGo tasks. Global switch (homogenous–heterogeneous), local switch (nonswitch–switch), and working memory (homogeneous–non-switch) costs were computed in terms of mean reaction time and accuracy for the switch task.

2.7. EEG/ERPs

During the switch and Go–NoGo task, EEG activity was recorded from 64 sintered Ag-AgCl electrodes (10 mm sensors; 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), arranged according to the International 10–10 system (Chatrian et al., 1985) using a Neuroscan Quik-cap (Neuroscan, 2003). EEG activity was referenced to averaged mastoids (M1, M2) with AFz serving as the ground electrode. In accordance with prior research (Hillman et al., 2014; Kamijo et al., 2012) and the Guidelines for Using Human Event-related Potentials to Study Cognition (Picton et al., 2000), electrode impedance was kept below 10 kΩ. Additional electrodes were placed above and below the left orbit and on the outer canthus of each eye to monitor electrooculographic (EOG) activity with a bipolar recording. Continuous raw EEG data were collected using Neuroscan Scan software (v 4.5) and amplified through a Neuroscan Synamps 2 amplifier with a 24 bit A/D converter and ±200 mV (mV) input range (763 μV/bit resolution). Data were sampled at 500 Hz and amplified 500 times with a DC to 70 Hz filter and a 60 Hz notch filter.

Prior to averaging, an off-line electro-oculographic (EOG) reduction procedure was applied to individual trials via a spatial filter, which performed a principle component analysis (PCA) to determine the major components that characterize the EOG artifact between all channels. This procedure then reconstructed the original channels without the artifact components (Neuroscan, 2003). Trials with a response error or artifact exceeding ±75 μV were rejected and artifact free data were retained for averaging.

Prior to segmentation and averaging, data were filtered with a zero phase shift 30-Hz low-pass and .1-Hz high-pass filters (24 dB/octave rolloff). Epochs were created using the −100 to 1000 ms stimuli onset period and were baseline corrected using the 100-ms prestimulus period. The N1 component was identified as the mean amplitude within a 30 ms interval surrounding the largest negative-going peak within 50–150 ms latency. The N2 component was identified as the mean amplitude within a 30 ms interval surrounding the largest negative-going peak within 150–350 ms latency. The P3 component was identified as the mean amplitude within a 50 ms interval surrounding the largest positive-going peak within a 300–700 ms latency window. Amplitude was measured as the difference between the mean pre-stimulus baseline and mean peak-interval amplitude; peak latency was defined as the time point corresponding to the maximum amplitude of the local peak.

2.8. Statistical analyses

Primary outcomes measures were behavioral indices of performance for the *n*-back task, and behavioral and neuroelectric indices of performance for the Go–NoGo and switch tasks. Behavioral measures for the *n*-back task were analyzed via a repeated measures ANOVA, 2 (Group: Concussion, Control) × 3 (Condition: 0-, 1-, 2-back) for target and non-target trials, and d' scores. Behavioral measures for the switch task were analyzed via 2 (Group: Concussion, Control) × 2 (Condition: homogeneous, heterogeneous) and performance costs transformations (global switch, local switch, working memory) were evaluated by Student *t*-tests. Behavioral measures for the Go–NoGo task were analyzed using a 2 (Group: Concussion, Control) × 2 (Condition: target, non-target: Go–Go, NoGo–NoGo) repeated measures ANOVA, and parametric measures (d', false alarms) were evaluated by Student *t*-tests.

Preliminary analyses of ERP epochs revealed that the number of trials retained for averaging did not significantly differ between groups for the homogeneous (concussion $m = 99 \pm 8$; control $m = 101 \pm 7$) and heterogeneous (concussion $m = 158 \pm 15$; control $m = 151 \pm 13$) conditions of the switch task, or the Go (concussion $m = 60 \pm 5$; control $m = 63 \pm 4$) and NoGo (concussion $m = 50 \pm 5$; control $m = 53 \pm 5$) conditions of the Go–NoGo task (p's $\geq .81$) (Fig. 2).

In accordance with previous research (Kamijo et al., 2012; Larson et al., 2012; Moore et al., 2014; Moore et al., 2015; Picton et al., 2000) we conducted preliminary ANOVAs, and *t*-tests to determine the site/s of maximal activation for each component, for each participant. Preliminary analysis of ERP component values revealed topographical maxima at sites FCz and Cz for the N1 and N2 components for both the switch and Go–NoGo tasks. Subsequently, N1 and N2 component values for each participant and each task were analyzed using a fronto-central region (FCz, Cz; Larson et al., 2012; Moore et al., 2015; Picton et al., 2000). A preliminary ANOVA and *t*-test of the P3 component revealed topographical differences in amplitude maxima (centrality and laterality) between participants. Subsequently, P3 component values for each participant and task were analyzed using a 9-site central-parietal region (C1, Cz, C2, CP1, CPz, CP2, P1, Pz, P2; Kamijo et al., 2012; Moore et al., 2014; Moore et al., 2015; Picton et al., 2000). ERP component values were then submitted to similar factorial ANOVAs as described above. All statistical analyses were conducted with $\alpha = .05$ using the Greenhouse–Geisser statistic with subsidiary univariate ANOVAs and Bonferroni corrected Student's *t*-tests for post-hoc comparisons. All values are expressed as means ± SD.

In addition, bivariate correlations were carried out examine the relation between performance variables and injury variables (time since injury, age at injury). Furthermore, partial correlations were carried out to examine the relation between performance variables and lost of consciousness. Lastly, given the number of statistical analyses only significant findings are reported herein. Please refer to Table 2 for the complete report.

3. Results

3.1. Demographics

Table 1 summarizes demographic data. Analyses failed to reveal group differences for any demographic factor, t's$(30) \leq .47$, p's $\geq .40$, suggesting that sample matching was successful.

3.2. Behavior

Behavioral data are summarized in Table 2.

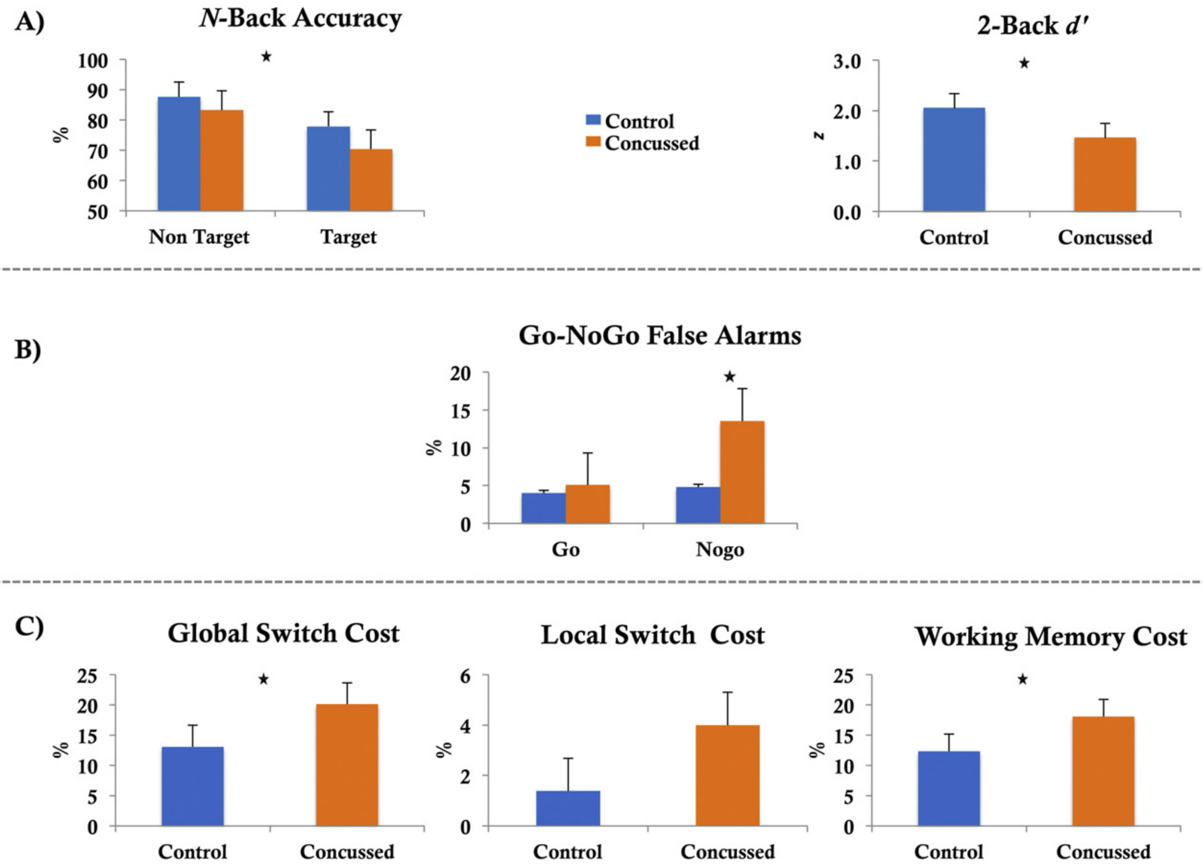

Fig. 2. Behavioral data for the control and concussed groups.

Table 2
Participants' behavioral performance (±1 SD).

Measure		Concussed	Control	Effect size
N-back	0-Back non-target RT	679.6 (±175.6)	707.7 (±137.8)	$d = 0.18$
	1-Back non-target RT	1079.0 (±217.2)	1085.1 (±188.6)	$d = 0.03$
	2-Back non-target RT	1229.6 (±365.0)	1143.7 (±260.9)	$d = 0.27$
	0-Back target RT	692.6 (±160.7)	737.0 (±157.4)	$d = 0.28$
	1-Back target RT	1027.6 (±316.9)	1045.0 (±211.3)	$d = 0.07$
	2-Back target RT	993.4 (±257.5)	1010.0 (±292.4)	$d = 0.06$
	0-Back non-target ACC	94.1 (±7.7)	97.0 (±4.7)	$d = 0.46$
	1-Back non-target ACC	85.6 (±13.2)	89.3 (±11.7)	$d = 0.29$
	2-Back non-target ACC	69.8 (±22.0)	76.8 (±22.8)	$d = 0.32$
	0-Back target ACC	87.5 (±0.6)	94.2 (±6.0)	$d = 0.82$
	1-Back target ACC	73.0 (±19.6)	76.3 (±17.6)	$d = 0.18$
	2-Back target ACC	50.7 (±17.9)	63.2 (±10.4)	$d = 0.88$
	N-back overall ACC*	77.0 (±11.1)	82.8 (±12.2)	$d = 0.38$
	0-Back d'	3.2 (±0.6)	3.6 (±0.6)	$d = 0.71$
	1-Back d'	2.5 (±0.9)	2.7 (±0.8)	$d = 0.17$
	2-Back d'*	1.4 (±0.8)	2.1 (±0.4)	$d = 0.98$
	N-back overall d'*	2.4 (±0.8)	2.8 (±0.6)	$d = 0.56$
Switch	Homogeneous RT	767.3 (±152.8)	737.4 (±159.4)	$d = 0.19$
	Heterogeneous RT	1481.3 (±151.1)	1463.6 (±134.6)	$d = 0.12$
	Non-switch RT	1372.9 (±166.7)	1355.6 (±146.5)	$d = 0.11$
	Switch RT	1593.9 (±213.32)	1576.5 (±161.7)	$d = 0.09$
	Global switch cost RT	714.0 (±230.0)	725.9 (±134.8)	$d = 0.07$
	Local switch cost RT	220.1 (±230.8)	220.8 (±145.4)	$d = 0.07$
	Working memory cost RT	605.7 (±199.0)	617.9 (±134.5)	$d = 0.07$
	Homogeneous ACC	91.9 (±9.4)	89.4 (±6.2)	$d = 0.40$
	Heterogeneous ACC	71.3 (±9.4)	75.6 (±9.3)	$d = 0.60$
	Non-switch ACC	73.4 (±9.9)	77.0 (±7.7)	$d = 0.41$
	Switch ACC	69.4 (±10.0)	76.3 (±7.1)	$d = 0.60$
	Global switch cost ACC*	20.6 (±9.7)	13.8 (±6.3)	$d = 0.83$
	Local switch cost ACC	4.0 (±6.3)	1.4 (±9.6)	$d = 0.33$
	Working memory cost ACC*	18.5 (±9.7)	12.3 (±6.3)	$d = 0.77$
Go–NoGo	Go_Go RT	507.8 (±175.6)	511.8 (±74.9)	$d = 0.37$
	NoGo_Go_RT	N/A	N/A	N/A
	Go_Go ACC	92.0 (±10.4)	94.9 (±6.1)	$d = 0.32$
	NoGo_NoGo_ACC	71.8 (±27.2)	75.9 (±14.7)	$d = 0.20$
	Go false alarms	2.1 (±2.4)	3.7 (±4.4)	$d = 0.45$
	NoGo false alarms*	4.8 (±2.8)	13.5 (±16.7)	$d = 0.73$
	Go d'	3.3 (±1.0)	3.6 (±0.8)	$d = 0.36$
	NoGo d'	2.0 (±1.0)	2.6 (±10.7)	$d = 0.61$

Note: Values in RT rows are in milliseconds and values in ACC are percentages.

* A significant difference of $p < .05$.

3.2.1. N-back task

Analyses revealed an effect of group, $F(1,28) = 4.92$, $p < .04$, $\eta^2 = .58$, indicating that across trial types and conditions, children with a history of concussion responded less accurately ($m = 77.0\% \pm 11.1$) than children in the control group ($m = 82.8\% \pm 12.2\%$). Analyses of d' scores also revealed a main effect of group, $F(1,28) = 4.55$, $p = .04$, $\eta^2 = .54$, and planned comparisons revealed an effect of group for the 2-back condition ($t(28) = 2.6$, $p < .02$; concussion history $m = 1.4z \pm .7z$; control $m = 2.1z \pm .4z$), indicating that children with a history of concussion experienced a deficit in discriminating target from non-target stimuli when working memory demands were at their greatest. Further, a negative correlation between age at injury, and d' scores for the 2-back condition, $r = .46$, $p = .02$, indicated that children who incurred injury earlier in life experienced a greater discriminability deficit.

3.2.2. Switch task

Analyses of accuracy revealed a group effect for global-switch cost, $t(28) = 2.50$, $p = .02$, indicating that children with a history of concussion experienced a greater performance decrement ($m = 20.6\% \pm 9.7\%$) when required to switch from the single- to the mixed rule-set condition of the task, relative to children in the control group ($m = 13.8\% \pm 6.4\%$). Analyses also revealed a group effect for working memory cost, $t(28) = 2.1$, $p = .05$, indicating that children with a history of concussion ($m = 18.5\% \pm 9.7\%$) experienced a greater performance decrement when asked to maintain multiple rule sets in working memory, relative to children in the control group ($m = 12.3\% \pm 6.3\%$). Lastly, a negative correlation between age at injury and commission errors for the heterogeneous condition of the task, $r = .51$, $p = .05$, indicated that children whom were injured earlier in life committed more errors when cognitive control requirements increased.

3.2.3. Go–NoGo task

Analyses revealed a group effect for commission errors during the NoGo condition of the task, $t(28) \geq 2.00$, $p = .05$, indicating that children with a history of concussion ($m = 13.5\% \pm 16.7\%$) exhibited greater false alarms when inhibitory requirements increased, relative to children in the control group ($m = 4.8\% \pm 2.8\%$). Further, a negative correlation was observed for age at injury and false alarms during the NoGo condition of the task, $r = .52$, $p = .04$, indicating that children whom were injured earlier in life exhibited the greatest impulsivity.

Neuroelectric data are presented in Figs. 3 and 4.

3.3. Switch task

3.3.1. N1

Analyses revealed a group effect for amplitude, $F(1,28) = 4.20$, $p = .05$, $\eta^2 = .51$, indicating that children with a history of concussion ($m = -4.9\ \mu\nu \pm 4.9\ \mu\nu$) exhibited smaller N1 amplitude across task

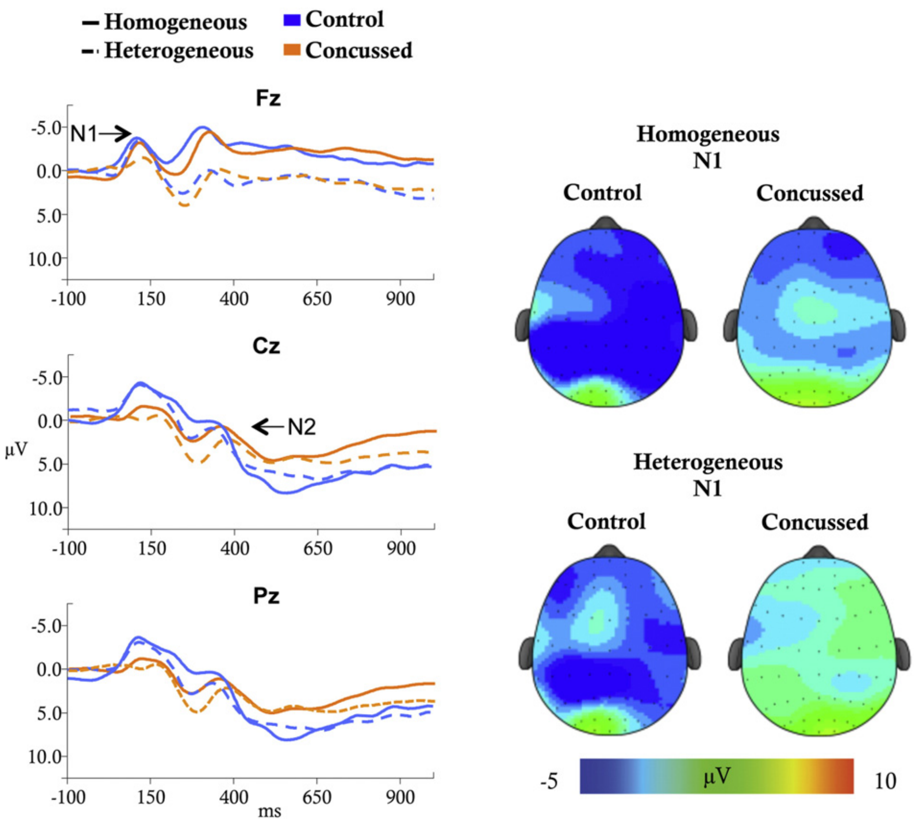

Fig. 3. Participants' ERP waveforms and topographic plots for the Go–NoGo task.

conditions, relative to children in the control group ($m = -8.7\ \mu v \pm 7.4\ \mu v$). Thus, children with a history of concussion evidenced a generalized deficit in the processing of task-relevant stimulus features.

3.3.2. N2

Analyses revealed a group effect for latency, $F(1,28) = 4.71$, $p = .04$, $\eta^2 = .14$, indicating that children with a history of concussion exhibited prolonged conflict resolution across task conditions. However, a group × condition interaction was also observed, $F(1,28) = 13.01$, $p < .01$, $\eta^2 \le .32$, and post-hoc testing revealed that group differences were largest during the homogeneous condition of the task (control: $m = 255.1$ ms ± 40.9 ms; concussion: $m = 302.0$ ms ± 44.4 ms; $t(29) = 4.94$, $p < .01$), which was counter to a priori predictions.

3.4. Go–NoGo task

3.4.1. N1

Analyses revealed a group trend for amplitude, $F(1,28) = 3.27$, $p = .06$, $\eta^2 = .12$, suggesting that children with a history of concussion ($m = -4.5\ \mu v \pm 3.4\ \mu v$) trended towards smaller N1 amplitude for both targets (Go–Go) and non-target (NoGo–NoGo) stimuli, relative to children without a history of concussion ($m = -7.1\ \mu v \pm 3.7\ \mu v$).

3.4.2. N2

Analyses revealed a group trend for latency, $F(1,28) = 3.00$, $p = .09$, $\eta^2 = .01$, suggesting that children with a history of concussion ($m = 315.1$ ms ± 32.6 ms) trended towards prolonged conflict resolution across both conditions of the task, relative to children in the control group ($m = 299.2$ ms ± 35.3 ms).

3.4.3. P3

Analyses revealed a group effect for amplitude, $F(1,28) = 4.67$ $p = .04$, $\eta^2 = .14$, indicating that children with a history of concussion exhibited smaller P3 amplitude ($m = 8.1\ \mu v \pm 5.5\ \mu v$) for both target and non-target stimuli, relative to children in the control group ($m = 14.0\ \mu v \pm 11.0\ \mu v$). Thus, children with a history of concussion were less able to allocate attentional resources during target detection and response inhibition.

4. Discussion

The current study sought to evaluate the persistent influence of sport-related concussion on pediatric neurocognition. Although matched on key demographic factors, children with a history of concussion exhibited behavioral deficits in attention, working memory and impulse control, as well as neuroelectric differences in visual attention (N1), conflict resolution (N2) and attentional resource allocation (P3). Neither time since injury, nor loss of consciousness was related to behavioral or neuroelectric function; however, similar to prior research (Anderson et al., 2005; Hessen et al., 2007; Hessen et al., 2006; Moore et al., 2015; Satz et al., 1997) age at injury was related to the magnitude of several behavioral deficits. Accordingly, a single concussive incident during childhood ($m = 2.1$ years prior to testing) is associated with subtle, yet pervasive alterations in behavioral and neural indices of attention and executive control, and age at injury may moderate injury outcomes.

Although traditionally it was believed that pediatric brain injuries were offset by physiological and adaptive factors, which served to increase tolerance and diminish recovery time (Browne and Lam, 2006; Kirkwood et al., 2006) a growing body of literature suggests that the immature brain is unique in its vulnerability to injury, rather than more resilient (Anderson et al., 2005; Baillargeon et al., 2012; Daneshvar et al., 2011; Giza and Prins, 2006; Prins and Giza, 2012). With regard to neurocognition, the protracted development of frontal brain areas in terms of myelination, connectivity, and density appears to lead to more extensive white and gray matter abnormalities following brain injury in developing populations (Giza and Prins, 2006; Prins and Giza, 2012). Therefore, a concussive insult incurred before or during "sensitive" developmental periods may alter or impair the developmental trajectory of a particular function or set of neurocognitive functions (Baillargeon et al., 2012; Crowe et al., 2012; Hessen et al., 2007; Moore et al., 2015; Satz et al., 1997). As attention and executive functions, and the neural architecture supporting them, develop and differentiate through adolescence (Luna, 2009; Rueda et al., 2004), a concussive injury may impede the 'typical' development, differentiation, and integration of these processes. In support of this assertion, children with a history of concussion in the current study exhibited multifaceted deficits in attention and executive functions.

4.1. Behavior

Children with a history of concussion exhibited both an overall decrease in response accuracy and discriminability (d') during the n-back task, as well as a selective deficit in discriminating between target and non-target stimuli (d') during the 2-back condition. Furthermore, children injured earlier in life exhibited the greatest discriminability deficit. These results are indicative of a general deficit in sustained attention punctuated by a specific deficit in the ability to discriminate between target and non-target stimuli during increasing working memory demands (2-back). Recent research evaluating children and adolescents observed a similar pattern of results during an externally-ordered working memory task during the post-acute phase of injury ($m = 41$ days; Keightley et al., 2014), and Moore et al. (2015) observed persistent and multifaceted deficits in sustaining attention during an executive control (flanker) task. Furthermore, a recent evaluation of concussed adults (Ozen et al., 2013) revealed persistent alterations in P3 component values during the 2-back condition of an N-back task. Therefore, irrespective of age, concussive injuries appear to negatively influence the ability to coordinate and modulate attention and working memory resources in accordance with task demands.

Similar to prior adolescent and adult concussion studies (Howell et al., 2013; Mayr et al., 2014; Moore et al., 2014), children with a history of concussion exhibited deficits during the switch task. Specifically, children exhibited greater global switch and working memory costs and children injured earlier in life exhibited the greatest costs. Compared to homogeneous conditions, which require control of a single rule set, heterogeneous conditions require sustained attention and executive control (Kiesel et al., 2010) in order to execute a correct response while holding multiple rule sets in the contents of working memory. Accordingly, heterogeneous relative to homogeneous conditions require greater working memory to maintain multiple rule sets in a state of readiness to track stimuli sequences (Monsell, 2003). Therefore similar to the n-back task, children with a history of concussion also exhibited a generalized deficit in sustained attention during increasing cognitive demands (global switch cost), punctuated by a specific deficit in working memory (working memory cost). Given the persistent nature of sustained attention and working memory deficits observed here and in prior research (Keightley et al., 2014; Moore et al., 2015), clinicians and researchers should diligently assess the long-term outcomes of these functions following pediatric concussion.

Children with a history of concussion also exhibited deficits in inhibition/impulse control, as indexed by increased false alarms during the NoGo condition of the Go–NoGo task. Again, children injured earlier in life exhibited the greatest impulsivity. The current results complement those of Ornstein et al. (2013), which together suggest that irrespective of severity and etiology, a brain injury incurred during development

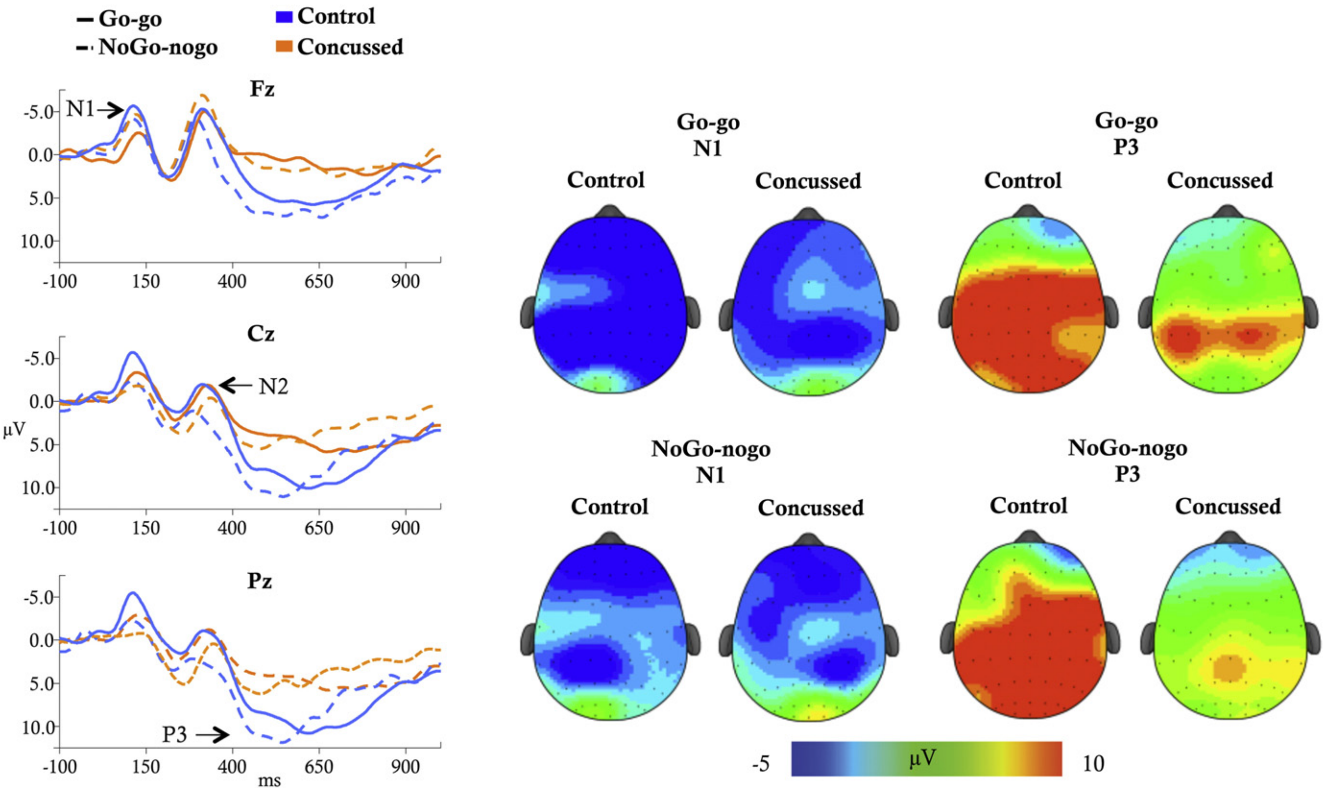

Fig. 4. Participants' ERP waveforms and topographic plots for the switch task.

may have a long lasting influence on impulse control. Given that impulse control is critical to the development of self-regulated behavior (Hoffman and Schraw, 2009), and inhibitory deficits are key factors mediating scholastic, vocational and social difficulties (Diamond, 2013; Luna, 2009), these deficits may manifest in a variety of settings (e.g., school and vocational); reaffirming the pressing need for further long-term evaluations of inhibition/impulse control in children with a history of concussion.

4.2. ERPs

Children with a history of concussion also exhibited multiple neuroelectric alterations during the switch and Go–NoGo tasks, including decreased N1 amplitude across conditions during the switch task and a trend towards decreased N1 amplitude across conditions during the Go–NoGo task. Similar to children with more severe brain injuries (Kaufmann et al., 1993; Max et al., 1999) children with a history concussion appear to have failed to adequately bias perceptual attention, irrespective of task demands. Accordingly, children with a history of concussion also exhibited longer N2 latency across conditions of the switch task, and trended towards exhibiting longer N2 latency across conditions during the Go–NoGo task. Thus, similar to prior child (Moore et al., 2015) and adult concussion studies (Larson et al., 2012; Moore et al., 2014), children with a history of concussion experienced altered stimulus–response conflict during tasks requiring executive control. Contrary to our predictions, however, these findings suggest that pediatric concussion is associated with global alterations in neuroelectric function. This general pattern may be due to deficits in perceptual processing, as the duration of stimulus–response conflict mirrored the magnitude of N1 alterations. Thus, as previously noted in child and adult brain injury studies (Kaufmann et al., 1993; Moore et al., 2014; Moore et al., 2015), alterations in perceptual processing may contribute to upper-level neurocognitive alterations.

Likewise, children with a history of concussion exhibited decreased P3 amplitude across conditions during the Go–NoGo task. Prior pediatric studies also observed persistent reductions in P3 amplitude during visual discrimination and flanker performance (Baillargeon et al., 2012; Moore et al., 2015). However, the P3 observed during the Go–NoGo task may be subdivided into two sub-components, the target (Go–Go) and non-target (NoGo–NoGo) P3. The P3 observed during Go–Go (target) trials, like the traditional P3b (elicited during visual discrimination and flanker tasks), is believed to reflect the allocation of attentional resources during stimulus engagement (Beste et al., 2010; Polich, 2007). The P3 observed during NoGo–NoGo (non-target) trials, however, is believed to reflect the monitoring or outcome of motor inhibition (Beste et al., 2010; Smith et al., 2010). As such, pediatric concussion may lead to multiple distinct deficits in the neuroelectric underpinnings of attentional and evaluative processes during impulse control.

Despite the differences observed during the Go–NoGo task, no group differences were observed for the P3 component during the switch task. Although perplexing, this discrepancy may reflect the heterogeneous nature of concussive injuries or maturational factors, as persistent reductions in P3 amplitude have been observed during switch tasks in young adults (Moore et al., 2014). Furthermore, switching paradigms are known to lead to variable and dampened P3 waveforms (Gajewski and Falkenstein, 2013). As such, the combination of injury variables, maturational factors and task parameters may have dampened group differences in P3 amplitude during the switch task. Future concussion research should be diligent in addressing these issues to optimize validity and interpretability of results.

4.3. Conclusions and limitations

In sum, relative to rigorously matched control children, children who were on average more than two years from a single concussive event exhibited deficits on the behavioral and neural levels. Furthermore, age at injury related to the magnitude of behavioral deficits. It should be noted that the current results are in contrast to longitudinal clinical trials (Jaffe et al., 1993; Satz et al., 1997; Yeates and Taylor, 2005), which found relatively good outcomes following pediatric concussions of non-sport or mixed etiologies. However, none of these studies employed any measure of brain function or experimental measures of cognition, which have proven invaluable for detecting and delineating persistent neurocognitive alterations in children, adolescents and adults, long after the clinical presentation of symptom resolve (Baillargeon et al., 2012; De Beaumont et al., 2007; Hung et al., 2014; Keightley et al., 2012; Moore et al., 2014; Moore et al., 2015; Sloburnov et al., 2002; Theriault et al., 2009; Thompson et al., 2005). Further, even studies and reviews reporting relatively good outcomes following mild brain injuries frequently suggest that children injured earlier in life may experience worse outcomes (Anderson et al., 2005; Hessen et al., 2007; Kirkwood and Yeates, 2012; Satz et al., 1997). As such, the combination of highly sensitive measures of brain and cognitive function and early injury age ($m = 7.1$ years) may account for current deficits being more pervasive than expected based on prior clinical assessments.

Although the current study is characterized by several strengths, including rigorous matching and multimodal neurocognitive assessment, it is not without limitations. Specifically, the cross-sectional design and relatively small sample size of the current investigation limits the ability to make causal statements, and although the current investigation represents one of the most rigorously matched concussion studies to date, it is possible that some unmeasured variable contributed to group differences in behavioral or neuroelectric function. Furthermore, the participants were a referred sample and children with abnormal recovery may be more likely to be referred or seek participation in research. However, this is unlikely to be the case given that participants were symptom-free at testing. That being said, concussion checklists are relatively coarse and it is possible that some unmeasured psychological difference (stress, anxiety, etc.) is contributing to the current results. Future research may mitigate these factors by including orthopedic controls and more comprehensive psycho-affective assessments. Also, participants were of relatively high intelligence and socioeconomic status, which may have biased injury outcomes and limited generalizability. Again, the influence of these variables is likely minimal given the demographic similarity between participants and the convergent pattern of neurocognitive deficits exhibited across concussed participants. Irrespective of limitations, the current findings add important information regarding the nature, breadth, and duration of neurocognitive deficits stemming from pediatric concussion and provide an impetus for future research.

Conflict of interest

The authors declare that no conflict of interest exists.

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