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Neuropsychological and neurophysiological assessment of sport concussion in children, adolescents and adults

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Abstract

Objective: To determine whether age differences exist with respect to neuropsychological and electrophysiological functioning following a sport concussion.
Design: Cross-sectional study.
Participants: Ninety-six athletes (9–12 years, $n = 32$; 13–16 years, $n = 34$; adults, $n = 30$), half of whom had a sport concussion.
Intervention: Cognitive functioning was assessed using standardized neuropsychological tests and event-related potentials elicited by a visual 3-stimulus oddball paradigm. The PCSS was used to assess symptoms experienced at the time of injury.
Main outcome measurements: Neuropsychological assessment with an adaptation of the battery used by the National Hockey League. Latencies and amplitudes of the P3a and P3b were analysed in terms of group (concussed vs. control) and age.
Results: All concussed athletes had significantly lower amplitude for the P3b component compared to their non-injured teammates ($p > 0.05$). Adolescents also showed persistent deficits in working memory ($p > 0.05$).
Conclusions: These data suggest persistent neurophysiological deficits that are present at least 6 months following a concussion. Moreover, adolescents are more sensitive to the consequences of concussions than are children or adults.

Keywords: *Sport concussion, event-related potentials, neuropsychology, children*

Introduction

A sport concussion is defined as a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces [1]. It occurs when a direct or indirect blow to the head results in the alteration of mental status, whether or not this is accompanied by loss of consciousness [2]. Studies with university and professional athletes show significant impairments in memory, attention, executive functions and information processing speed immediately following a concussion [3–6], that usually resolve within 7–10 days [6–11]. The incidence of concussion among high school athletes is estimated between 3–6% [12–14] and the proportion of concussion to the total number of injuries is nearly twice as important in high school compared to college athletes [12]. However, more than 50% of high school athletes who are concussed fail to report their injury, either because they do not recognize it or to avoid being removed from the sporting competition [15].

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The consequences of a concussion appear more serious in younger athletes. Compared to college and professional athletes, high school athletes have more severe cognitive sequelae immediately after injury and present a more protracted recovery [16]. When compared to a pre-season baseline, immediately following a concussion, high school athletes have greater deficits in memory than collegiate athletes. Further, they are still worse than their baseline 7 days after the injury, whilst college athletes recover within 3 days [16].

Event-related potentials (ERPs), a sensitive measure of subtle changes in brain activity after a concussion [17–22], are averaged electrical brain responses that are time-locked to the presentation of a stimulus during a cognitive task. Most of the literature in sport concussion investigated the modulation of the P3b component evoked by an oddball task. The P3b is a positive potential with maximum amplitude in the parietal region and it usually appears 300–700 ms after stimulus onset [23]. In addition to the P3b component, the P3a is elicited by infrequent and novel stimuli. The P3a is characterized by a shorter latency than the P3b and is generally largest over the frontal and central brain areas [23, 24], but some studies found maximum amplitude over the central/parietal areas [25, 26]. P3a is thought to reflect the orientation of attention [27]. Adult athletes who sustained a concussion experience a reduction in the amplitude of the P3b [17, 18, 20, 21], indicating that fewer attentional resources are allocated to updating the contents of the working memory. Only one study investigated the impact of a sport concussion in children with electrophysiology [28]. This longitudinal study of an 8-year-old girl found that, although neuropsychological impairments resolved 22 weeks post-injury, persistent electrophysiological deficits were present up to 1 year after injury.

Although sport concussions are more prevalent in children than in adults, most research has been directed towards collegiate and professional athletes. The literature on sport concussion with younger groups mainly comes from high school athletes and little to nothing is known about the outcome of a sport concussion in children. The aim of the present study was to determine whether age differences exist with respect to cognitive outcome following a sport concussion. This cross-sectional study assessed cognitive functioning using standardized neuropsychological tests as well as ERPs in children, adolescents and adults who sustained a sport concussion. Specifically, three distinct age groups were included in the study. Adolescents aged between 13–16 years were selected because previous studies suggest that this age group is more vulnerable to concussion than adults [16] and children aged between 9–12 years were included because practically nothing is known about the consequences of sport concussion on pre-adolescents. Given that adolescent athletes demonstrate greater deficits and slower recovery, it is hypothesized that, following a sport concussion, the younger participants will present more severe deficits when compared with the older groups. Specifically, the children will have more severe deficits compared with the adolescents and adults and the adolescents will in turn have more severe deficits than the adults.

Methodology

Participants

A total of 96 male athletes were included. Athletes were divided into three age groups (9–12 years, $n = 32$; 13–16 years, $n = 34$; adults, $n = 30$), half of whom suffered from a sport concussion. Athletes were soccer, hockey, rugby and football players from competitive level amateur leagues. They were referred to the study by the team coaches or medical personnel. It has been suggested that outcome after a concussion may vary based on gender [29, 30]. To obtain an homogenous sample, this study investigated male athletes only. Concussions were identified and diagnosed by a specialized health professional at the time of injury. The control athletes never suffered a concussion. All participants had normal or corrected-to-normal vision and none reported a history of learning disabilities, attention-deficit disorder, neurological or psychiatric disorder, alcohol/substance abuse or a history of traumatic brain injury unrelated to contact sport. The study was approved by the ethics committee of the University of...... Informed consent was obtained from all athletes as well as from the parents of the participants who were under 18 years of age. All participants were made aware of the purpose of the study and the specific procedures before providing their consent.

All athletes sustained a concussion[1] in the year preceding testing and each participant was asymptomatic at the time of assessment. The athletes either practiced their sport at the time of the study or they were in their off season. All teams had a return-to-play protocol that allowed the athletes to reintegrate the game only when they no longer reported symptoms under conditions of physical exertion. To maintain sample homogeneity of the concussed groups, time elapsed since the last concussion averaged 6 months for each age group (9–12 years, $M = 5.8 \pm 3.9$; 13–16 years, $M = 5.8 \pm 4.1$; adults, $M = 6.3 \pm 3.5$). The time elapsed since the last concussion was less than 1 year and the number of concussions sustained was no more than two

Table I. Demographic profile of the participants.

		Participants					
		n	Age (years)	Years playing sport	Education (years)	# Concussion sustained	Time since last concussion (months)
Concussed group	9–12 years	16	11 ± 1.2	3.8 ± 1.3	4.9 ± 1.2	1.3 ± .5	5.8 ± 3.9
	13–16 years	17	14.8 ± 1.1	5.5 ± 3.5	8.8 ± 1.1	1.6 ± .7	5.8 ± 4.1
	Adults	15	23.3 ± 3.3	12.4 ± 4.8	16.2 ± 2.2	1.5 ± .8	6.3 ± 3.5
Control group	9–12 years	16	10.5 ± 1.2	4 ± 1.6	4.6 ± 1.3	–	–
	13–16 years	17	14.2 ± 1.0	3.9 ± 1.9	8.1 ± 1.2	–	–
	Adults	15	23.4 ± 2.1	12.7 ± 5.4	16.1 ± 1.4	–	–

Values are given as mean ± standard deviation.

(see Table I). The inclusion criteria for the concussed group were based on the consensus reached at the Third International Conference on concussion in Sport [1] and the guidelines of the American Academy of Neurology [2]. Symptom intensity was assessed with the Post-Concussion Symptoms Scale (PCSS) [31]. This scale comprises 21 symptoms that are susceptible to be reported following a sport concussion and each is assessed by the athlete on an intensity scale that ranges from 0–6 (0 = no symptoms, 3 = moderate, 6 = severe).

Neuropsychological assessment

Participants underwent a neuropsychological assessment with the testing battery used by the National Hockey League [31] to which was added the Brown-Peterson test, a sensitive measure of traumatic brain injury. These tests are known marker tasks for different cognitive functions and have been used in previous studies to identify the cognitive sequelae associated with a sport concussion [32, 33]. When necessary, tests were used that had versions that were specifically adapted to age and in other instances the tests used were appropriate for all age groups tested. The neuropsychological testing took place in a quiet environment and the procedure lasted ~40 minutes. The order of testing was randomized across participants to avoid any practice effects. The tests used are presented below.

- *Symbol Digit Modalities Test* (SDMT). This task assesses visuo-motor speed. Using a reference key, participants had 90 seconds to transcribe numbers in order to pair them correctly with geometric symbols. The dependent measure is the total number of items completed correctly.
- *Hopkins Verbal Learning Test-Revised* (HVLT-R). This task assesses verbal memory and learning. Participants heard a list of 12 words, presented three times in a row, and after each presentation they were asked to provide an immediate recall. Without any further presentation or warning, participants were asked to recall the words from the list 20 minutes after the last recall (delayed recall). The two dependent measures are the total number of words produced during the first three immediate recalls (providing a measure of learning) and the total number of words reported during the delayed recall (providing a measure of long-term memory).
- *Brief Visuospatial Memory Test-Revised* (BVMT-R). This task assesses visuospatial memory and learning. Participants were presented with six abstract figures on a page, presented three times in a row. After each presentation they were asked to provide an immediate recall (i.e. to draw as many figures as possible at their location on the page). Without any further presentation or warning, participants were asked to recall the figures from the list 20 minutes after the last recall (delayed recall). The two dependent measures are the total number of figures produced during the first three immediate recalls (providing a measure of learning) and the total number of figures produced during the delayed recall (providing a measure of long-term memory).
- *Colour Trails*. This task assesses speed of attention, sequencing and mental flexibility. Age-appropriate versions of this task were used. In the experimental condition participants were presented with an 8 × 11 sheet that showed numbers from 1–25 (15 for children) twice, once in yellow and once in pink. The task required participants to link numbers using a pencil according to their incremental order, but alternating from yellow to pink. The baseline version simply required participants to link numbers without regards to the colour scheme. The dependent variable is the time taken to correctly complete each of the two conditions.
- *Pennsylvania State University Cancellation Task* (PSU). This task assesses information processing speed and selective visual attention. Participants were presented with a 40 × 20 grid of abstract

symbols on a single 8 × 11 sheet of paper and they were asked to strike as many symbols as they could during a period of 90 seconds that correspond to a target symbol. The dependent measure is the number of symbols that are correctly identified.

- *Brown-Peterson test*. This task assesses mental manipulation of content held within short-term memory (i.e. working memory). Age-appropriate versions of this task were used. The participants were asked to count backwards by 3 (adults and teenagers) or by 1 (children) after hearing a set of three consonants. They were then asked to recall the trigram after a time lapse of 0–30 seconds. The dependent variable is the total number of consonants correctly recalled.
- *Controlled Oral Word Association Test* (COWAT). This test, which provides a measure of word retrieval and word fluency, assesses another aspect of frontal lobe functioning. In this task participants had 60 seconds to say as many words as they could think of that began with a given letter. This task was repeated with three letters (each participant was presented with the same set of letters). The dependent variable is the total number of correct words produced, minus any repetitions (perseverations).

ERP stimuli and procedure

The visual oddball task consisted of three white rectangles (2.5 cm × 8.5 cm) on a black background. Participants had to make a perceptual discrimination among a randomly and frequently occurring vertical line (76%), an infrequent target with a slight tilt (12%) and an infrequent non-target horizontal line (12%) [34]. The results of pilot testing determined that accuracy (i.e. hits/false alarms) was similar for the three age groups when for the 9–12 year olds the target had a 3° tilt, for the 13–16 year olds the target had a 2.5° tilt and for the adults it had a tilt of 2°. The stimuli were presented at the centre of the screen, their duration was 70 ms and inter-stimulus intervals varied randomly between 1600–2000 ms.

All recordings were performed in an electromagnetic isolated (Faraday) and soundproof chamber. The participants were instructed to fixate the centre of the screen, to remain still, to blink as little as possible and to press a key with their dominant hand as soon as they perceived the target. A brief training (15 trials) was run to ensure that each participant understood the task and was able to accurately discriminate the target from the standard stimulus. The task consisted of three blocks of 169 trials each and lasted 18 minutes.

EEG recording

EEGs were measured using the Geodesic Sensor Net^{TM} (GSN) (Electrical Geodesic System Inc., Eugene, OR) consisting of 128 sponges. Before the installation of the net, sponges were soaked in a saline solution and Nuprep gel (Nuprep, Weaver & Co., Aurora, CO) was applied on the scalp of the subjects with an alcohol pad (PDI) to reduce skin impedance. Electrode impedance was kept below 50 kΩ and each electrode was referenced to Cz. EEG signal was amplified with Net Amps 200 amplifier and analogue bandpass filtered from 0.1–100 Hz. The signal was digitized at 250 Hz and recording was done with Net Station software. A G4 Macintosh computer controlled data acquisition.

ERP calculation

Offline analyses were performed with Brain Vision Analyser 1.05 software (Brain Products GmbH, Munich, Germany). Data were digitally filtered with a 0.1–30 Hz (24 dB/octave) bandpass. Eye movement artifacts were corrected using Gratton and Coles algorithm [35]. Data were re-referenced to average mastoids and semi-automatic artifact rejections of voltage exceeding ±100 μV were performed [36]. Before averaging, segments containing EEGs with incorrect responses or with a reaction time ±2.5 SD from the mean were rejected. The EEG was segmented in 1400 ms epochs, was averaged after artifact rejection and baseline corrected based on the mean amplitude of the activity recorded 200 ms before stimulus onset. Topographic maps were used to determine the sites of maximum amplitude for each age group. The P3a was obtained by averaging at central and parietal sites (Cz, Pz), whilst the P3b was computed by averaging at centro-parietal and parietal sites (CPz, Pz). P3a peaks were detected semi-automatically by identifying the maximum positive deflection within a time-window of 250–450 ms for 9–12 and 13–16 year olds and 220–420 ms for adults. P3b peaks were defined as the maximum amplitude occurring within 400–900 ms for 9–12 year olds, 350–800 ms for 13–16 year olds and 300–700 ms for adults [26].

Statistical analyses

For each age group, differences related to participant characteristics were compared by a series of *t*-tests with group (concussed and control) as a factor. Separate analyses were conducted for each neuropsychological test and for the reaction time and accuracy data from the Oddball task, using a series of two-way ANOVAs with age (9–12, 13–16 and adults) and group (concussion and control) as factors. A Benjamini-Hochberg correction was applied because of multiple comparisons. Effect sizes for significant ANOVAs were estimated by calculating a partial eta-squared and, for simple effects, they were estimated using Cohen's d statistic. Latencies and amplitudes for P3a and P3b components were submitted to a 3 (Age) × 2 (Group) ANOVA. Simple effect analyses were performed to decompose any interaction. When the ANOVAs revealed a main effect of concussion, linear regressions were calculated to investigate the nature of the relationship between P3 and the post-concussion symptoms. Statistical analyses were performed with SPSS 16.0.

Results

Participant characteristics

A series of t-tests that were performed between the control group and the concussion group for each age group did not reveal any significant difference regarding age ($ps > 0.05$), level of education ($ps > 0.05$) and the number of years practicing a sport ($ps > 0.05$). A series of one-way ANOVAs performed with the concussed athletes with age as factor revealed that the three age groups did not differ according to the time since the last concussion ($p > 0.05$), the number of concussions sustained ($p > 0.05$) and the number of symptoms experienced ($p > 0.05$).

Neuropsychological results

Results for the neuropsychological tests are presented in Table II. Specifically, no significant difference was found between the concussed and non-concussed athletes and that for each age category, for the following measures: SDMT, BVMT-R, HVLT-R, Colour Trails, PSU and the COWAT ($ps > 0.05$). A Group × Age interaction was found for the total number of items recalled on the Brown Peterson test ($F(2, 90) = 3.83$, $p < 0.05$). Tests of simple effects of the interaction indicate a significant difference between the adolescent concussed and the adolescent control group ($F(1, 90) = 4, 39$, $p < 0.05$). Adolescents who sustained a concussion ($M = 46.0$; $SD = 3.8$) recalled significantly fewer items than their non-concussed counterparts ($M = 49.6$; $SD = 3.4$), $t(32) = 2.10$, $p < 0.05$, $d = 1.06$.

ERP task performance

There was no significant difference between the concussed and the control groups for RT ($p > 0.05$), although there was a significant main effect of age ($F(2, 95) = 10{,}768$, $p < 0.001$, $\eta_p^2 = 0.99$). As expected, adults were faster than children and adolescents to press the response key. The participants who underwent a concussion were as accurate as those from the control group ($ps > 0.05$). The analysis did not reveal a main effect of age ($p > 0.05$), confirming that behavioural performance was equivalent for the three age groups and that the task was correctly equated for difficulty.

Electrophysiological results

Latency. Figures 1 and 2 depict the grand averaged ERPs elicited by the target (P3b component) and the

Table II. Neuropsychological tests results for children, adolescents and adults.

	9–12 years		13–16 years		Adults			
	Control	Concussed	Control	Concussed	Control	Concussed	F	p
SDMT								
Total	39.1 ± 10.9	40.5 ± 7.5	53.0 ± 8.1	58.9 ± 13.2	62.7 ± 7.7	62.2 ± 12.4	0.825	0.44
HVLT								
Total	23.1 ± 4.1	24.6 ± 3.9	27.5 ± 3.3	28.5 ± 3.5	27.9 ± 4.1	27.8 ± 3.2	0.427	0.65
Delayed	8.2 ± 2.5	7.7 ± 2.7	9.9 ± 2.0	10.0 ± 1.7	10.1 ± 1.6	9.8 ± 1.5	0.192	0.83
BVMT								
Total	27.3 ± 6.6	28.1 ± 3.2	31.9 ± 3.3	29.7 ± 8.6	32.1 ± 2.9	30.9 ± 4.7	0.737	0.48
Delayed	10.8 ± 1.9	11.3 ± 1.0	11.7 ± 0.6	11.6 ± 1.1	11.8 ± 0.4	11.7 ± 0.8	1.002	0.37
PSU								
Total	29.4 ± 9.2	30.7 ± 5.4	39.79 ± 6.9	38.7 ± 5.8	50.1 ± 6.1	48.2 ± 7.4	0.455	0.64
Colour Trail								
T1	21.8 ± 10.4	20.2 ± 5.1	18.0 ± 7.6	18.7 ± 7.7	25.2 ± 10.3	25.3 ± 7.9	0.177	0.84
T2	44.7 ± 15.7	41.3 ± 8.9	32.7 ± 12.9	33.1 ± 6.3	50.6 ± 11.6	52.1 ± 13.4	0.367	0.69
Brown								
Total	40.4 ± 4.1	43.0 ± 3.7	49.2 ± 2.9	46.0 ± 3.8*	53.8 ± 4.9	52.1 ± 6.6	3.885	0.04
COWAT								
Total	20.3 ± 6.9	19.5 ± 6.2	32.3 ± 9.4	29.5 ± 8.9	41.7 ± 12.1	39.1 ± 10.5	0.127	0.88

Values are given as mean ± standard deviation.
*$p < 0.05$ represents significant mean difference only for the group of 13–16 year old athletes.

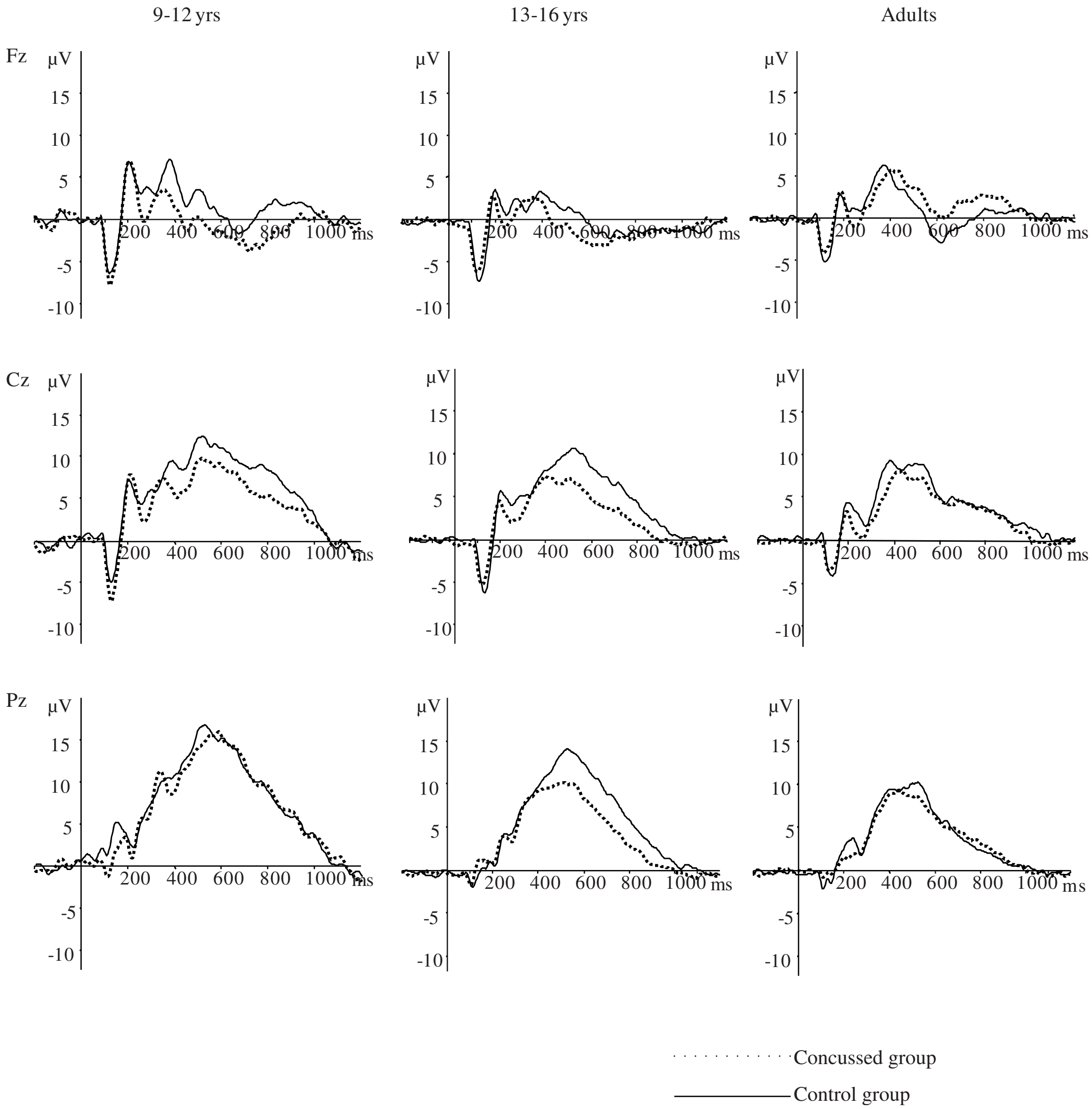

Figure 1. Grand average ERP waveforms in response to the infrequent target stimulus (P3b) recorded at Fz, Cz and Pz for children, adolescents and adults. The concussed group exhibited a reduction in the amplitude of the P3b compared to the control group. The solid lines represent ERP waveforms for the control group and the dashed lines present the ERP curves for the concussed group. Regardless of age, participants who sustained a concussion had a significant reduction in amplitude compared with the control group.

non-target (P3a component). The ANOVA on the P3b latency yielded no significant interaction between group and age ($p > 0.05$). As expected, a significant main effect of age was found ($F(2, 96) = 10{,}864$, $p < 0.001$, $\eta_p^2 = 0.54$). The between-group comparisons computed for the P3a did not reach significance for any of the factors ($p > 0.05$).

Amplitude. As shown in Figure 1, the amplitude of the P3b was lower for all concussed athletes compared with the control groups. Further, concussed adolescents displayed an even lower amplitude of their P3b (24.3% lower than the control group) compared with children (16.8% lower than controls) and adults (12.7% lower than controls). The analysis indicated a main effect of group (concussed/control) for the amplitude of the P3b ($F(2, 96) = 5{,}970$, $p < 0.05$, $\eta_p^2 = 0.99$), whilst no Age × Group interaction was found ($p > 0.05$). Therefore, regardless of age, participants who sustained a concussion had a significant reduction in amplitude compared with the control group. A main effect of age was found ($F(2, 96) = 6{,}800$, $p < 0.05$, $\eta_p^2 = 0.99$), indicating that amplitude changes with age.

As illustrated in Figure 2, the P3a waveform seems similar between the concussed and non-concussed athletes for each age group. The results of the statistical analyses confirm this observation as no

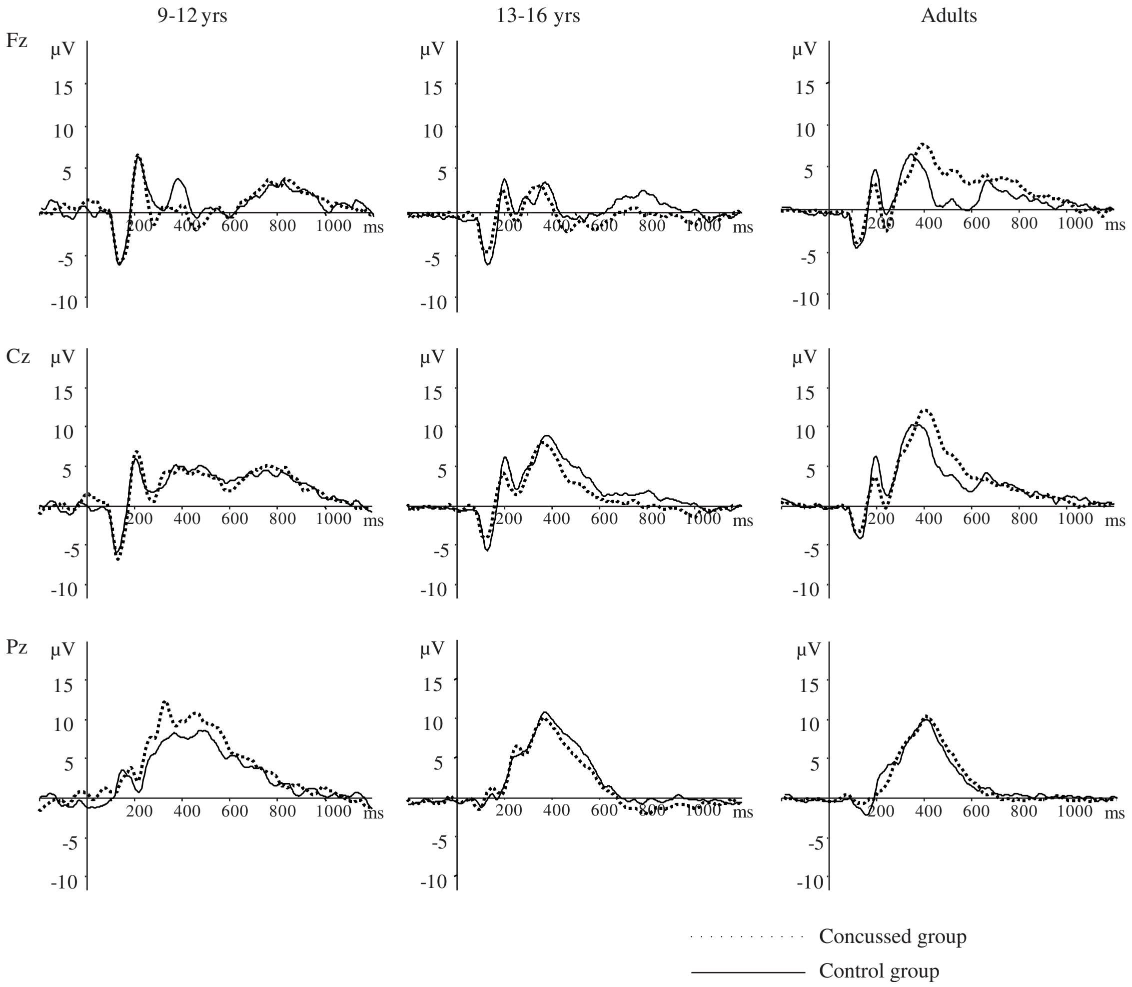

Figure 2. Grand average ERP waveforms in response to the infrequent non-target stimulus (P3a) recorded at Fz, Cz and Pz for children, adolescents and adults. The solid lines represent ERPs waves for the control group and the dashed ones present the ERP curves for the concussed group.

between-group difference was found ($p > 0.05$), nor any main effect regarding age ($p > 0.05$) or group ($p > 0.05$).

Relation between symptoms reported at the time of injury and the P3. A series simple regression analysis revealed a significant negative relationship between the total symptom score and the amplitude of the P3b for the adolescent concussed group ($F(1, 16) = 6.548$, $p < 0.05$, $R^2 = 0.3$), but not for the children ($p > 0.05$) or adults ($p > 0.05$). Specifically, adolescents who experienced more symptoms at the time of injury had a lower amplitude of the P3b at the time of testing ($\beta = -0.6$; $p < 0.05$). Regression analyses were also performed to investigate the relationship between the amplitude of the P3b and the number of concussions sustained in a lifetime. The statistical analyses did not reveal a significant relationship for any of the age groups (ps > 0.05).

Discussion

The aim of the present study was to determine whether age differences exist with respect to cognitive outcome following a concussion. The results indicate that, despite the absence of symptoms at the time of the assessment, concussed athletes, regardless of age, displayed a reduction in the amplitude of the P3b and adolescents had deficits on a standard neuropsychological task assessing working memory.

The amplitude of the P3b component, which is thought to reflect the amount of attentional resources available for the updating of information in working memory [23], was attenuated across all ages in the concussed group. This suggests a failure to efficiently recruit neuronal resources involved in processing the target stimulus. However, no change was found regarding the P3a component, which is thought to reflect the orientation of attention [27]. The differential pattern of deficit could be explained by differences in the complexity of the cognitive processes engaged in each of these components. Specifically, the P3b solicits more attentional resources than the P3a, which involves automatic processes. Therefore, the results suggest that complex neuropsychological processes are more vulnerable to the impact of a sport concussion. The findings of ERP abnormalities in concussed adults, despite normal performance on the standard neuropsychological tests and the absence of symptoms at the moment of the assessment, are consistent with those of previous studies [20, 21]. Using a 3-stimulus visual oddball task, Broglio et al. [21] found a significant reduction in the amplitude of the P3b in a group of concussed athletes without any change in the P3a. Athletes in this study had their injury on average 3 years prior to the evaluation. Similarly, Lavoie et al. [18] found significant reductions in the amplitude of the P3b in a group of asymptomatic concussed athletes who were injured up to 2 years prior to testing.

Children and adolescents who sustained a concussion displayed a reduction in the amplitude of the P3b that was similar to that found for the adults. Even though the group × age interaction of the ANOVA was not significant, the concussed adolescents have a greater reduction in the amplitude of the P3b (24.3%) compared to the children (16.8%) and adults (12.7%). Moreover, the adolescents were the only group that presented deficits in working memory as assessed by means of a neuropsychological task.

As proposed by Ellemberg et al. [32], the normal results on the neuropsychological tests in the light of persisting neurophysiological deficits suggest that recovery following a concussion could take place in two phases. Specifically, following a head injury there might be an initial and rapid phase of functional recovery in which compensatory mechanisms (adoption of new strategies and/or functional reorganization via brain plasticity) allow the athletes to perform normally on standard clinical assessments. This period could then be followed by a prolonged neuronal recovery during which subtle deficits in brain functioning are present but not apparent with standard clinical assessment tools. Although the implications of these changes in everyday life are not yet known, ERPs are a highly sensitive measure of subtle neurofunctional deficits that do not seem to be detectable by other behavioural methods.

The present findings do not support the hypothesis that the children have more severe deficits compared with the older participants. The concussed children had a similar pattern of deficits to that of the concussed adults. Like adults, participants aged 9–12 years did not show any cognitive impairment on the neuropsychological assessment battery, but had a significant reduction in the amplitude of the P3b, suggesting that the younger brain is as sensitive as the adult brain to the deleterious effects of a sport-related mild traumatic brain injury. The present findings are inconsistent with several reports of worse outcome in children who suffered from a traumatic brain injury that are not sport-related (e.g. playground accidents, motor vehicle accidents, physical abuse, etc.) [37–41]. However, the children in the aforementioned studies suffered mainly moderate-to-severe traumatic brain injuries. In this study, children sustained a mild brain injury while participating in a sporting activity. Because of the heterogeneity of the sample in the studies assessing paediatric traumatic brain injury it is difficult to compare these findings to their results.

The findings suggest that the adolescents are more vulnerable than children and adults to the deleterious effects of a sport concussion. The adolescents have persisting deficits on the neuropsychological task assessing working memory and present a greater reduction in the amplitude of the P3b, which is also associated with working memory. Moreover, the concussed adolescents were the only group for whom the severity of the self-reported symptoms at the time of injury significantly correlated with the amplitude of the P3b component. However, these results are unlikely to be related to the severity of injury given that there are no differences in the symptoms reported among the different age groups. The greater vulnerability found in this age group could be related to the fact that the frontal part of the brain, responsible for working memory and other executive functions, undergoes its final stages of maturation during adolescence [42–44]. Therefore, it is possible that a blow to the head during this critical period of development could result in more severe deficits for adolescents compared to the other age groups.

Certain factors should be taken into consideration when interpreting the present results. First, because most studies rely to some extent on self-reports, it is possible that athletes under-estimated the number of injuries sustained. However, there is no reason that symptom report was less accurate for the adolescents than it was for the two other age groups. If anything, university athletes might have the greatest motivation to under-estimate the number and severity of injuries. Second, the retrospective design of the present study does not allow one to compare participants to their own baseline. In fact, most if not all studies on non-sport-related traumatic brain injuries have the same retrospective design. This is likely not a concern given that the control groups were well matched for age, years of education, sport-practice and no participant had a history of learning disabilities or other neurological or medical disorders. Third, although some of the tests used were not initially designed to assess children, like the HVLT and the BVMT, they were nonetheless appropriate for all age groups given that they closely correspond to well-known tests specifically designed for children and that data were collected from age-matched non-concussed athletes.

In summary, the results provide evidence that sport concussion may specifically affect working memory processes as revealed by a lower amplitude of the P3b component, a marker of working memory updating, in all age groups. Moreover, adolescents seem more susceptible to display working memory impairments following sport concussion as both their neuropsychological and electrophysiological results suggest deficits in this particular cognitive domain. This is consistent with the hypothesis that sport concussion more likely disrupt frontal lobe functions [33].

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***Declaration of Interest*:** The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

Note

1. As reported in the 3rd Consensus Statement on Concussion in Sport (Zurich, 2008) grading systems of the concussion severity have been abandon because of their non-specificity.

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