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

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ABSTRACT

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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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,