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The Impact of Sports-Related Concussions on the Language System: A Case for Event-Related Brain Potentials

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Abstract

Sports-related Concussions (SRC) and their potential long-term effects are a growing concern among athletes and their families. Research utilizing functional brain imaging/recording techniques (e.g., fMRI, ERP) seeks to explain how neurocognitive brain activity changes in the days and years following SRC. Although language deficits are documented following non-sports related concussion there remains a striking lack of research on how SRCs may influence the language system and their supporting neural mechanisms. Neuroimaging findings, however, demonstrate that SRCs alter structural and functional pathways within the frontotemporal language network. Brain regions included in this network generate language-related event-related brain potentials (ERPs), including the N400 and P600. ERPs have been used to demonstrate long-term neurocognitive alterations associated with concussion and may also provide objective and robust markers of SRC-induced changes to the language system.

Keywords: Sports-related concussion; Traumatic brain injury; Language; ERP

Abbreviations: AF: arcuate fasciculus; CTE: chronic traumatic encephalopathy; DTI: diffusion tensor imaging; ERP : event-related potentials; fMRI: functional magnetic resonance imaging; IOFF: inferior occipito-frontal fasciculus; LAP: Late Anterior Positivity; IFG: inferior frontal gyrus; ITG: inferior temporal gyrus; MTG: middle temporal gyrus; SRC: sports-related concussion; SLF: superior longitudinal fasciculus, TBI: traumatic brain injury; UF: uncinate fasciculus; STG: superior temporal gyrus

Introduction

The potential long-term effects of SRC are a growing concern given the increasing rates across sports [1]. The Center for Disease Control estimates that 1.6-3.8 million sports-related brain injuries occur in the U.S. every year [2]. These incidence rates, however, are likely underestimated given that 43-52% of SRCs may go unreported or undetected [3-6]. SRCs impact a diverse array of outcomes, including mental health symptoms [7-10], postural control [11-14], oculomotor eye movements [15-18], post-concussion symptomatology [19,20], and neuropsychological/cognitive abilities [11,21,22]. The

findings from this research have worked to advance the clinical management of sports-related concussions. However, the results of this review indicate a lack of understanding on if and how SRCs influence speech and language. Findings from functional magnetic resonance imaging (fMRI) and diffusion tensor imaging (DTI), however, demonstrate that SRCs alter neurocognitive mechanisms and white matter pathways within the frontotemporal language network. Investigators have used event-related brain potentials (ERPs) to examine how SRCs influence neurocognitive mechanisms, such as those underlying attention and working memory. Similarly, ERPs can be used as a temporally sensitive,

objective, reliable, and replicable method for examining SRC-related language deficits. An enriched understanding of how SRCs affect the language system will serve to improve the clinical care of the recovering athlete.

Post concussion Language Deficits

This section begins with a clarification of the terms “mild TBI” and “concussion” as they are often incorrectly used interchangeably, which can make comparisons of findings across studies somewhat onerous. Mild TBIs vary in severity, in part, based on the presence (“complicated”) or absence (“uncomplicated”) of abnormal structural neuroimaging findings such as an intracranial hematoma or lesion [23]. Concussions are uncomplicated mild TBIs resulting from a blow to the head, neck or body [24] and may occur either during sport (e.g., head-to-head contact) or non-sporting events (e.g., motor vehicle accident). Following a concussive impact, the rapid acceleration-deceleration of the head causes axons to “stretch,” resulting in a pathophysiological cascade of events that leads to the structural degradation of axonal cytoarchitecture (“secondary axotomy”), ultimately altering neural communication [25]. These structural changes are thought to be transient [23] but may lead to the re-organization of neural networks supporting cognition and learning [26]. For the purpose of this review, the term “concussion” is used to denote uncomplicated mild TBIs, whereas “SRC” refers to those uncomplicated mild TBIs specifically experienced during sport.

To the author’s knowledge only two studies report on language impairments after SRC. Both Salvatore and colleagues and Białńska and Salvatore identified auditory comprehension deficits on the Computerized Revised Token Test in a sample of high school, college, and semiprofessional athletes [27,28]. During this test, participants follow auditory commands to correctly reorganize the location of objects relative to one another (e.g., “in front of,” “to the left,” “to the right”). Results indicated that concussed athletes (within 12 days post-SRC) committed significantly more errors and delayed reaction times than age- and sex-matched controls [28]. These group-differences persisted through 3 weeks post-injury although accuracy did improve throughout recovery [27].

In contrast to SRC, language deficits following non-sports related concussion are well-documented. For example, individuals more than 6 months post-concussion demonstrated deficits on the *Association* and *Synonyms* subtests of The Word Test-Revised (TWT-R) and

on four subtests of the Test of Language Competence (TLC-E): Expanded Edition: *Ambiguous sentences*, *Listening comprehension- making inferences*, *Oral expression*, and *Figurative language* [29]. Concussed individuals also performed 2 SD below a control group on TLC-E subtests (*Language comprehension- making inferences*, *synonyms*) and TWT-R total score [30,31]. *Confrontation naming*, the ability to retrieve a word from long-term memory, deficits are also identified within the acute [32,33] and post-acute concussion period [29].

Non-standardized assessments can also elucidate the potential cognitive-communication impairments that may result from concussion. For example, concussed adults describe picture narratives less accurately [34], slower [35], and with more global coherence errors (e.g., tangential utterances, incongruent utterances, repetitions) [36]. These alterations reside at the intersection between cognition and language, providing empirical support for the “high-level language hypothesis”: language deficits following TBI may be the result of cognitive, not linguistic alterations [37]. These deficits following non-sports-related concussion demonstrate the need for examining how SRCs may influence speech and language.

Effects of SRC on Cognitive-evoked ERPs

ERPs are portions of the ongoing electroencephalogram (EEG) time-locked to the onset and presentation of stimuli during sensory/cognitive tasks. ERPs are favored for their temporal sensitivity, typically recording changes in brain activity at 250-1000Hz and are generally considered as valuable tools for predicting cognitive-communication outcomes [38], such as those following traumatic brain injuries [39].

The SRC-ERP literature has primarily examined changes in two cognitive-evoked ERP components, the N200 and P300 (see Brush and colleagues [40] for review). This research indicates that the amplitude and latency of the P300, reflecting context-updating and resource allocation [41,42], are altered following SRC during selective attention [43-45] and working memory [46,47]. The effects of SRC on the N200, indexing mismatch/novelty detection, cognitive control, and/or response monitoring depending on task demands [48], are less clear than the P300. Some report altered N200 amplitudes [43,44,49] and latencies [49,50] associated with a history of concussion, whereas others failed to find differences in amplitude [46,50] or latency [43]. Importantly, these altered ERP correlates often occur despite normative performance on behavioral neuropsychological assessments [43,44,46].

Concussion-related changes to the N200 and P300 may result from the reorganization of neural networks following concussion [26] and persist for more than 30 years after injury [51]. Similarly, language-related ERPs, such as the N400 and P600, may provide robust markers of neurolinguistic changes following SRC.

Candidate Psycholinguistic ERPs

ERP findings indicate that sports-related concussions are associated with long-term changes in cognitive brain function [44,46,51]. However, there remains a lack of understanding on how SRC may influence neural mechanisms of language processing. The diffuse axonal injury that is characteristic of SRC [52] would suggest that outcomes relying on intricate networks of brain regions and white matter pathways, such as the left-lateralized frontotemporal language network [53-56], may be impacted. Importantly, brain activity within this network generates the scalp-recorded N400 and P600 ERPs, providing neural markers of potential SRC-induced language deficits.

N400

First discovered by Kutas and Hillyard [57] the N400 is a broad negative deflection between 200-600 ms post-stimulus onset, peaking at approximately 400 ms at centroparietal electrodes [58] (Figure 1). The N400 is thought to reflect the access/retrieval of lexical information from semantic memory [59-61] and is commonly elicited during sentence verification and semantic priming tasks. Its amplitude is strongly correlated to the semantic fit of a stimulus within a given context which is often determined by cloze probability, the percentage of respondents who use a specific word to complete an unfinished sentence. In sentence verification tasks, amplitudes are larger to sentence-final endings that are incongruent within a discourse [62-64] or sentence [57,65,66], such as in "*He spread the warm bread with **socks***" [57]. In a semantic priming task, individual words are presented in pairs in which the semantic relationship between the first word ("prime") and second word ("target") is manipulated. Reduced N400 amplitudes are recorded to targets that were semantically primed [67,68]. For example, "*apple*" would semantically prime "*orange*," leading to smaller amplitudes than if the target and prime were not semantically related (e.g., "*apple*"-"*car*").

The effects of SRC on the N400 await examination. Two studies, however, reported N400-changes after more severe TBI, demonstrating its potential clinical utility for SRC. First, Münte and Heinze reported that patients (>2 Annal Behav Neurosci, 1(1): 36-46 (2018)

years post-TBI) generated smaller N400 amplitudes to incongruent words than a control group in a sentence verification task [69]. The TBI group also failed to generate an N400-effect to semantically primed targets and word repetitions. Knueppfer and colleagues examined the N400 in 14 adults with a pediatric TBI, ranging in severity from mild to severe [70]. During a semantic priming task, participants were simultaneously presented with a spoken word and a picture. The semantic agreement between the two stimuli were either (a) coherent (e.g., "orange," and picture of an orange), (b) related (e.g., "orange" and a picture of an apple) or (c) unrelated. The expected N400-effects occurred for the control group: amplitudes were significantly reduced from the unrelated, related and coherent conditions. In the pediatric-TBI group, however, N400 amplitudes did not differ between related and unrelated conditions [70]. Given the greater severity of TBIs in these studies, it is difficult to speculate how SRCs would impact the N400. Findings from fMRI, however, suggest that SRCs alter functional brain activity in a heterogeneous set of cortical regions, including the neural generators of the N400.

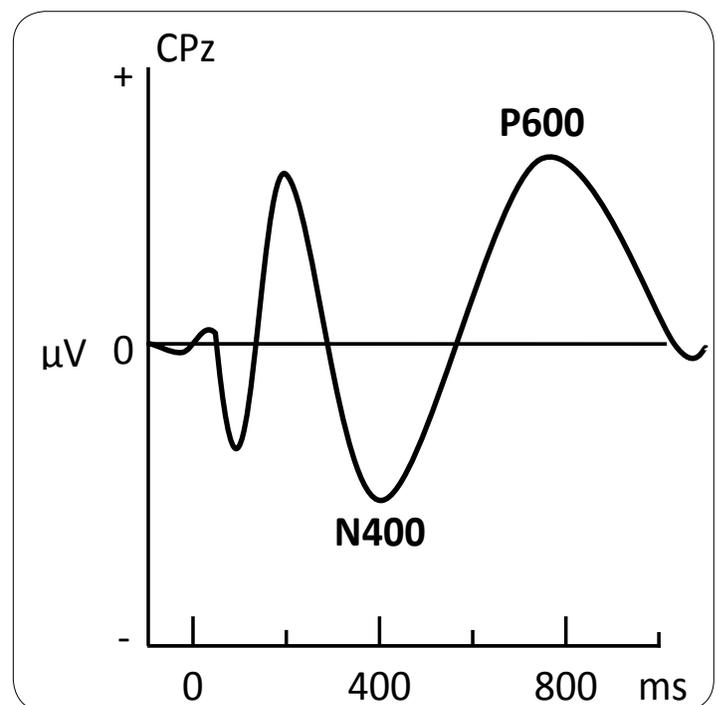


Figure 1: N400 and P600 Components of the ERP.

The N400-effect reflects broad activity of the left temporal cortex, with its epicenter in the left mid-to-posterior middle temporal gyrus (MTG; for review see [59,61]). The time course of the N400-effect begins in the superior temporal gyrus (STG) [71-74], likely reflecting early phonological processing from Wernicke's area [55,71] and spreads anteroventrally to the MTG [72,75]

and inferior temporal gyrus (ITG) [71,73,74]. Frontal effects are also commonly identified in the latter latency portion of the N400, but likely index activation underlying the parietal post-N400 positivity (“semantic P600”) as suggested by others [61,76].

During cognitive tasks, concussions alter functional activity in these left temporal areas that underlie the N400, including the STG (working memory [77,78]; selective attention [79], MTG (working memory [77,78]; orienting [80]), and ITG (orienting [80]; selective attention [81]). Consequently, the N400, underlying lexical-semantic processing [59-61] may provide a neural marker for the word-retrieval deficits that follow concussion [29,32,33]. Although awaiting examination in concussed populations, the N400 has been used to investigate mechanisms of word-retrieval deficits in populations with language disorders, including primary progressive aphasia [82,83]. Likewise, the N400 may be used to track changes in neurolinguistic processing throughout concussion recovery.

P600

Historically, researchers have demonstrated that P600 amplitudes fluctuate to syntactic deviations/complexity [84], such as in “*the spoilt child throw the toys on the floor*” [85]. Recently, however, it has been suggested that the P600 (centro-parietal maximum; 500-900 ms post-word onset) may reflect a more general mechanism indexing aspects of both syntax and semantics [59,86] (Figure 1). For example, P600 amplitudes increase to new or inferred

referents within a discourse [87] and semantic anomalies that fit the global context of a discourse [88-90]. P600-effects with similar morphologies are also identified to both syntactic and spelling errors [91] and both semantic and syntactic anomalies [92]. Given these reports, it seems likely that the P600 may in fact reflect a more general cognitive process, such as conflict monitoring [91,92] context updating [93] and/or reanalysis [86]. Only one study examined TBI-related changes of the P600. Specifically, a small sample of four individuals who experienced TBI (>24 months post-injury) failed to generate a P600-effect to syntactic anomalies, although this effect was present in a group of age-matched controls [94]. Similar to the N400-studies reviewed above [69,70], it is unclear how these findings would replicate in a concussed population.

Evidence from lesion-patients [95], fMRI [91], and ERPs [91] indicate that activity in the left inferior frontal gyrus (IFG) generates the P600 (also see [59,61,76]). Importantly, concussions alter functional activity of the left IFG during working memory [96-98] selective attention [79,81,98], and auditory orienting [80]. The left IFG is theorized to support cognitive processes of verbal working memory [99,100] and/or executive control [101]. Therefore, the left IFG may support cognitive processing necessary for, but not exclusive to, language comprehension.

It is possible that SRC-induced changes to the frontotemporal language pathways may lead to the altered activity of the neural generators of the N400

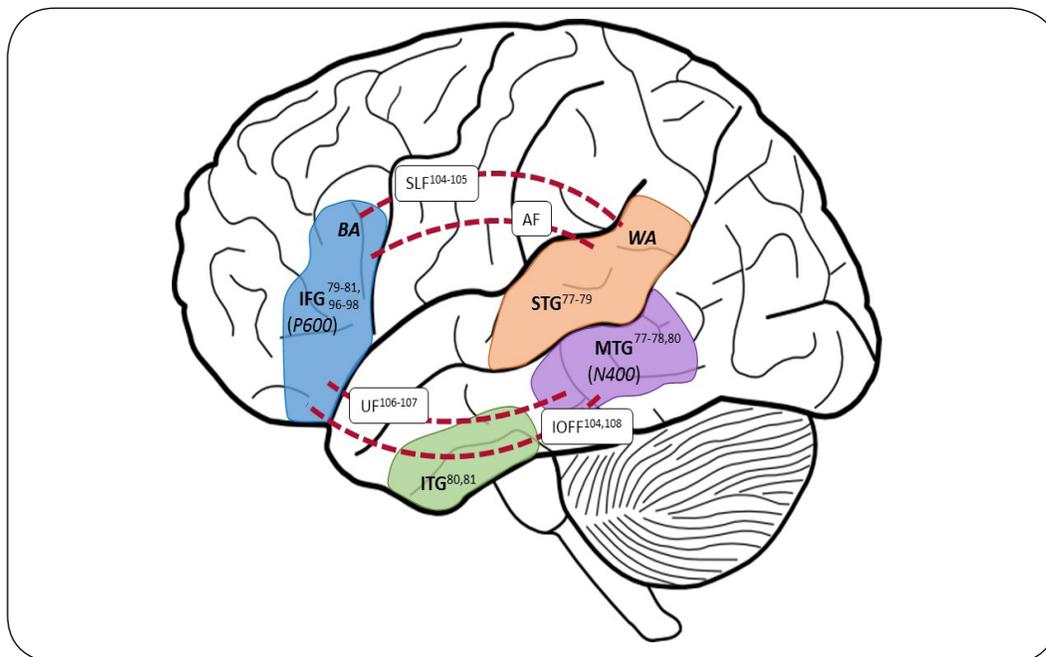


Figure 2: Structural and functional changes to the left frontotemporal language network associated with concussion.

and P600 ERPs (Figure 2). Specifically, SRC may destabilize the dorsal and ventral routes that link the left temporal and frontal lobes. The *dorsal* route supports motor-speech planning [55] linking the posterior left STG ("Wernicke's area") to posterior Broca's area (BA44) and dorsal pre-motor cortex via the the arcuate fasciculus (AF) [53,54,56] and superior longitudinal fasciculus (SLF) [53,54,56,102,103]. Concussions reduce the white matter integrity of the SLF [104-105] which may lead to the altered neurocognitive activity of the left STG [77-79] and/ or left IFG [79,81,96-98]. Speech production has yet to be examined after SRC, however, and thus provides an avenue for future research.

The *ventral route* facilitates language comprehension through connections between the left temporal and frontal lobes, including the uncinata fasciculus (UF) [53,102] and extreme fiber capsule (EC) /inferior occipito-frontal fasciculus (IOFF) [53,56,102]. Reduced white matter integrity of UF was reported in former boxers experiencing cognitive deficits [106] and adolescents with an acute concussion [107]. Structural alterations to the IOFF were also identified in professional boxers [108] and concussed athletes [104].

SRC-induced structural changes to this ventral pathway [104,106-108] may alter the activity of the left temporal cortex [77-81] and/or left IFG [79-81,96-98]. Although a matter of speculation, the disintegration of this lexical-semantic network may influence the auditory comprehension deficits that follow SRC [27,28]. However, it is also possible that SRCs exclusively alter functional activity in these cortical regions during cognitive (e.g., attention, working memory), but not linguistic, processing. Nevertheless, the N400 and P600, reflecting activity in the left temporal and left IFG regions respectively, provide neural markers to investigate potential changes in language comprehension abilities throughout recovery from SRC.

Late Anterior Positivity

The Late Anterior Positivity (LAP) is a sustained frontocentral deflection, reaching its maximal amplitude between 600-900 post-word onset [109,110]. Although the functional significance of the LAP remains tenuous, researchers recently suggested the LAP is elicited to failed semantic predictions [76]. For example, greater LAP amplitudes are recorded to improbable, but plausible, sentence endings [109-112]. Kaan and Swaab also identified a larger LAP to more syntactically complex two noun phrases (e.g., "*I cut the cake beside the pizzas*

that were brought by Jill") than one noun phrase ("*The man in the restaurant doesn't like the hamburgers that are on his plate*") [113]. The researchers concluded that the amplitude of this frontal positivity may be positively related to the complexity of a discourse or resolution of ambiguity during comprehension.

Investigators more recently suggested that tasks assessing ambiguous sentence comprehension may be used to evaluate individuals with cognitive-communication impairments, such as those with traumatic brain injury. Key-DeLyria and Altmann argued that ambiguous sentence comprehension relies on executive functions and that their supporting neural mechanisms are often altered following TBI [114]. Researchers also suggested that the LAP can provide a marker for discourse processing deficits in individuals with cognitive-communication disorders such as TBI [39]. Given the purported comprehension deficits following SRC [27,28], it is possible that these deficits are due to challenges with comprehending ambiguous meanings in discourse, such as when comprehension relies on the ability to form inferences. There are several accounts of concussion-related deficits in making inferences [29,31] and comprehending ambiguous sentences [30]. If the LAP reflects aspects of contextual revision and or ambiguity resolution, it may also provide an evaluative tool for SRC. Establishing the functional significance of the LAP remains in its infancy, however, and certainly warrants further investigation in neurotypical populations before it may demonstrate clinical utility after SRC.

Conclusion

Findings are limited regarding if and how sports-related concussions impact the language system. There are several possible explanations for this paucity of research. First, perhaps language deficits are specifically associated with non-sports-related concussion [29-36], but not SRC. Alternatively, the current lack of research may result from how language assessment batteries were developed. These assessments were designed to test speech and language disorders (e.g., apraxia, aphasia) and may not be sensitive to cognitive-communication deficits associated with TBI [37]. Lastly, gold-standard return-to-play protocols utilize computerized neurocognitive batteries (e.g., ImPACT) that do not overtly examine the language system [24,115,116]. The time required to complete a standard neurocognitive battery and other post-concussion assessment measures, such as symptomatology, postural control, and case history interview is considerable. Consequently, clinicians and

researchers may infrequently administer additional assessments to examine possible language deficits.

Given recent associations between exposure to repetitive head trauma and chronic traumatic encephalopathy (CTE) in former contact-sport athletes [117,118] the acute and potentially long-term effects of sports-related concussions on neurocognitive health are an important and growing concern. Functional MRI findings indicate that SRCs alter neurocognitive brain activity in frontotemporal language networks that generate the N400 [77-81] and P600 ERPs [79-81,96-98]. Consequently, these ERPs serve as candidate neural markers for investigating the extent to which SRCs alter speech and language, particularly in the domain of language comprehension [27,28]. Knowledge of sports-related concussions and how they impact neural, cognitive, and linguistic outcomes remains in its infancy. This burgeoning research area necessitates interdisciplinary collaborations between clinicians, athletic trainers, and researchers to continue its advancement and ultimately improve the clinical management of the concussed athlete.

Conflict of Interest

The author reports no competing financial interests.

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