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The Impact of Sleep on the Relationship between Soccer Heading Exposure and Neuropsychological Function in College-Age Soccer Players

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Abstract

Objective: Soccer is the most popular sport worldwide and is the only sport where athletes purposely use their head to deflect the ball during play, termed "heading" the ball. These repetitive head impacts (RHI) are associated with worse neuropsychological function; however, factors that can increase risk of injury following exposure to such head impacts have been largely unexamined. The present study provided a novel examination of the modifying role of sleep on the relationship between RHI exposure and neuropsychological function in college-age soccer players. **Methods:** Fifty varsity and intramural college soccer players completed questionnaires assessing recent and long-term heading exposure, a self-report measure of sleep function, and a battery of neuropsychological tests. **Results:** A high level of recent heading exposure was significantly associated with poorer processing speed, independent of concussion history. With reduced sleep duration, a high level of recent heading exposure was related to worse sustained attention. However, with greater hours of sleep duration, heading exposure was related to preserved neuropsychological outcome in sustained attention. **Conclusions:** We replicated our earlier finding of an association between recent head impact exposure and worse processing speed in an independent sample. In addition, we found that sleep may serve as a risk or protective factor for soccer players following extensive exposure to head impacts. Ultimately, this study furthers the understanding of factors impacting neuropsychological function in soccer players and provides empirical support for sleep interventions to help ensure safer soccer play and recovery from injury.

Keywords: Brain injuries, Sleep, Risk factors, Soccer, Cognition, Repetitive head impacts

INTRODUCTION

Participation in sports play is typically associated with a range of positive outcomes, such as health (Janssen & Leblanc, 2010), psychosocial (Eime, Young, Harvey, Charity, & Payne, 2013), and neuropsychological benefits (Archer, Ricci, Massoni, Ricci, & Rapp-Ricciardi, 2016). Despite these known benefits, athletes involved in contact sports are exposed to head impacts at a broad range of frequency, which places them at risk for brain injury and potentially compromised neuropsychological function (Belanger & Vanderploeg, 2005; Belanger, Vanderploeg, & McAllister, 2016). Soccer, the most popular sport worldwide (FIFA, 2007), is the only sport where athletes purposely use their head to deflect the ball during play, termed "heading" the ball. These repetitive head impacts (RHI, heading) do not result in recognized, overt concussive events (Spiotta, Bartsch, & Benzel, 2012), yet they are associated with brain injury, concussive symptoms (e.g., dizziness, pain, feeling dazed), and poorer neuropsychological function (Koerte, Ertl-Wagner, Reiser, Zafonte, & Shenton, 2012; Stewart et al., 2017).

Specifically, in soccer, there is support for an exposure–response relationship between cumulative number of RHI and worse neuropsychological function (Belanger et al., 2016). RHI exposure is most commonly associated with statistically significant poorer performance in the domains

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of learning and memory (Downs & Abwender, 2002; Matser, Kessels, Jordan, Lezak, & Troost, 1998; Matser, Kessels, Lezak, Jordan, & Troost, 1999) and attention and processing speed (Matser, Kessels, Lezak, & Troost, 2001; Tysvaer & Lochen, 1991; Witol & Webbe, 2003), but these findings are small to moderate in magnitude and not at levels of clinical impairment. Importantly, studies that have examined the independent role of RHI on neuropsychological function by controlling for concussion history in analyses have demonstrated consistent findings (Lipton et al., 2013; Moore, Lepine, & Ellemberg, 2017). Most recently, in a sample of 311 amateur soccer athletes, long-term RHI (heading over the prior 12 months) was related to poorer learning and memory, while recent RHI (heading over the prior two weeks) was independently related to poorer processing speed (Levitch et al., 2018). These findings were independent of concussion history, suggesting that heading may account for a significant share of neuropsychological deficits in soccer, possibly through the accumulation of brain injury over time. With over 265 million active soccer players worldwide, additional research is necessary to replicate these findings. As such, an aim of this study was to provide replication, in an independent sample, of prior findings examining the relationship between long-term and recent RHI exposure and neuropsychological function utilizing uniform methodology and statistical controls for concussion history. Based on previous findings in independent samples of soccer players (Levitch et al., 2018; Lipton et al., 2013), it was hypothesized that long-term RHI exposure would be associated with worse learning and memory, recent RHI exposure would be associated with worse processing speed, and these associations would be independent of one another.

Additionally, this study sought to provide a novel examination of factors that could increase the risk of brain injury following exposure to RHI. Sleep is one such potential risk factor. Sleep is associated with numerous aspects of sports play – including physical athletic performance (Samuels, 2008) and neuropsychological function (Fullagar et al., 2015; Taheri & Arabameri, 2012; Wickens, Hutchins, Laux, & Sebok, 2015). Among athletes in contact sports, poor sleep is associated with increased risk of concussive head injury (Luke et al., 2011; Milewski et al., 2014) and prolonged recovery of concussive symptoms (Chan & Feinstein, 2015; Worthington & Melia, 2006). Of concern, sleep disruptions associated with concussion are quite common (Towns, Silva, & Belanger, 2015) and may exacerbate injury-related difficulties on a variety of neuropsychological tasks (Bloomfield, Espie, & Evans, 2010; Mahmood, Rapport, Hanks, & Fichtenberg, 2004; Wilde et al., 2007). Conversely, treatment of the concussion-related sleep disruption appears to have a positive effect on recovery of neuropsychological function (Wiseman-Hakes et al., 2013).

However, sleep's role as a risk and/or protective factor following brain injury from RHI such as those incurred in soccer play has been unexplored. Therefore, an aim of the present study was to examine the interrelationship of sleep and RHI exposure on neuropsychological function in soccer athletes. It was hypothesized that self-reported sleep duration and quality would moderate the relationship between RHI exposure and neuropsychological function, such that in individuals with lower sleep duration or poorer sleep quality, a high level of RHI would be associated with worse neuropsychological function.

METHODS

Study Participants

Participants were recruited as part of the protocol, "Heading Exposure, Sleep, and Neuropsychological Function in College Soccer Players." This study recruited a sample of 50 undergraduate students at Fordham University who were engaged in varsity or intramural competitive soccer play. The Fordham University Institutional Review Board approved the study, and all study subjects provided written informed consent.

Inclusion criteria were age greater than 18 years; current soccer play; at least four years of active soccer play; at least four months of soccer play per year; and English language fluency. Exclusion criteria were known neurological disorder; schizophrenia, bipolar disorder; and prior moderate or severe traumatic brain injury (TBI).

Exposure Assessment

HeadCount is a structured, Web-based, self-administered questionnaire of soccer play characteristics that has been described in detail previously and has demonstrated adequate reliability and validity across settings (Catenaccio et al., 2016; Lipton et al., 2017; Lipton et al., 2013; Stewart et al., 2017). In brief, HeadCount has demonstrated sufficient convergent validity with a daily HeadCount measure (Lipton et al., 2017) and with recorded number of head impacts observed by trained raters for collegiate soccer teams (Catenaccio et al., 2016). This study used two versions of HeadCount: HeadCount-12m inquired about soccer activity during the prior 12 months and HeadCount-2w inquired about soccer activity during the prior two weeks. In brief, HeadCount-12m is organized into four modules focused on indoor practice, outdoor practice, indoor games, and outdoor games. Questions are also asked about lifetime history and symptoms associated with concussion. HeadCount-2w included the same four modules as well as a fifth module on unintentional head impacts. For all soccer activities in the last two weeks, participants are asked how often they experienced unintentional head impacts from specific causes (e.g., ball hitting the back of the head, head to goal post, head to head).

Sleep Assessment

The Pittsburg Sleep Quality Index (PSQI) (Buysse, Reynolds, Monk, Berman, & Kupfer, 1989) is a self-report inventory that assesses subjective sleep quality over a one-month time period.

On this 19-item questionnaire, participants rate severity of sleep disturbance on a four-point scale (0–3). It provides seven component scores that assess different aspects of sleep (quality, latency, duration, efficiency, disturbances, sleeping medication, and daytime dysfunction). The total PSQI score is calculated by combining these seven component scores, with higher scores indicating poorer overall sleep quality. A total score of five or greater is indicative of poor sleep quality (Buysse et al., 1989). The variables of interest in the present study were total PSQI score and reported sleep duration ("How many hours of actual sleep did you get at night?").

Neuropsychological Outcome Variables

Participants completed a computerized and paper-and-pencil neurocognitive battery as well as the Wechsler Test of Adult Reading (WTAR; Corporation, 2001) as a measure of premorbid intellectual functioning. The battery lasted between 60 and 90 minutes and was administered and scored by trained study staff and supervised by a licensed clinical neuropsychologist. Raw test scores were first converted to z-scores based on the best available demographically corrected normative data. Next, z-scores for each individual neuropsychological test were averaged to create four neuropsychological domain z-scores: attention/working memory, processing speed, executive functioning, and learning and memory. Of note, two tasks (Groton Maze Chase Test (GMCT) and Psychomotor Vigilance Test (PVT)) did not have normative data available. As such, they were not included in the relevant domain z-score, and raw test scores were used in the analyses.

Cogstate

Computerized neuropsychological assessment was administered via Cogstate, a reliable and valid test battery (Maruff et al., 2009). Two tasks were used to evaluate attention: Identification measured how quickly (log10 of reaction time) participants correctly identified the color of a playing card, whereas the One Back Test measured how accurately (arcsine of square root of proportion of correct responses) participants determined if a playing card was the same as the card shown previously. Working memory was assessed with the Two Back Test (TWOB), which measured how accurately (arcsine of square root of proportion of correct responses) participants determined if a playing card was the same as the card shown two cards previously. Processing speed was assessed with the GMCT, which measured how quickly and accurately (total number of correct moves per second) participants chased a target through a maze. The International Shopping List – Immediate and Delayed Recall tasks measured verbal learning and memory abilities, respectively. Participants were asked to remember a list of 12 words on three consecutive learning trials and then to recall the list following a delay period. Number of correct responses was the primary outcome variable. The Groton Maze Learning and Delayed Recall tasks measured nonverbal learning and memory abilities, respectively. Participants were instructed to find a hidden pathway in a grid across five learning trials. Following a delay period, participants were asked to recall the hidden pathway. Number of errors made in learning or remembering the maze pathway was the primary outcome variable.

Delis Kaplan Executive Function System

The Delis Kaplan Executive Function System (D-KEFS) is a test battery of executive functioning, demonstrating sensitivity to executive function deficits in numerous clinical populations (Delis, Kramer, Kaplan, & Holdnack, 2004). The Color-Word Interference Test includes four conditions: the first two conditions measure processing speed (i.e., rapid naming of colors and words, respectively), while the third and fourth conditions measure aspects of executive functioning (i.e., inhibitory control, set-shifting). The primary variable of interest was total time to complete each condition (seconds). The secondary variable of interest was number of errors in each condition. The Tower Test is a measure of nonverbal planning, in which participants move disks varying in size from small to large across three pegs to build a designated tower using the fewest number of moves possible. The primary variable of interest was total achievement score.

Trail Making Test

The Trail Making Test (TMT) (Reitan & Wolfson, 1985) is divided into two parts, Part A and Part B. Both parts assess psychomotor speed, but Part B also measures aspects of executive functioning (e.g., set-shifting, cognitive flexibility). Part A requires participants to connect numbered circles in sequential order. Part B involves alternating between number and letter circles. The primary variable of interest was total time the participant takes to complete the task (seconds).

Psychomotor Vigilance Test

The PVT (Dinges & Powell, 1985) is a measure of sustained attention and behavioral activation. Participants were shown a visual stimulus on a computer screen at random times during a ten-minute interval and asked to respond to the visual stimulus by pressing a mouse button. Reaction time (milliseconds) was the primary outcome variable.

Potential Covariates

Beck Depression Inventory-II

The Beck Depression Inventory-II (BDI-II) (Beck, Steer, & Brown, 1996) is a self-report inventory that assesses depression symptoms. In this 21-item questionnaire, participants rate severity of depression symptoms on a four point scale (0–3), with higher scores indicating a more severe level of the symptom. The variable of interest was total depression score (maximum = 63).

Beck Anxiety Inventory

The Beck Anxiety Inventory (BAI) (Beck, Epstein, Brown, & Steer, 1988) is a self-report measure of anxiety. It is a 21-item multiple choice questionnaire designed to assess the emotional, physiological, and cognitive symptoms of anxiety. Participants are asked to report the extent to which they have been bothered by each symptom during the past week, ranging from 0 = not at all to 3 = severely. The variable of interest was total anxiety score (maximum = 63).

Wender Utah Rating Scale

The Wender Utah Rating Scale (WURS) (Ward, Wender, & Reimherr, 1993) was developed to assess adults' retrospective account of childhood symptoms associated with a diagnosis of attention deficit/hyperactivity disorder (AD/HD). It is a 25-item self-report questionnaire answered by the adult recalling his/her childhood behavior, with five possible responses ranging from zero ("Not at all or very slightly") to four ("Very much"). A cutoff score of ≥ 46 is used to evaluate the presence of childhood AD/HD (maximum = 100) (Ward et al., 1993). The primary variable of interest was if the WURS total score was above the cutoff score or not (Yes/No).

Procedure

Data were collected from August to November 2018, which coincided with the Division I varsity and intramural soccer team seasons. Participants were recruited through flyers, emails to soccer team members, and presentations at team practices. All study visits took place at Fordham University and were individual visits.

During Study Visit One, participants completed informed consent, provided demographic and soccer play information, and completed questionnaires for potential covariates (depression, anxiety, and AD/HD history). During Study Visit Two (two weeks after visit one), participants completed a battery of neuropsychological tasks, the PSQI, and the HeadCount questionnaires. All participants returned for study visit two and were compensated for their time via a gift card. Of note, one participant did not complete the HeadCount questionnaires and was not included in subsequent analyses.

Analysis

Exploration of associations between demographic and psychosocial variables (age, race, ethnicity, gender, premorbid reading ability, AD/HD diagnosis, depression, anxiety, years of heading exposure, concussion history), the independent variables (long-term and recent heading exposure, sleep), and dependent variables (neuropsychological domain scores) was conducted using Pearson product-moment correlation coefficients (r), chi-square analyses, and t-tests to determine model covariates. Heading reported in HeadCount (both versions) was positively skewed. Therefore, heading exposure was categorized into two groups based on the median value (HeadCount-2w, $Mdn = 39$; HeadCount12m, $Mdn = 469$). The Low Headers group ($n = 25$) reflects participants with low RHI exposure, whereas the High Headers group ($n = 24$) reflects participants with high RHI exposure. The use of categories to form head impact exposure groups is consistent with methodological approaches used in prior studies examining RHI in soccer players (Levitch et al., 2018; Lipton et al., 2013; Witol & Webbe, 2003). Given the sample size of the study, it was decided that heading exposure would be best expressed as two groups rather than quartiles to maximize study power. Self-reported sleep duration and sleep quality (PSQI sleep duration and total score, respectively) were normally distributed and were treated as continuous variables.

Three separate regression models were constructed examining the effect on neuropsychological domain score of the following exposures: recent-heading, long-term heading, and a model incorporating both recent and long-term heading. Next, a series of linear regression models examined if self-reported sleep duration and sleep quality moderated the relationship between recent- and long-term heading exposure and each neuropsychological domain score. The models included an interaction term of self-reported sleep multiplied by heading exposure to probe for a moderation effect.

RESULTS

Participant Characteristics

Demographic and psychosocial data for the 50 participants are presented in Table 1 by low and high heading groups for recent heading (HeadCount-2w) and long-term heading (HeadCount-12m). No participants met criteria for childhood diagnosis of AD/HD. Table 2 shows the distribution of low and high heading groups for soccer play characteristics. The sample was composed of 46% ($n = 23$) varsity level soccer players and 54% ($n = 27$) intramural level soccer players.

Table 3 shows the distribution of low and high heading groups for neuropsychological function and sleep characteristics. In terms of neuropsychological variables, the sample's mean premorbid intellectual functioning ($M = 113.40$, $SD = 8.15$) was in the high average range, and all z-scores for neuropsychological tasks and domain scores were normatively average and fell within ±1.0 SD of the mean. Regarding sleep, the overall sample reported a mean of 7.22 hours of sleep per night ($SD = 1.03$; range = 5–10) over the prior month. The mean level of sleep quality on the PSQI was 5.39 ($SD = 2.41$; range = 1–11), with 56% ($n = 28$) of scores in the "poor quality" sleep range (≥ 5). Varsity and intramural level soccer players did not differ in duration or quality of sleep. Thirty-six percent ($n = 18$) of the sample reported a lifetime history of concussion, with 22% ($n = 11$) reporting two or more lifetime concussive events. One participant reported a concussion within the prior year (nine-months prior), and no participants incurred a concussion between the study visits. Regarding heading exposure,

Table 1. Demographic characteristics by heading group presented as mean (SD) or % (*n*)

	HeadCount-12m		HeadCount-2w	
	Low headers ($n = 25$)	High headers ($n = 24$)	Low headers ($n = 25$)	High headers ($n = 24$)
Demographic				
Age	19.60 (1.12)	19.50 (1.53)	19.40 (1.19)	19.71 (1.46)
Education	13.48 (1.05)	13.38 (1.21)	13.32 (1.15)	13.54 (1.10)
Female	48% (12)	50% (12)	40% (10)	58.3% (14)
Race/Ethnicity				
Non-Hispanic White	76% (19)	75% (18)	72% (18)	79.2% (19)
Hispanic/Latino	16% (4)	16.7% (4)	20% (5)	12.5% (3)
Asian American	8% (2)	4.2% (1)	8% (2)	4.2% (1)
African American	0% (0)	4.2% (1)	0% (0)	4.2% (1)
Learning Disability	4% (1)	8.3% (2)	8.0% (2)	4.2% (1)
Psychosocial				
Depression	3.84 (3.20)	4.29 (3.43)	4.08 (2.77)	4.04 (3.82)
Anxiety	4.40 (4.92)	3.71 (4.33)	5.48 (5.54)*	2.58 (2.80)*
AD/HD	0% (0)	0% (0)	0% (0)	0% (0)

Note. Depression = Beck Depression Inventory-II, Anxiety = Beck Anxiety Inventory, AD/HD = Wender-Utah Rating Scale, *Indicates statistically significant difference between low and high headers, $p < .05$.

Table 2. Soccer exposure characteristics by heading group presented as mean (SD) or % (*n*)

	HeadCount-12m		HeadCount-2w	
	Low headers ($n = 25$)	High headers ($n = 24$)	Low headers ($n = 25$)	High headers ($n = 24$)
Highest Level of Soccer Play				
Varsity	56% (14)	37.5% (9)	60% (15)	33.3% (8)
Intramural	44% (11)	62.5% (15)	40% (10)	56.6% (16)
Years of Heading	10.19 (3.59)	11.33 (3.47)	10.38 (3.22)	11.17 (3.83)
Months of Soccer Play	8.44 (2.36)	9.63 (2.46)	8.52 (2.38)	9.54 (2.48)
History of Concussion	36% (9)	37.5% (9)	32% (8)	41.7% (10)
HeadCount-2w				
Mean	–	–	18.16 (13.28)	125.63 (98.61)
Median	–	–	17.00	87.50
HeadCount-12m				
Mean	170.15 (147.69)	1692.24 (1309.03)	–	–
Median	121.66	969.44	–	–

Note. There were no statistically significant differences between low and high header groups.

participants had a mean of 70.8 head impacts ($SD = 87.71$; range = 0–450; $Mdn = 39$) over the prior two weeks and a mean of 915.66 head impacts ($SD = 1192.89$; range = 0–5171; $Mdn = 469.26$) over the prior year.

Covariates were retained in the models that exhibited a bivariate association with heading, sleep, or neuropsychological domain score at a significance level $p < .05$. Participants in the recent high heading group reported fewer symptoms of anxiety. Participants with higher PSQI total scores (i.e., poorer sleep quality) reported greater anxiety symptoms, greater symptoms of depression, had fewer years of heading exposure, and had higher premorbid intellectual abilities (WTAR total score). Depression and race were associated with the learning and memory domain score. Thus, these variables were included as covariates in relevant subsequent analyses. Although not associated with heading or neuropsychological domain score, concussion history and WTAR total score were also included as covariates to account for their role, if any, in explaining exposure-outcome associations for heading.

Long-Term Head Impact Exposure and Neuropsychological Function

An aim of this study was to provide replication, in an independent sample, of prior findings examining the relationship

Table 3. Neuropsychological function and sleep characteristics by heading group presented as mean (SD) or % (*n*)

	HeadCount-12m		HeadCount-2w	
	Low headers ($n = 25$)	High headers ($n = 24$)	Low headers ($n = 25$)	High headers ($n = 24$)
Neuropsychological				
WTAR[a]	114.44 (7.28)	111.96 (8.93)	115.12 (7.56)	111.25 (8.41)
Attention/Working Memory[b]	−0.22 (0.43)	−0.12 (0.48)	−0.16 (0.47)	−0.19 (0.45)
Identification[b]	−0.26 (0.70)	−0.14 (0.78)	−0.20 (0.62)	−0.21 (0.86)
One Back Test[b]	−0.54 (0.88)	−0.62 (1.27)	−0.44 (0.93)	−0.73 (1.21)
Two Back Test[b]	0.13 (0.71)	0.08 (0.71)	0.17 (0.81)	0.05 (0.57)
PVT (ms)	270.72 (34.37)	262.07 (33.65)	266.61 (27.38)	266.35 (40.19)
Processing Speed[b]	0.28 (0.51)	0.27 (0.54)	0.40 (0.61)*	0.15 (0.37)*
GMCT (mps)	1.77 (0.28)	1.74 (0.34)	1.83 (0.29)	1.67 (0.32)
Trail Making Test-Part A[b]	−0.13 (0.93)	0.10 (1.06)	0.10 (1.08)	−0.14 (0.90)
CWI Trial 1[b]	−0.39 (0.62)	0.25 (0.56)	0.40 (0.66)	0.24 (0.51)
Errors[c]	0.24 (0.44)	0.13 (0.34)	0.20 (0.41)	0.17 (0.38)
CWI Trial 2[b]	0.59 (0.65)	0.47 (0.60)	0.71 (0.71)*	0.35 (0.47)*
Errors[c]	0.40 (0.65)	0.38 (0.50)	0.40 (0.65)	0.38 (0.50)
Executive Functioning[b]	0.25 (0.43)	0.35 (0.41)	0.25 (0.47)	0.36 (0.38)
CWI Trial 3[b]	0.81 (0.51)	0.76 (0.60)	0.80 (0.56)	0.78 (0.55)
Errors[c]	1.12 (1.45)	0.88 (0.95)	1.12 (1.45)	0.88 (0.95)
CWI Trial 4[b]	0.68 (0.56)	0.65 (0.63)	0.75 (0.56)	0.58 (0.61)
Errors[c]	1.04 (0.89)	1.17 (1.34)	1.00 (1.08)	1.21 (1.18)
Trail Making Test-Part B[b]	0.14 (0.96)	0.43 (1.21)	0.27 (1.08)	0.29 (1.13)
Tower Test-Achievement[b]	0.11 (0.72)	0.18 (0.57)	0.11 (0.72)	0.18 (0.57)
Learning and Memory[b]	−0.12 (0.42)	0.11 (0.37)	−0.14 (0.40)*	0.13 (0.39)*
ISL Immediate[b]	0.06 (0.62)	0.00 (0.53)	−0.02 (0.57)	0.08 (0.58)
ISL Recall[b]	−0.08 (0.70)	0.08 (0.73)	−0.12 (0.75)	0.12 (0.67)
Groton Maze Learning[b]	−0.66 (0.65)*	−0.08 (0.94)*	−0.61 (0.64)	−0.15 (0.98)
Groton Maze Recall[b]	0.21 (0.50)	0.44 (0.60)	0.19 (0.57)	0.47 (0.53)
Sleep				
PSQI Sleep Duration	7.36 (1.08)	7.08 (0.97)	7.16 (1.11)	7.29 (0.95)
PSQI Total Score	5.48 (2.65)	5.29 (2.20)	5.80 (2.60)	4.96 (2.18)

Note. WTAR = Wechsler Test of Adult Reading, PVT = Psychomotor Vigilance Test, GMCT = Groton Maze Chase Test, mps = moves per second, CWI = Color Word Interference Test, PSQI = Pittsburgh Sleep Quality Index, Normative data scale indicated by superscript: [a]Standard Score; [b]z-Score; [c]raw score. *Indicates statistically significant difference between low and high headers, $p < .05$.

between long-term RHI exposure and neuropsychological function utilizing uniform methodology and statistical controls for concussion history. It was found that long-term heading exposure (HeadCount-12m) was not associated with neuropsychological function. Linear regressions revealed that the level of long-term heading exposure was not associated with learning and memory ($F(1,43) = 3.22$, $p = .08$). Model covariates included depression, race, WTAR total score, and concussion history. Long-term heading exposure was not associated with performance on other domains of neuropsychological function (p's $> .05$). Additionally, lifetime concussion history was not associated with neuropsychological function.

Recent Head Impact Exposure and Neuropsychological Function

Another aim of this study was to provide replication, in an independent sample, of prior findings examining the relationship between recent RHI exposure and neuropsychological function. Recent heading exposure (HeadCount-2w) was associated with poorer neuropsychological function. Linear regressions revealed that level of recent heading exposure was associated with processing speed domain score, ($F(1,44) = 4.47$, $p = .04$). Specifically, the high heading group ($M = 0.15$, $SD = 0.37$) had a lower processing speed domain score (indicating slower reaction time) than the low heading group ($M = 0.40$, $SD = 0.61$). The effect size for this finding fell in the small range ($\beta = .32$, $\eta_p^2 = .09$). When the p-value was adjusted using the Benjamini and Hochberg method (Benjamini & Hochberg, 1995), with a false discovery rate estimated using the method described in Dalmasso, Broet, and Moreau (2005), it was at a trend level ($p = .08$). Exploratory analyses of individual processing speed tests revealed that recent heading exposure was related to performance on the GMCT ($F(1,44) = 5.82$, $p = .02$) and Color Word Interference – Trial 2 ($F(1,44) = 4.66$, $p = .04$). Specifically, the high heading group ($M = 1.67$, $SD = 0.32$) performed slower (made fewer moves per second) on the GMCT than the low heading group ($M = 1.83$, $SD = 0.29$).

Table 4. Linear regressions of heading exposure group by neuropsychological task ($n = 49$)

	Low headers ($n = 25$)		High headers ($n = 24$)		F value			
	M	SD	M	SD	(1, 42)	p	B	η_p^2
NP Test								
Processing Speed[b]	0.40	0.61	0.15	0.37	7.06	.01*	0.62	.14
GMCT[a]	1.83	0.29	1.67	0.32	7.38	.01*	0.35	.15
CWI Trial 2[b]	0.71	0.71	0.35	0.47	4.96	.03*	0.67	.13
Learning/Memory[b]	−0.14	0.40	0.13	0.39	1.58	.22	−0.02	.04

Note. GMCT = Groton Maze Chase Task, CWI = Color Word Interference. Superscript indicates data scale: [a]moves per second, higher score = better performance. [b]z-score, higher score = better performance.

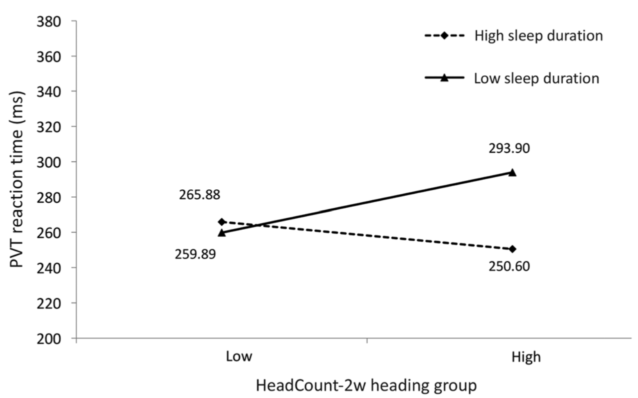

Fig. 1. Moderating effect of self-reported sleep duration on the relationship between recent head impact exposure (HeadCount-2w) and sustained attention (PVT, lower score = better performance).

Similarly, the high heading group ($M = 0.35$, $SD = 0.47$) performed worse on Color Word Interference – Trial 2 than the low heading group ($M = 0.71$, $SD = 0.71$). Covariates for the linear regression models included anxiety, WTAR total score, and concussion history. For all analyses, neuropsychological domain/task scores were normatively average, and lifetime concussion history was not independently associated with neuropsychological function.

Recent heading exposure was also associated with learning and memory domain score ($F(1,42) = 4.51$, $p = .04$). Specifically, the high heading group ($M = 0.13$, $SD = 0.39$) had a higher learning and memory domain score than the low heading group ($M = -0.14$, $SD = 0.40$). The effect size for this finding was small ($\beta = -.26$, $\eta_p^2 = .09$). Model covariates included anxiety, depression, WTAR total score, and concussion history. Exploratory analyses revealed that recent heading exposure was not related to performance on any individual learning and memory test (p's > .05). Given that this finding was not an *a priori* hypothesis, the p-value was adjusted using the methodology described above, and was no longer significant ($p = .08$). Recent heading exposure was not associated with performance on other domains (p's > .05).

Long-term Head Impact Exposure, Recent Head Impact Exposure, and Neuropsychological Function

To account for their relative contributions to neuropsychological function, both long-term RHI exposure (HeadCount-12m) and recent RHI exposure (HeadCount-2w) were included in a single model. As shown in Table 4, the relationship between high level of recent heading and lower processing speed domain score was preserved ($F(1,42) = 7.06$, $p = .01$). The effect size for this finding fell in the moderate range ($\beta = .62$, $\eta_p^2 = .14$). Exploratory analyses revealed that the relationships between high level of recent heading exposure and poorer performance on the GMCT ($F(1,42) = 7.38$, $p = .01$) and Color Word Interference – Trial 2 ($F(1,42) = 4.96$, $p = .03$) were preserved as well. Covariates for the aforementioned linear regression models included anxiety, WTAR total score, and concussion history. However, the relationship between high level of recent heading and better learning and memory was no longer significant ($F(1,40) = 1.58$, $p = .22$). Model covariates included anxiety, depression, WTAR total score, and concussion history. Of note, neuropsychological domain/task scores were normatively average for all groups, and lifetime concussion history was not independently associated with neuropsychological function. No other associations emerged (p's > .05).

Sleep, Head Impact Exposure, and Neuropsychological Function

An aim of the study was to examine the interrelationship of sleep and RHI exposure on neuropsychological function. As seen in Figure 1, self-reported sleep duration moderated the relationship between recent heading exposure and a measure of sustained attention, the PVT, $b = -0.47$, 95% CI [−41.79, −6.26], $t(42) = -2.73$, $p = .01$. Following adjustment for multiple comparisons, the moderating effect was preserved ($p = .03$). Examination of moderating effects revealed that at low sleep duration (fewer hours of sleep), a high level of recent heading exposure was related to slower reaction time on the PVT, $b = 0.51$, 95% CI [6.90, 61.13], $t(42) = 2.53$, $p = .02$. At high self-reported sleep duration (greater hours of sleep), there was a nonsignificant relationship between a high level of recent heading exposure and faster reaction time on the PVT, $b = -0.23$, 95% CI [−39.70, 9.14], $t(42) = -1.26$, $p = .21$. Model covariates included anxiety, WTAR total score, and concussion history.

Self-reported sleep duration and sleep quality did not significantly moderate the relationship between recent heading and other domains of neuropsychological function (p's > .05). In addition, no significant interactions between self-reported sleep duration and sleep quality and long-term heading exposure emerged (p's > .05). Findings for the moderator analyses are reported in Supplementary Material.

DISCUSSION

The present study was the first to examine relationships among sleep, RHI exposure, and neuropsychological function in college-age soccer athletes. This sample had a high level of exposure to RHI, with a median count of 469 headers/year and 39 headers/two weeks, and they reported high levels of sleep disturbances, with over 50% of participants meeting criteria for "poor quality" sleep. This is of concern because it was found that with reduced sleep duration, a high level of exposure to recent RHI was related to poorer sustained attention. Conversely, greater sleep duration preserved sustained attention even with a high level of exposure to RHI. Additionally, the results replicated our prior finding in an independent sample that frequency of RHI exposure was related to worse processing speed. In sum, these findings illustrate that head impact exposure and sleep should be closely monitored in college-age soccer athletes.

Consistent with our hypothesis, the present study replicated prior findings (Levitch et al., 2018) demonstrating that recent RHI exposure was related to poorer processing speed in a model that accounted for long-term RHI exposure and concussion history. Recent RHI exposure was sufficient to produce declines in processing speed, despite this study sample being younger in age and having fewer years of cumulative lifetime exposure to RHI than in Levitch et al. (2018). This suggests that processing speed may be the most sensitive neuropsychological domain for detecting early associations between recent RHI exposure and neuropsychological function in college-age soccer athletes and can potentially highlight players who are at risk for further neuropsychological decline with continued high level of exposure. The relationship of recent RHI exposure to neuropsychological function may reflect acute changes in brain networks (Di Virgilio et al., 2016), though longitudinal studies with neuroimaging are required to determine if these changes are transient or if they accumulate over time to produce further network dysfunction. Of note, the relationship between recent RHI exposure and processing speed was, as expected, slightly weaker and at a trend level following adjustment for multiple comparisons. This trend-level finding remains good support for the *a priori* hypothesis (Glickman, Rao, & Schultz, 2014) and is likely reflective of the sample size of the study. Lastly, although recent heading exposure was associated with better learning and memory, this finding should be interpreted with caution; when the p-value was adjusted for the false discovery rate, this exploratory finding was no longer significant, suggesting that it may be due to Type I error.

The hypothesis that long-term RHI exposure would be related to learning and memory was not supported. A potential explanation for the lack of an association is that college-age soccer athletes may not have accumulated sufficient exposure to RHI to demonstrate the same decrements in learning and memory seen in studies of adult amateur soccer players (Levitch et al., 2018; Moore et al., 2017). Specifically, these samples were relatively older (26.1 years and 23.4 years, respectively) and reported greater years of soccer play (17.9 years and 15.4 years, respectively) than the present sample of young adult college-age soccer players (19.6 years old, with 10.8 years of heading exposure). Another consideration is that prior studies have utilized four exposure groups (quartiles) and found that the highest quartile of exposure was related to worse learning and memory (Levitch et al., 2018; Lipton et al., 2013). Due to sample size, the present study utilized only two exposure groups (high and low headers); it is possible that this method was not sensitive enough to detect associations between those with the highest levels of exposure and worse learning and memory. Further studies with larger samples are required to fully characterize the relationship between long-term RHI exposure and neuropsychological function in college-age soccer athletes.

A novel finding of the present study was that sleep moderated the relationship between recent RHI exposure and sustained attention, such that at low levels of self-reported sleep duration, a high level of recent RHI exposure was related to worse sustained attention. This finding aligns well with studies that have examined the relationship between sleep and sustained attention following a recent TBI (Bloomfield et al., 2010; Wilde et al., 2007). For example, in Bloomfield et al. (2010), participants with poor sleep quality following a recent TBI had significantly worse sustained attention abilities than those with good sleep quality. In general, sleep disruptions have a strongly negative impact on sustained attention abilities (Lim & Dinges, 2010), with reports of increased reaction time on the PVT following less than seven hours of sleep per night (Belenky et al., 2003). To explain this strong association, it is thought that vigilance is a fundamental process impacted by sleep disturbances and is taxed during monotonous sustained attention tasks, resulting in declines in performance (Lim & Dinges, 2010). Additionally, studies of college-age soccer athletes have most commonly reported difficulties with attention (Rutherford, Stephens, Fernie, & Potter, 2009; Rutherford, Stephens, Potter, & Fernie, 2005). Overall, this finding suggests that sleep disturbances can exacerbate difficulties in sustained attention following exposure to recent RHI.

Conversely, for participants with greater sleep duration, sustained attention was preserved even following a high number of RHI. This is similar to a study that demonstrated improvements in sustained attention with treatment of TBI-related sleep disturbances (Wiseman-Hakes et al., 2013). The relationship of greater sleep duration to preserved neuropsychological function supports the notion that sleep is a neurorestorative behavior, during which the brain rests and recovers from injury (Nédélec, Halson, Abaidia, Ahmaidi, & Dupont, 2015). This finding suggests that sleep may also serve as a protective factor for neuropsychological function following exposure to recent RHI.

Several limitations of this study should be noted. As the present study was cross-sectional, the findings cannot impute a causal relationship between exposure to RHI, sleep disturbances, and declines in neuropsychological function. With this limitation in mind, however, the association of RHI and sleep with neuropsychological function was not diminished when accounting for lifetime concussion history. This helps clarify an area of discussion in the sports-related neuropsychology literature as it indicates that heading contributes to neuropsychological outcomes in soccer, independent of prior concussive events.

An additional limitation is the head impact exposure measures and sleep measures were obtained from self-report questionnaires. The HeadCount questionnaires (Catenaccio et al., 2016; Lipton et al., 2017; Lipton et al., 2013; Stewart et al., 2017) and PSQI (Carpenter & Andrykowski, 1998; Mollayeva et al., 2016) have demonstrated reliability and validity across settings but caution should still be taken when interpreting the results as recall bias cannot be excluded. Of note, all study participants completed the HeadCount questionnaires and PSQI in the same laboratory setting and at the same time point in the study visit to maximize recall reliability. Future studies can include both self-report and objective measures of sleep (e.g., actigraphy), as well as collateral information from significant others when available, to better address this limitation. The present study did not include a brain neuroimaging component, such as Diffusion Tensor Imaging. Associations found between RHI, sleep disturbances, and neuropsychological function may have been mediated by transient cellular or molecular changes to brain tissue. Neuroimaging of participants could have allowed for better understanding of the brain pathology underlying these associations. Additionally, given that normative data did not exist for all neuropsychological tasks, the inclusion of a control group would have been beneficial for inter-individual comparison.

Regarding the study sample, the sample size may not have had sufficient power to detect all meaningful interactions between RHI, sleep, and neuropsychological function. It is possible that with a larger sample, additional interactions between RHI and sleep on neuropsychological function would have been detected. Further, a larger sample would have allowed for the creation of four exposure groups, which, as mentioned above, may help to detect associations between long-term RHI exposure and neuropsychological function. As participation in the study was voluntary, a self-selection bias cannot be ruled out. However, there was equal representation among members of varsity and intramural teams and genders. Additionally, as participants were informed of the title and procedures of the study during informed consent, a potential for expectancy effects should be noted.

Lastly, the present study examined college-age soccer players from one university in the northeast region of the United States with a high-average level of estimated premorbid intellectual functioning. As such, the findings may not generalize to soccer athletes from other geographic regions or adolescent, adult amateur, or professional athletes, who may experience different patterns of head impact exposure. That said, the present study did require a high level of commitment to soccer play, participants incurred a comparable level of recent head impacts as seen in prior studies (Levitch et al., 2018), and had an equal gender representation (50% female).

Regarding clinical implications, the present study provides evidence that sleep interventions to improve sleep duration may mitigate the risks to sustained attention from RHI in soccer players. One potential intervention is extending sleep duration by requiring athletes to be in bed at least eight hours per night during the soccer season, which has improved athletic performance for basketball and tennis players (Mah, Mah, Kezirian, & Dement, 2011; Schwartz & Simon, 2015). Other interventions include emphasis of sleep hygiene strategies, such as limiting exposure to blue light before bedtime, limiting daytime naps, avoiding stimulants close to bedtime, establishing a bedtime routine, and being in a dark and quiet environment (Brown, Buboltz Jr, & Soper, 2002).

In conclusion, this study replicated our earlier finding of an association between recent head impact exposure and worse processing speed in an independent sample. In addition, we found that sleep may serve as a risk or protective factor for sustained attention in soccer players following extensive exposure to head impacts. Although differences in neuropsychological function between high and low exposure groups were not large enough to indicate a clinical impairment and may represent a transient phenomenon, the existence of even a subclinical effect of RHI on neuropsychological function provides a necessary, though not necessarily sufficient, substrate for cumulative functional decline over time. With over 265 million soccer players worldwide, any indication that heading exposure may account for declines in neuropsychological function, albeit it mild, is noteworthy. Future studies should continue to explore risk factors to inform public health interventions for soccer athletes. Ultimately, the present study provides empirical support for the use of sleep-hygiene interventions for soccer athletes to help ensure safe soccer play, minimize risk of declines in sustained attention, and optimize athletic performance.

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CONFLICT OF INTEREST

The authors have nothing to disclose.

SUPPLEMENTARY MATERIAL

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