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Sleep correlates of brain network activation and clinical measures in youth American football players

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Insufficient sleep can alter cognitive function and increase symptom reporting. We hypothesized that average sleep duration in youth American football players would correlate with higher-level processing event-related potentials (ERPs), symptom reporting, and objective measures of cognitive function on neuropsychological testing. We performed a prospective observational cohort study with 70 middle school and 64 high school American football players. Subjects completed preseason baseline assessments, including paper-pencil and computerized neuropsychological testing, a symptom scale, a neurological evaluation including self-reported sleep characteristics, and a Brain Network Activation (BNA) auditory oddball task assessing ERP activity. There was a correlation between shorter sleep duration and decreased capacity for memory and attention based on ERP amplitudes and latencies. Additionally, subjects with short sleep reported more "balance problems" and "sensitivity to noise," and feeling less "nervous or anxious" compared to subjects reporting recommended sleep. High school subjects with short sleep were also more likely to have a diagnosis of headache or migraine. There were no differences between the short and recommended sleep groups on neuropsychological testing. BNA may be a more sensitive measure of cognition than neuropsychological testing or standard clinical evaluation, detecting pre-clinical markers of decreased memory and attention capacity in athletes with short sleep duration.

KEYWORDS
baseline, children, concussion, evoked response potentials, insomnia, sports

1 | INTRODUCTION

Sleep is essential; studies have shown that insufficient sleep can cause impairments in both cognitive function and self-reported symptoms.[1-3] Previous studies have demonstrated that components of event-related potentials (ERPs) can be used to assess attention and memory capacity while performing a task.[4-8] Gumenyuk et al[9] reported a significant decrease in the amplitude of attention-related ERPs in adult patients who reported short sleep compared to normal sleep, suggesting decreased attention capacity. After having the habitual short sleepers extend their sleep duration for 1 week, they saw significant improvements in the gating amplitude of P50, which is a measure of attention function.[9,10] Studies looking at other ERP components, including P3, P2, N1, and P300, have shown effects on attention- and memory-related activity related to sleep disruption or deprivation.[11,12] Additionally, there have been recent longitudinal studies looking at predictors of cognitive impairment and dementia that found both quantitative and qualitative impairments in sleep were correlated with worse results on neuropsychological testing and a higher incidence of dementia and other cognitive complaints.[13-15]

Many athletes undergo a variety of symptom measures and neurocognitive testing at baseline and after injuries to help diagnose and manage concussion and other neurological injuries related to playing sports. Research suggests that sleep impairment can produce similar symptoms and cognitive difficulties to those commonly seen after concussion or as part of postconcussion syndrome.[1,3,16-18] Additionally, insufficient or inefficient sleep after traumatic brain injury is correlated with increased symptom reporting and worse cognitive performance.[16,19,20] Concussion is a complex injury lacking any single objective test to confirm diagnosis and thus is diagnosed clinically. Therefore, it is important to understand the many factors that can influence and mimic symptoms and signs of a concussion. Sleep is an extremely important factor to consider when diagnosing and managing an individual with concussion, and therefore, it is essential to understand the effects of both sleep quality and quantity on healthy individuals. In a study done by Beebe et al,[1] they asked healthy 14-17-year-old athletes to sleep either 6.5 or 9.5 hours over a 5-night period. During the short sleep period, subjects reported significantly more concussion-like symptoms such as headache, fatigue, irritability, and feeling slowed down, though they only performed worse on the verbal memory portion of the computerized neuropsychological testing.

Sleep symptoms are common after concussion, but sleep impairments occur frequently in the general population and can be a contributor to many of the common symptoms seen with concussion, both at baseline and after an injury. We hypothesized that average hours of reported sleep in middle school and high school American football players presenting for preseason baseline evaluations would correlate with increased latency and decreased amplitude of higher-level processing ERPs, symptom reporting, and objective measures of cognitive function on neuropsychological testing.

2 | MATERIALS AND METHODS

2.1 | Subjects

IRB approval was received through IntegReview, and informed consents were signed prior to any data collection. Middle school and high school varsity American football players from a local town were recruited to come in for baseline neurological evaluations prior to the start of the 2016 season as part of a longitudinal prospective study. Seventy middle school American football players aged 9-12 and 64 high school varsity American football players aged 15-17 were enrolled in the study, and they were each asked to report average hours of overnight sleep as part of a preseason neurological evaluation. All participants in the local youth American football program and all varsity players at the local high school were eligible to enroll in the study. Recruitment was done at player and parent meetings prior to the start of the season.

Subjects were grouped based on age and then divided into short sleep and recommended or higher sleep groups based on the guidelines from the National Sleep Foundation.[23] The recommended amount of sleep for the middle school participants (age 9-12) was defined as 9-11 hours. There were 19 middle school subjects who reported an average sleep duration shorter than the recommended amount and 51 who reported sleeping 9 hours or greater. The National Sleep Foundation recommends 8-10 hours of sleep per night for the high school-aged subjects (age 15-17). There were 26 high school subjects who reported having less than the recommended amount of sleep and 38 who reported sleeping 8 hours or greater.

2.2 | Oddball task

Event-related potential activity was recorded while participants performed an auditory oddball task. In this 600 trial task, subjects had to identify the Target tone, which were 100 Hz stimuli that occurred 10% of the time, by pressing a button. During the remainder of the task, subjects heard 2000 Hz stimuli that occurred 80% of the time (Frequent) and 10% of the time heard non-target stimuli that consisted of various tones (Novel). This task has been described in detail elsewhere.[24]

2.3 | EEG Recording and BNA STEPs algorithm

Recordings were obtained using a HydroCel Geodesic Sensor Net of 64 channels and a Net Amps 300 amplifier (Electrical Geodesic Inc, Eugene, OR, USA) with a sampling rate of 250 Hz. Artifact removal included noisy electrode removal (extensive temporal sections of the signal with an amplitude outside the range of ±100 μV or high dissimilarity to neighboring electrodes), noisy epoch removal (epochs with amplitudes outside the range of ±100 μV or amplitudes that were more than 7 standard deviations from the mean), and eye artifact correction using independent component analysis (ICA). All artifact removal stages were done using EEGLAB software (v. 9.0.4s).[25] Each EEG datafile was bandpass filtered into three distinct bands: delta (0.5-4 Hz), theta (3-8 Hz), and alpha (7-13 Hz). Each of these three bands is then epoched between −200 and 1200 ms around the stimulus trigger of each experimental condition, to create ERPs per frequency band. Trials with errors (misses and commissions) were rejected from the data prior to ERP averaging. The rate of errors was <2% for all subjects, with no differences between groups.

Event-related potentials were analyzed using the Brain Network Activation (BNA) algorithm as described in detail in Stern et al (2016).[24] In brief, ERP activity in each frequency band is segmented into spatiotemporal ERP peaks and their surroundings. The peaks are the local extremum of the amplitude in time and space. This results in a set of spatiotemporal parceled events (STEPs), that is, a set of segments that encapsulate the dynamic spatiotemporal information surrounding the ERP peaks. Reference BNA models were created by aligning and clustering the STEPs of all individual subjects of the reference population (as described below). Finally, STEPs extracted from subjects of the current study's ERPs were scored compared to the reference group's averaged STEP. Several STEPs' amplitude and latency scores were considered in the current study: the STEP corresponding to the N100 ERP component in the Frequent stimulus, the STEP corresponding to the P300a ERP component in the Novel stimulus, and the STEP corresponding to the PN component in Frequent stimulus. Examples are shown in Figure 1. These components were chosen based on known associations with higher cognitive functions, including attention.

In order to determine BNA STEP scores for the study participants, a large healthy control database collected from participants performing the auditory oddball task was utilized to generate an age and gender-specific electrophysiological network. The reference network for the high school group consisted of 120 healthy male subjects in the age range of 14-19 (mean age = 16.01, SD = 1.38); the reference network for the middle school group consisted of 120 healthy male subjects in the age range of 12-16 (mean age = 14.24, SD = 0.94). Exclusion criteria were as follows: a history of severe TBI or brain surgery, a history of mild TBI in the last year, a history of more than one concussion, any neurological or psychiatric disorder, substance abuse or current use of any medication affecting the central nervous system. Importantly, data from the subjects who generated the reference model were *not* included in the dataset of this study. All participants signed informed consent forms for undergoing the procedures, which were approved by the Institutional Review Boards of the respective centers.

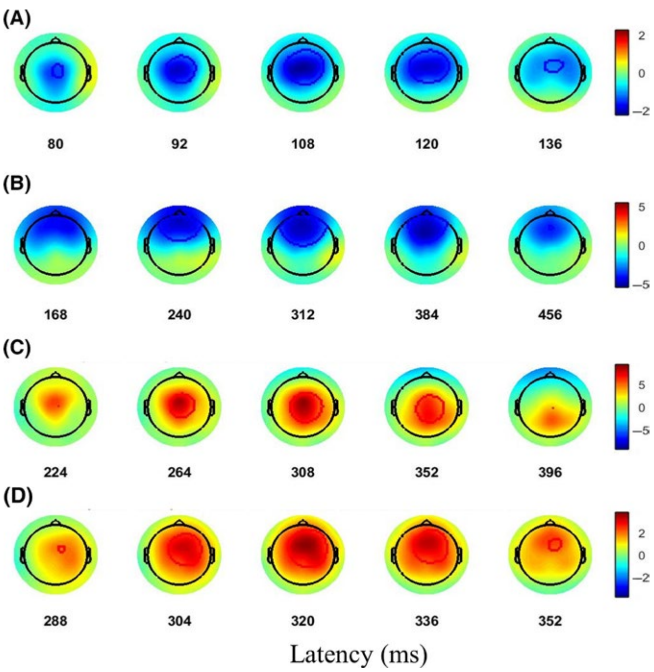

FIGURE 1 Spatiotemporal parcels (STEPs) of the BNA model reference group (14-19 year olds). Each STEP represents an encapsulated EEG activity at a specific frequency band, evolving during a specific time frame, and having a specific spatial distribution. The contours that appear inside the activation maps define each STEP's peak and surroundings. A, STEP activation corresponding to the N100 component in Frequent stimuli (theta 3-8 Hz filtering); B, STEP activation corresponding to the PN component in Frequent stimuli (delta 0.5-4 Hz filtering); C, STEP activation corresponding to the P300a component in Novel stimuli (delta 0.5-4 Hz filtering). Latencies (in msec) of the activation maps are indicated below every group, with the peak latency of each STEP stated below the central map and amplitude (in μV) is indicated on the vertical axis

2.4 | Additional assessments

Additionally, each participant completed a Sport Concussion Assessment Tool 3 (SCAT-3) symptom evaluation checklist, complete neurological history and exam, and a neuropsychological testing battery consisting of the following paper-pencil and computerized tests: CogState Brief Battery (Detection Test, Identification Test, One Card Learning Test, One Back Test), Test of Variables of Attention (TOVA), Child and Adolescent Memory Profile (ChAMP, Lists and Objects), and Wechsler Adult Intelligence Scale (WAIS, Digit Span, if 17 or older) or Wechsler Intelligence Scale for Children (WISC, Digit Span, if under 17). Part of the history included a survey of sleep characteristics where participants were asked to report the average amount of time it takes to fall asleep, the average duration of overnight sleep over the past year, and whether or not they snore.

2.5 | Statistical analysis

Amplitude and latency scores of the N100, P300a, and PN STEPs (see EEG recordings and BNA algorithm section) were correlated with reported average overnight sleep duration within each age group using a Pearson's correlation. Student's t tests were performed comparing sleep latency, total and sum and total symptom scores from SCAT-3, and scaled scores on formal neuropsychological testing batteries between the short and recommended sleep groups. The individual SCAT symptoms were also compared between the short and recommended sleep groups via a non-parametric Mann-Whitney test. A Bonferroni correction was applied for the SCAT-3 symptoms; there are 22 symptoms on the scale, so the P value was set to 0.002. Fisher's exact test was done on categorical data, the reported past medical history elements. All measurements were completed through Microsoft excel, except for the Fisher's exact test, which were completed through GraphPad.

TABLE 1 Demographics and medical history

	HS short sleep	SE	HS recom-mended sleep	SE	*P*-value	Youth short sleep	SE	Youth recom-mended sleep	SE	*P*-value
Number	26		38			19		51		
Age	16.46	0.138	16.32	0.11	0.20	10.79	0.096	10.53	0.098	0.068
Sleep										
Average hours of overnight sleep (h)	**6.96**	**0.107**	**8.62**	**0.11**	**<0.001**	**8.13**	**0.075**	**9.78**	**0.11**	**<0.001**
Average sleep latency (min)	26.92	7.070	19.41	3.85	0.16	**29.76**	**6.65**	**18.14**	**2.30**	**0.019**
Snoring	9 (34.6%)		7 (18.4%)		0.16	3 (15.7%)		6 (11.7%)		0.70
Past medical history										
Anxiety	0 (0%)		2 (5.3%)		0.51	1 (5.2%)		1 (1.9%)		0.47
Depression	1 (3.8%)		1 (2.6%)		1.00	0 (0%)		0 (0%)		1.00
Headache/Migraine	**15 (57.7%)**		**7 (18.4%)**		**0.003**	6 (31.6%)		25 (49%)		0.28
ADD/ADHD	6 (23.1%)		3 (7.9%)		0.14	4 (21.1%)		5 (9.8%)		0.24
1 or more previous concussion	13 (50%)		15 (39.5%)		0.45	2 (10.5%)		4 (7.8%)		0.66

ADD, attention deficit disorder; ADHD, attention deficit hyperactivity disorder; HS, high school; SE, standard error.
Bold indicates significance with $P \leq 0.002$.

TABLE 2 SCAT-3 Scores: individual and totals

	HS short sleep	SE	HS recommended sleep	SE	*P*-value	Youth short sleep	SE	Youth recommended sleep	SE	*P*-value
Total SCAT-3 score	3.65	0.87	3.63	0.76	0.49	3.58	1.10	2.96	0.55	0.29
Total SCAT-3 # of symptoms	2.39	0.54	2.50	0.48	0.44	2.21	0.51	2.30	0.42	0.45
Headache	0.19	0.079	0.21	0.094	0.12	0.11	0.072	0.14	0.063	0.12
"Pressure in head"	0.077	0.053	0.11	0.063	1.00	0.053	0.053	0.080	0.038	0.71
Neck pain	0.35	0.16	0.21	0.10	0.42	0.32	0.13	0.20	0.10	0.17
Nausea or vomiting	0.00	0.00	0.026	0.026	0.43	0.00	0.00	0.040	0.028	0.39
Dizziness	0.00	0.00	0.079	0.044	0.81	0.053	0.053	0.040	0.028	0.83
Blurred vision	0.00	0.00	0.026	0.026	0.43	0.053	0.053	0.080	0.048	0.91
Balance problems	0.19	0.11	0.00	0.00	0.15	0.00	0.00	0.040	0.028	0.39
Sensitivity to light	0.077	0.053	0.13	0.086	0.37	0.16	0.16	0.020	0.020	0.47
Sensitivity to noise	0.077	0.053	0.00	0.00	0.25	0.11	0.11	0.14	0.075	0.72
Feeling slowed down	0.23	0.14	0.21	0.077	0.14	0.00	0.00	0.24	0.10	0.12
Feeling "in a fog"	0.077	0.077	0.053	0.037	0.35	0.00	0.00	0.020	0.020	0.56
"Don't feel right"	0.038	0.038	0.079	0.058	0.79	0.00	0.00	0.080	0.038	0.23
Difficulty Concentrating	0.27	0.12	0.24	0.096	0.20	0.16	0.12	0.20	0.080	0.86
Difficulty remembering	0.19	0.096	0.21	0.094	0.43	0.16	0.086	0.16	0.052	0.99
Fatigue	0.62	0.17	0.66	0.15	0.45	0.16	0.086	0.22	0.091	0.79
Confusion	0.12	0.085	0.16	0.096	0.35	0.053	0.053	0.080	0.038	0.71
Drowsiness	0.54	0.19	0.47	0.14	0.074	0.16	0.12	0.12	0.054	0.93
Trouble falling asleep	0.35	0.18	0.32	0.15	0.56	**1.11**	**0.30**	**0.18**	**0.054**	**<0.001**
More emotional	0.077	0.077	0.00	0.00	0.43	0.21	0.16	0.12	0.046	0.93
Irritability	0.12	0.12	0.21	0.086	0.44	0.21	0.15	0.18	0.061	0.68
Sadness	0.038	0.038	0.00	0.00	0.43	0.11	0.11	0.12	0.054	0.58
Nervous or anxious	0.038	0.038	0.24	0.088	0.88	0.42	0.27	0.44	0.090	0.27

HS, high school; SCAT-3, sport concussion assessment tool; 3rd edition, SE, standard error.
Bold indicates significance with $P \leq 0.002$.

TABLE 3 Neuropsychological tests

	HS short sleep	SE	HS recommended sleep	SE	*P*-value	Youth short sleep	SE	Youth recommended sleep	SE	*P*-value
ChAMP										
Lists scaled score	11.040	1.92	10.16	0.94	0.33	11.16	0.47	11.29	0.42	0.43
Objects scaled score	10.54	2.15	8.66	0.40	0.15	10.16	0.68	10.98	1.09	0.33
WAIS/WISC										
Digit span scaled score	10.23	0.47	11.00	0.44	0.12	10.16	0.56	10.80	0.40	0.20
TOVA										
Variability *Z*-score	−1.46	0.55	−0.69	0.18	0.063	−2.10	0.32	−2.57	0.37	0.23
Reaction time *Z*-score	0.28	0.23	0.65	0.14	0.078	−0.89	0.31	−1.20	0.23	0.23
Commission *Z*-score	−0.68	0.20	−0.77	0.17	0.37	−0.73	0.30	−0.55	0.18	0.30
Omission *Z*-score	−5.96	3.35	−3.32	1.51	0.22	−1.96	0.50	−1.57	0.38	0.29
Attention comparison score	−0.26	0.79	0.88	0.39	0.081	−3.06	0.59	−3.31	0.52	0.40
CogState										
Processing speed	105.77	1.96	108.62	1.44	0.12	103.95	1.81	103.60	1.61	0.45
Attention	108.44	2.15	109.88	1.29	0.27	102.33	2.42	99.19	1.60	0.15
Learning	107.79	3.00	107.86	2.26	0.49	97.63	3.22	99.30	1.53	0.30
Working memory	108.08	1.71	107.82	1.38	0.45	99.26	2.09	96.04	1.75	0.16

ChAMP, child and adolescent memory profile; HS, high school; SE, standard error; TOVA, test of variables of attention; WAIS, Wechsler intelligence scale for children; WISC, Wechsler intelligence scale for children.

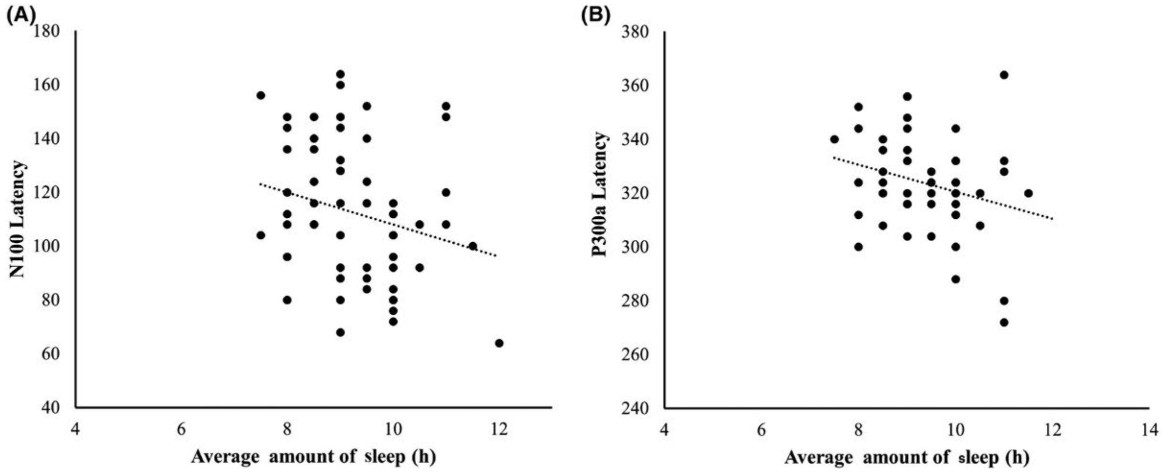

FIGURE 2 The correlation between the average reported amount of sleep (h) in middle school subjects. A, Correlation (−0.24) between the average amount of sleep and N100 latency ($P = 0.041$). B, Correlation (−0.26) between the average amount of sleep and P300a latency ($P = 0.029$)

3 | RESULTS

There was no significant difference between the age of the individuals in the short sleep group in comparison with the normal or higher sleep group in the middle school or high school players (middle school 10.79 vs 10.53 $P = 0.068$; HS 16.46 vs 16.32 $P = 0.20$) (Table 1). The average amount of reported overnight sleep in the middle school short sleep group was significantly lower than the average amount of reported sleep in the middle school recommended sleep group (8.13 ± 0.075 vs 9.78 ± 0.11 hours; $P < 0.001$). For the high school short sleep group, subjects reported a significantly lower average overnight sleep duration compared to the high school recommended sleep group (6.96 ± 0.11 vs 8.62 ± 0.11 hours; $P < 0.001$) (Table 1). The middle school short sleep group reported significantly longer average sleep latency than the middle school recommended sleep group (29.76 ± 6.65 vs 18.14 ± 2.30 minutes; $P = 0.019$). In high school subjects, there was no significant difference in reported sleep latency between the short and recommended sleep groups (26.92 ± 7.07 vs 19.41 ± 3.85 minutes; $P = 0.16$). There was no difference between any of the groups in self-report of snoring during sleep (Table 1).

In the middle school subjects, there were no significant differences between the short and recommended sleep groups for any of the past medical history elements that were assessed (anxiety, depression, headache, ADD/ADHD, and history of one or more prior concussions). In high school participants, there was a significant difference between groups for history of headache or migraine, with 15 (57.7%) individuals in the short sleep group having a history of headache or migraine compared with 7 (18.4%) individuals in the recommended sleep group ($P = 0.003$). There were no significant differences between the high school groups for any of the other past medical history elements (Table 1).

There was no difference between groups in either middle school or high school participants for total symptom score or the total number of symptoms reported on the SCAT-3 symptom evaluation. For individual symptoms, the middle school short sleep group reported "trouble falling asleep" significantly more in comparison with the recommended sleep group (1.11 ± 0.30 vs 0.18 ± 0.054; $P < 0.001$). There were no significant differences found in the symptoms for the high schoolers (Table 2).

There were no significant differences in any of the paper-pencil or computerized neuropsychological test scores between the short and recommended sleep groups for both high school and middle school participants (Table 3).

There was a significant correlation in middle school subjects between the average amount of reported sleep and the N100 latency STEP score ($r = -0.24$, $P = 0.047$) and P300a latency STEP score ($r = -0.26$, $P = 0.029$), with fewer hours of sleep correlating with prolonged latencies (Figure 2A,B). In high school subjects, there was a significant correlation between reported sleep duration and the PN amplitude STEP score ($r = -0.29$, $P = 0.020$) and P300a amplitude STEP score ($r = 0.30$, $P = 0.015$), with fewer hours of sleep correlating with decreased amplitudes (Figure 3A,B).

4 | DISCUSSION

Our results show that ERP activity involved in attention allocation and memory updating is associated with average overnight sleep duration in adolescence. Longer duration of sleep was correlated with larger amplitudes of the PN and the target detection-related P300a, implying the engagement of greater attentional resources during the task. PN is associated with executive attentional capacity and resource allocation.[26] Therefore, the finding that inadequate sleep is

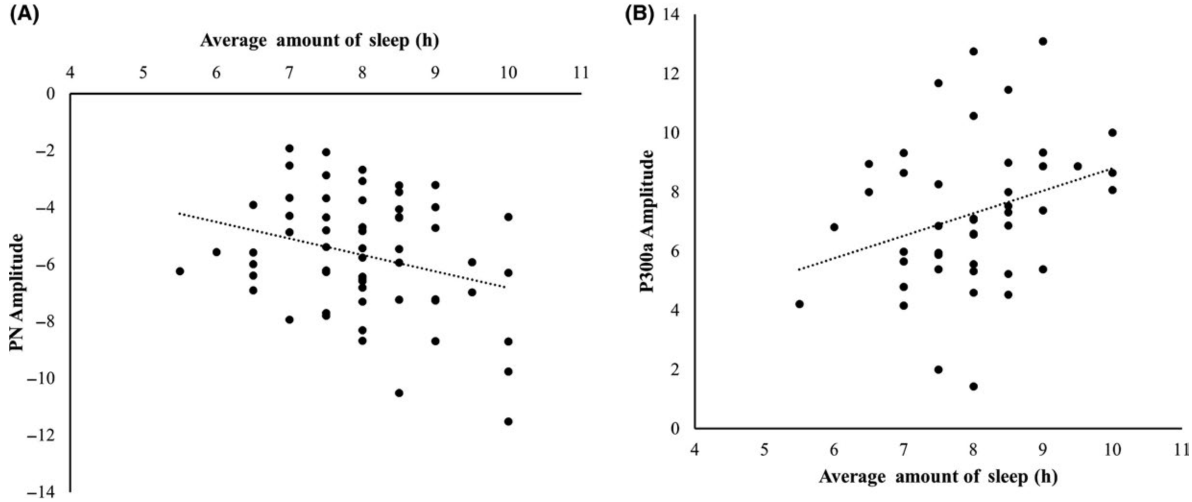

FIGURE 3 Correlations between ERPs and the average amount of reported sleep (h) in high school subjects. A, Correlation (−0.29) between the average amount of sleep and PN amplitude ($P = 0.020$). B, Correlation (0.30) between the average amount of sleep and P300a amplitude ($P = 0.015$)

associated with lower PN amplitude suggests a decreased attention capability. To our knowledge, there have been no other studies that report the effect of sleep on PN. P300a is associated with attention switching, novelty detection, and orienting of response to stimuli and has been shown to have a decreased amplitude in sleep deprived individuals.[10,27] Furthermore, this effect can be reversed with restoring normal sleep.[28] Other studies have shown P300 amplitude to be correlated with improved memory performance efficiency in young adults, with decreased amplitude being associated with worse efficiency.[29] Overall, this suggests that high school subjects reporting a short amount of overnight sleep on average may have an impaired learning ability due to diminished attention capacity and lengthened memory updating processes.

In middle school subjects, there were significant correlations to N100 latency and P300a latency with longer latencies associated with shorter amounts of reported sleep. N100 has a role in sensory encoding processes and is modulated by attention. This result suggests that lack of sufficient sleep may affect attention and can therefore modify sensory encoding processes. Previous studies also support our finding and show that sleep can affect N100, as well as behavioral performance.[30,31] Similar to our finding in high school subjects, there are alterations in P300a in individuals with short sleep, but rather than decreased amplitude, middle school subjects have prolonged latency. This change in latency suggests an impaired or delayed response with sleep deprivation. Latency in P300a is thought to represent neural speed and efficiency that stabilizes around the age of 12. P300a amplitude increases with brain maturation and represents growing cognitive capabilities.[32,33] Therefore, the differences seen in ERP latency vs amplitude in high school or middle school subjects could be due to the differences in their pubertal stages of brain development.[35]

While short sleep duration significantly correlated with ERP activity, there was a lower to no effect seen on past medical history, symptom reporting, and neuropsychological testing. After dividing the middle school and high school groups further into short sleep and recommended sleep groups, the middle school subjects with short sleep had significantly longer sleep latency and only reported more “trouble falling asleep.” The high school short sleep subjects were more likely to have a diagnosis of headache or migraine. For both middle school and high school participants, there was no difference between the short and recommended sleep groups on computerized or paper-pencil neuropsychological testing related to attention and memory.

These findings suggest that there are minimal to no significant differences in symptom reporting and neuropsychological testing measures of attention or memory in individuals reporting shorter average amounts of sleep. The finding that high school subjects with short sleep are more likely to have a diagnosis of headache or migraine supports previous published research that has described the complex interplay between headache and sleep, with sleep problems being associated with increased headaches and vice versa.[36,37]

Given the differences seen in ERP activity associated with memory and attention based on sleep duration, one potential explanation is that BNA could be considered an objective measure of brain function that is more sensitive to detecting changes that are not yet apparent clinically as symptoms or on neuropsychological testing. It is also possible that these ERP differences in short sleep individuals suggest that they may be more susceptible to having symptoms and cognitive difficulties in the event that an additional insult occurs, such as a concussion. In the future, it will be valuable to assess whether individuals with short sleep duration and altered ERP activity at baseline will be more likely to have severe or prolonged symptom courses and whether they specifically have more cognitive difficulties after injury.

One limitation of this study that could have allowed for bias in the results is that subjects were self-reporting on average hours of overnight sleep. These evaluations were conducted before the start of the fall American football season; therefore, the subjects were not currently in school and may have different sleep habits and patterns during the school year. To improve on this in the future, it would be valuable to have more objective measures of sleep, such as formal sleep questionnaires, detailed sleep diaries, or using wearable technology for portable sleep monitoring. Our study also only looked at sleep duration, snoring, and sleep latency. It would be of interest to compile a more comprehensive assessment of sleep quantity and quality, preferably looking at more objective measures in order to better evaluate the effect of sleep on these cognitive measures. Another limitation is that this study only included male football players, so may have limited generalizability to other populations of athletes, including females and participants in other sports.

5 | PERSPECTIVE

These results demonstrate that sleep factors, including sleep duration, can affect ERP activity related to attention and memory, but not necessarily cognitive functioning on formal neuropsychological testing and symptom reporting. Furthermore, there has been recent research suggesting an association between inadequate amounts of sleep and an increased risk of all injuries among athletes.[39] Additionally, there is recent evidence that impaired sleep, as measured via subjective reporting and objective testing, is associated with cognitive impairment later in life.[14] While our study only looked at baseline tests, it is possible that the memory- and attention- related ERP changes seen in the short sleep groups could make those individuals more susceptible to cognitive impairment after concussion. This warrants further investigation, given that many post-injury evaluations for concussion rely on measures of cognitive processing, and therefore, it could be important to consider the potential effect that altered sleep can have on each test when evaluating and managing individuals with concern for concussion. In addition to the need to account for the possible effects of sleep on ERPs when used in the context of concussion, ERP can be also be considered a potential tool for evaluating sleep primarily and in the context of other neurological disorders.

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