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ORIGINAL RESEARCH

Objective Neurophysiological Measures of Cognitive Performance in Elite Ice Hockey Players

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Introduction: Athletic peak performance is increasingly focused on cognitive and mental factors. In the current study, cognitive performance was measured by neurophysiological responses in elite Junior-A hockey players.

Methods: Neurophysiological brain vital signs were extracted from event-related potentials (ERPs) to evaluate auditory sensation (the N100), basic attention (the P300), and cognitive processing (the N400). In total, we evaluated 348 athletes, across 17 teams, throughout different hockey arenas in British Columbia, Canada. While brain vital signs were collected to help manage concussion, the current investigation focused on a retrospective performance analysis of cognitive processing differences.

Results: The results revealed three interesting findings: 1) Player position differences were detectable in sensory N100 latency, with significantly faster responses for forwards compared to defense; 2) Goalies showed significantly higher attention P300 amplitude compared to all other positions; and 3) Cognitive N400 processing differences were detectable only during competitive combine testing, showing 60ms latency differences between forwards and defense on average.

Discussion: The current findings suggest that neurophysiological responses, which are also sensitive to concussion, may be used to identify sensory, attentional, and cognitive processing differences to help optimize peak performance.

Keywords: electroencephalography, event-related potentials, brain vital signs, performance optimization, ice hockey

Introduction

Elite sports performance involves an intricate interplay of physical and cognitive/mental optimization. While athlete performance has advanced greatly in the physical domain, there is an increasing focus on cognitive/mental performance.[1] The multifaceted nature of sports performance incorporates a range of cognitive/mental skills to guide decision-making, anticipation, and strategic execution. Previous research has revealed that athletes generally show superior performance on measures of attention, processing speed, and response time than controls (reviewed by Voss et al and Mann et al),[2,3] suggesting that maintaining and optimizing cognitive/mental performance is an important contributing factor to athletic success. Consequently, optimizing cognitive performance has become a focal point for many athletes aiming to maintain a competitive edge.

Cognitive performance is improved through training.[4,5] Essentially, cognitive performance in an athletic context involves complex information processing from low-level sensation and perception to higher levels of attention and cognitive processing required for motor preparation and execution.[6–10] Athletes often engage in repeated practice of skills, offering a unique opportunity to study learning-based neuroplasticity,[11] the brain's inherent ability to rewire neural networks to adapt. Non-invasive brain imaging studies investigating neuroplasticity during motor skill learning have frequently shown that repetitive practice leads to changes in neural motor systems, which can vary depending on an array of factors.[12–17] These brain imaging methods have also been applied to elite athletes, revealing both structural[18] and functional electrophysiological differences[19–21] between elite athletes and control subjects. Outside of neuroimaging, cognitive tests have been employed to better understand functional cognition in elite athletes compared to control subjects[22] or amateur athletes,[23] as well as between different positions.[22,24] However, there remains a gap in

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understanding how cognitive performance improvements through training translate into measurable neurophysiological changes, particularly in elite athletic populations.

The brain vital sign framework[25] utilizes portable and accessible electroencephalography (EEG) to extract well-established event-related potentials (ERPs) as objective neurophysiological indicators of cognitive information processing.[26,27] As depicted in Figure 1, this framework has historically been applied to evaluate brain injury, more specifically concussion and subconcussion in athletes.[28–30] However, recent work has begun to use brain vital signs to track rehabilitation,[31,32] as well as attention training differences in healthy individuals.[33] Brain vital signs are also sensitive to subtle normative differences in elite hockey players compared with age-matched general population.[20] While evaluating brain vital signs across athletes presents a critical means for tracking concussive and subconcussive effects of contact sports, using brain vital signs to optimize cognitive performance represents a novel application. In turn, this may further reduce concussive and subconcussive impact exposure through quicker defensive reactions and responses.

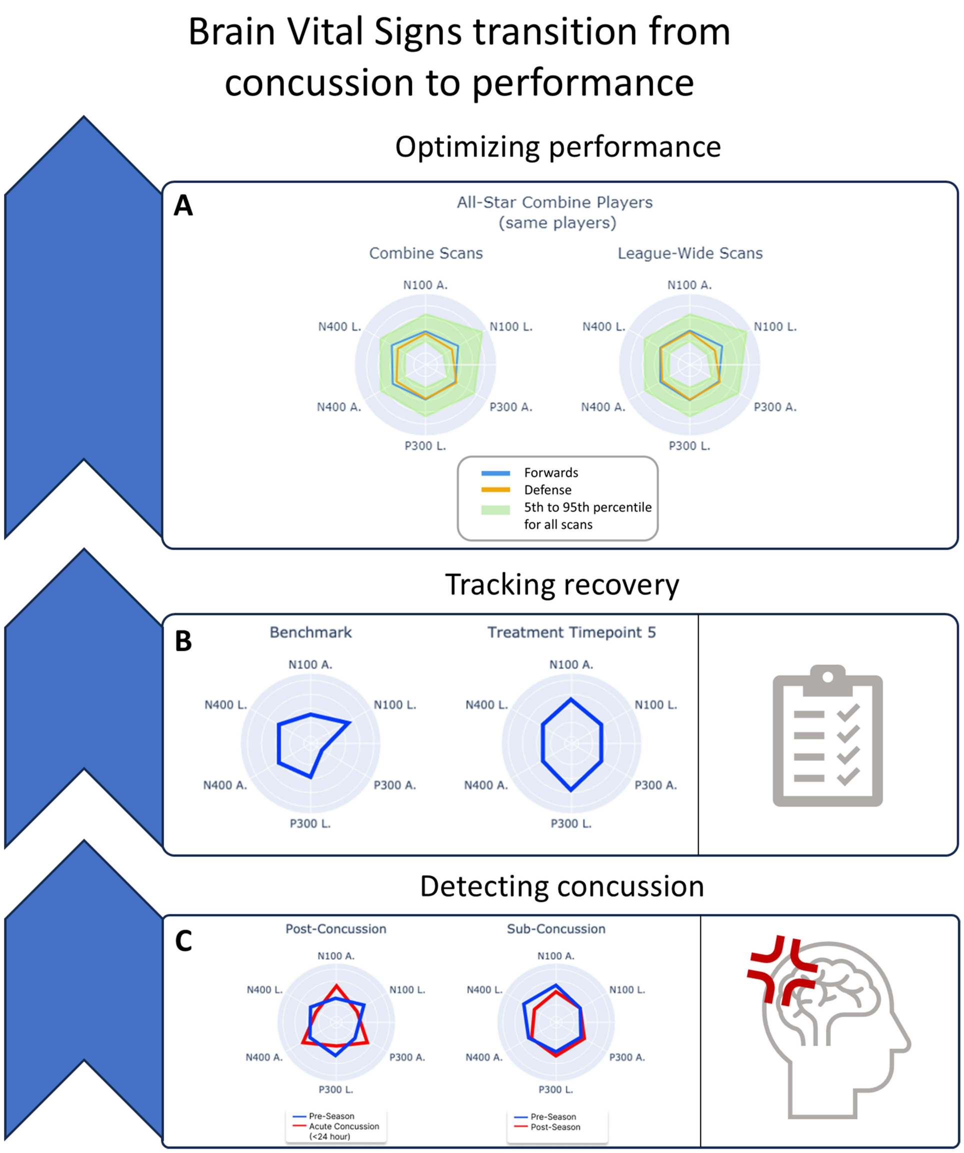

Figure 1 While injury management remains important; brain vital signs have also recently expanded to cognitive performance optimization in elite athletes and professionals. The figure portrays the use of brain vital signs across domains. (**A**) Radar plots of elite Junior-A ice hockey forwards and defense in the current study. (**B**) Figure depicted from Fickling et al 2020 showing the objective tracking of an open TBI survivor's recovery. (**C**) Figure depicted from Fickling et al 2019 (left) detecting acute (<24 hour) concussion and Fickling et al 2021 (right) objectively detecting the effect of subconcussive impact from pre (blue) to post (red) season of contact sport.

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The brain vital signs framework includes the N100 (associated with auditory sensation[34]), the P300 (associated with basic attention[35]), and the N400 (associated with higher-level cognitive processing[36]). These components are of particular interest as they are robust to within-subject variance across time[37,38] and can be reliably elicited in healthy individuals. The brain vital signs framework elicits and records the N100, P300, and N400 in a portable, rapid and automated device that can be readily integrated at point-of-care in sport facilities (ie, the NeuroCatch® Platform). Response latency (speed) and amplitude (size) are plotted for each of the three components, resulting in a symmetric hexagon shape as indicative of a normal healthy profile (Figure 1). Slower and reduced responses, such as those for severe cognitive impairment in dementia, shrink towards the center of the plot.[39]

EEG is a non-invasive electrophysiological measure of brain activity that has been previously used to investigate the neurophysiology underlying the neural efficiency of athletes[19,40–43] and the neurophysiological states associated with elite performance.[44] Derived from EEG, brain vital sign ERPs are stimulus time-locked responses extracted by signal averaging to obtain a specific recording of sensory, perceptual, and cognitive brain activity.[26,27,45] ERPs have been extensively studied since the 1960s and represent the brain's evoked neural responses to cognitive and sensory stimuli with high test-retest reliability.[37] ERP amplitude and latency are often used as the primary measures for these underlying neural responses.[46] Specifically, ERP amplitude changes represent relative increases or decreases in the number of neurons activated in synchrony, while ERP latency is a measure of stimulus processing time.[47]

As mentioned above, detecting brain vital sign effects of concussion and subconcussive impacts in athletes has an emerging support role in brain health and athlete safety. Importantly, these neurophysiological responses essentially measure sensory, attentional, and cognitive processing speed with millisecond resolution, along with the response size measuring the extent of cortical activation.[26] The N100 and P300 responses can be used as direct measures of sensory and attentional information processing speed, respectively. Perhaps more importantly, the N400 can provide a valuable measure of cognitive anticipation. The N400 has been previously linked to higher-level cognitive processing.[36,48] The N400 is best elicited when unexpected or incongruent stimuli mismatch from an expected pattern or outcome (eg, when hearing "Bread…Sing" rather than "Bread…Butter"). Accordingly, the N400 latency directly tracks the speed of cognitive anticipation or "readiness".

We have previously shown that cognitive training combined with neuromodulation can specifically modulate the N400 in terms of cognitive readiness or vigilance.[33] Further, we have recently reported that sleep deprivation negatively impacts both the P300 and N400 responses.[49] Cognitive training has also been shown to modulate ERP responses in parallel with performance changes in athletes.[50] Accordingly, the present study involved an observational, retrospective analysis of brain vital signs from Junior-A ice hockey athletes in British Columbia, Canada. We evaluated whether cognitive performance differences were detectable in a large sample of competitive contact male ice-hockey players. Two primary avenues of investigation included:

1. A comprehensive league-wide assessment was evaluated across all athletes. Preliminary analyses indicated that player position was a key factor in which significant brain vital sign differences were detectable. Therefore, we conducted a more in-depth examination of positional differences in a second follow-up analysis.
2. A specific evaluation of top-ranked players during competitive performance skills testing setting (All-Star combine) compared with league-wide evaluations. This analysis focused on brain vital sign differences as a function of common factors, such as player position and performance statistics. All-Star combine testing, compared to regular season testing demanded athletes to perform at their highest level in terms of high-level cognitive processing (N400, specifically).

As this was a retrospective, observational study in which previously de-identified data was analyzed, informed consent was not required by the Institutional Review Board. Despite this exemption, all participants signed a general services consent and waiver prior to completing the NeuroCatch EEG scans. This included the provision that NeuroCatch may use their de-identified data for the purpose of research.

This retrospective study did not require recruitment. The evaluation of brain vital signs using NeuroCatch was mandated by the league for all athletes.

Methods

Study Design

The present study involved a retrospective analysis of brain vital sign data from 348 (195 forwards, 118 defense, 35 goalies) elite, male, Junior-A (Junior-A refers to the league level) ice hockey players (mean age=19.6 years, range=17–21 years), collected during the 2022–2023 hockey season. A subset of 40 top players who participated in the All-Star combine completed additional brain vital sign scans during the combine event. The All-Star combine took place around the middle of the season. This retrospective study was reviewed and approved by the Advarra IRB (Pro00071356) and complies with the Declaration of Helsinki.

Data Collection

Brain vital signs were recorded using the NeuroCatch® Platform (Version 2.0). Subjects were fitted with a low-density EEG sensor cap (ANT Neuro Waveguard) with standard Ag/AgCl electrodes, and skin-electrode impedances were prepared to below 25 KOhms. Data were recorded from 3 midline electrodes (Fz, Cz, and Pz), with a ground electrode located at AFz, a reference electrode placed on the left earlobe, and a single electrooculogram (EOG) recorded from FPz. The scans took approximately 10 minutes in total, with brain vital sign testing for about 6 minutes. All athletes received passive repeated auditory stimulation (ear insert headphone) of standard tones (80 dB) and random rare deviant tones (105 dB) ahead of basic spoken word pair primes that either matched or mismatched. The tones stimuli elicited the N100 and P300 and the word pair stimuli elicited the N400.

Preprocessing

Recorded EEG traces were processed in Python. EEG data were filtered using a 0.1–20Hz bandpass and 60Hz notch filter. Ocular artifacts were corrected using an adaptive filter[51] with the EOG derived from the FPz channel. Stimulus-locked evoked epochs were extracted according to stimulus condition (ie standard/deviant tones, congruent/incongruent words). Epochs containing artifacts were rejected using an automated EEG signal-quality index.[52] Artifact-free epochs were averaged for each stimulus condition to form representative ERP waveforms for each participant. The N100, P300, and N400 peaks were automatically detected and manually verified.

Statistics

To assess positional effects across all league scans, a between (position [3]: forward, defense, goalie) subjects MANOVA was run. As a sub-analysis to assess the differences between league and combine testing, univariate analyses were done on forwards and defense that took part in both league-wide and combine scans (N=36) comparing each brain vital sign component at these two timepoints. All univariate analyses were *Bonferroni* corrected. Henze-Zirkler multivariate normality test was run on the different groups of MANOVA variables to assess normality of dependent variables. If any Henze-Zirkler multivariate normality tests deemed the dependent variables were non-normal, Kruskal–Wallis test was used. Additionally, non-parametric Dunn's test with False Discovery Rate (Ben-Hochberg) was used as the post-hoc testing of Kruskal–Wallis test results. All MANOVAs were run in SPSS (version 28)[53] and non-parametric Kruskal–Wallis and Dunn's tests were run in Python (version 3.9) with the SciPy package.[54]

Results

League-Wide Positional Effects

Figure 2 presents the observed differences between player position. The league scan between subjects MANOVA revealed a significant main effect of position ($F[12, 682] = 1.969$, $p = 0.025$, $\eta_p^2 = 0.033$). This analysis also revealed that assumptions of normality were not met, therefore Kruskal–Wallis test results were done to confirm significant effects of position on N100 latency ($X^2 = 9.999$, $p = 0.007$) and P300 amplitude ($X^2 = 6.381$, $p = 0.041$). Post-hoc non-parametric Dunn's test with Ben-Hochberg FDR correction revealed significantly faster N100 latencies for forwards relative to both defense ($p = 0.0456$, Figure 2A) and goalies ($p = 0.0175$, Figure 2A). Furthermore, P300 amplitudes were significantly higher in goalies than both forwards ($p = 0.0410$, Figure 2B) and defense ($p = 0.0364$, Figure 2B).

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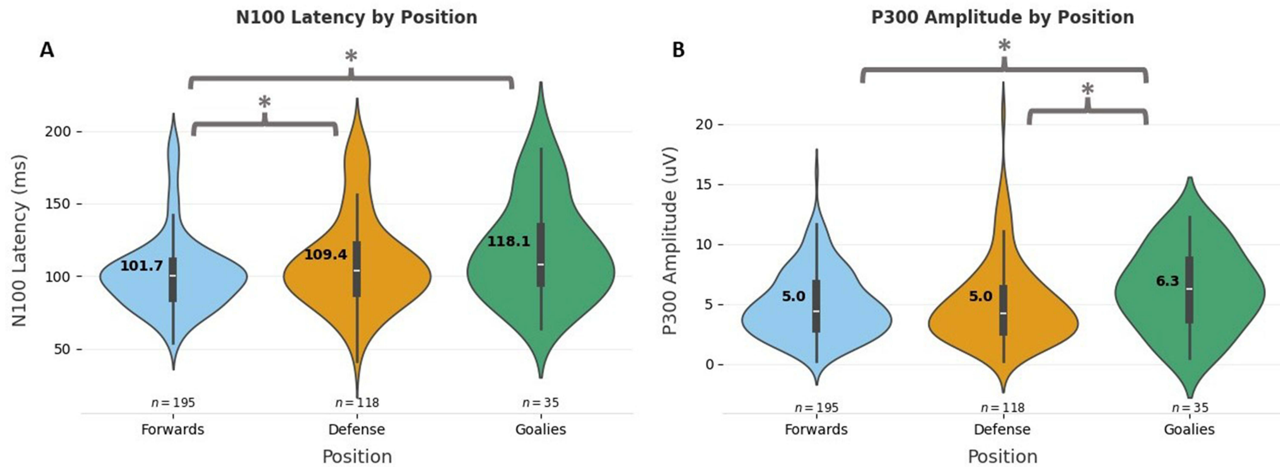

Figure 2 Violin plots showing the N100 latency (**A**) and P300 amplitude (**B**) differences between positions on a league-wide level (standard deviation lines and sample numbers included) *$p < 0.05$.

Figure 3 Radar plots of all six brain vital signs of All-Star players at their league and combine scans. N400 latency (N400 L.) only shows differences in the combine scans, while the N100 latency (N100 L.) difference can be seen in both league and combine scans. Green background shading includes the 5th to 95th percentile of all ice hockey player scans.

Combine-Effects

Figures 3 and 4 show the results in the smaller All-Star combine sub-sample. Univariate analysis revealed a significantly reduced N400 latency for forwards versus defense at the competitive environment timepoint (All-Star combine) scans ($F(1, 32) = 6.539$, $p = 0.015$, $\eta_p^2 = 0.170$) (Figures 3 and 4). Comparisons of the N100 latency for forwards and defense in combine testing collapsed across both timepoints also trended toward significance ($F(1, 32) = 3.623$, $p = 0.066$, $\eta_p^2 = 0.102$) (Values in Supplementary 1 – Supplementary Tables 1–3). Variables used in this analysis passed the Henze-Zirkler multivariate normality test.

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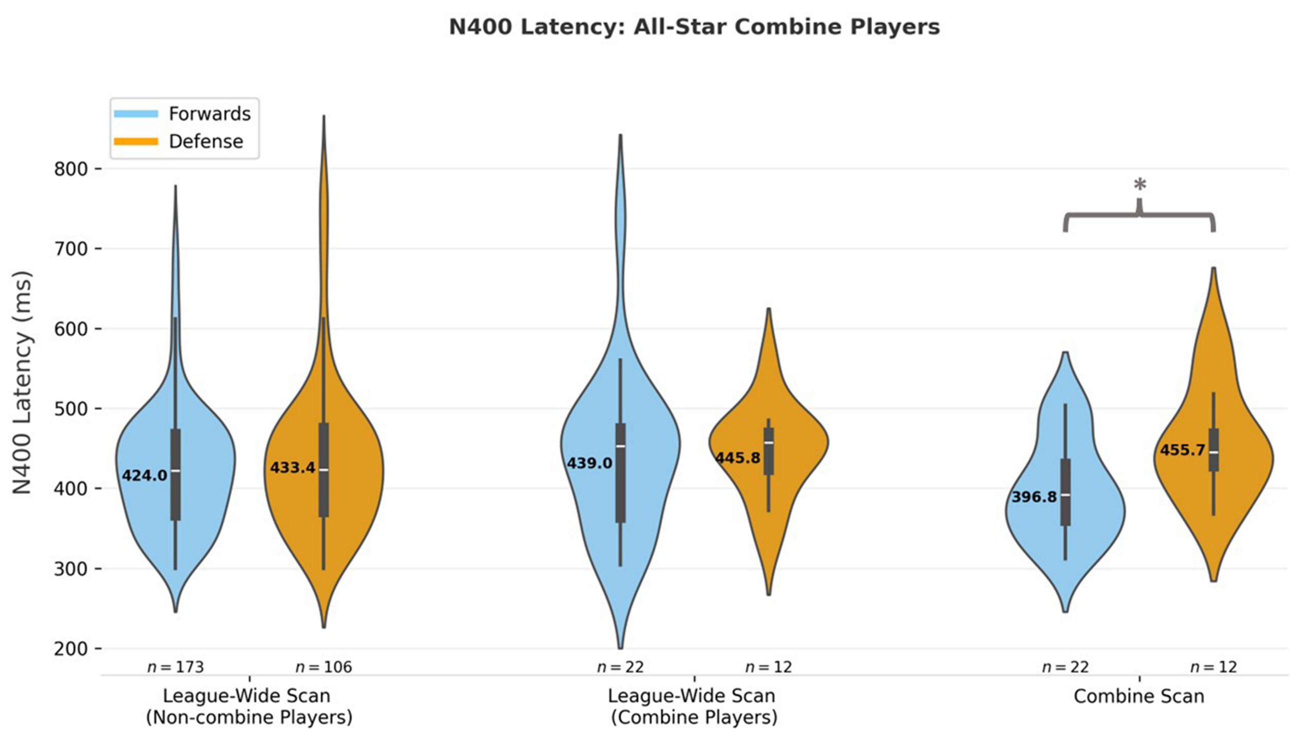

Figure 4 Paired violin plots comparing N400 latency in forwards (blue) and defense (green) in All-Star players at their league-wide and All-Star combine scans (standard deviation lines and sample size included). League-wide N400 latency of players not invited to the combine is also shown $*p < 0.05$.

Discussion

The current brain vital sign study investigated objective neurophysiological differences in the cognitive performance of elite ice hockey players. The investigation included 1) evaluating the effect of position across the entire league, with different positions showing significant differences in sensory N100 (forwards faster than defense) and attentional P300 (increased in goalies) processing responses; and 2) specifically evaluating positional differences at the All-Star combine event, with significant cognitive processing N400 differences (significantly faster responses for forwards relative to defense), which was further supported by similar N100 difference trends between forwards and defense. The analysis demonstrated that brain vital signs, initially shown to be sensitive to concussive and subconcussive impact exposure, may also be sensitive to cognitive performance factors.

The N100 and Auditory Sensory Processing

Across the whole league, we collected 348 brain vital signs scans. Results showed a position effect on a league-wide level, highlighted by N100 latency and P300 amplitude differences. Localized to the primary auditory cortex,[55] the N100 response has been associated with early cortical auditory sensory processing,[34] which has in-turn been linked to selective attention.[56,57] The league wide N100 latency effect (forwards faster than defense and goalies) may reflect greater utilization of auditory cues within the competitive environment of the forward position role. The forwards' heightened ability to rapidly process incoming sensory information may facilitate enhanced cognitive anticipation, enabling them to quickly anticipate the constantly changing environment on the ice. By comparison, defensive players are required to constantly adjust their position to keep the play in front of them most of the time, therefore having less dependence on cognitive anticipation.

The P300 and Attention

In addition to the innate N100 latency effect pertaining to different positional requirements, an effect of position on P300 amplitude was observed in goaltenders. Specifically, goaltenders showed significantly larger P300 amplitudes compared to both forwards and defense. Consistent with the positional requirements, increased P300 responses indicate enhanced engagement of cortical attentional networks, particularly related to the awareness of an individual's surrounding environment.[58] Jin et al[59] used a more direct sport-related task to elicit the P300, finding an increase in P300 amplitudes in professional badminton players over controls. The authors attributed the increased P300 amplitude in badminton professionals to primed access and/or directing of attention to game-related memory representations in the players.[59] In our study, the increased P300 amplitude in goaltenders may underly their strong ability to direct attention needed to stop hockey pucks during quick plays around the net. The P300 ERP component has long been connected and studied with reaction time,[60–62] which is an important skill to train in goaltending positions. Similar to our amplitude modulation findings, Ramchurn et al[60] determined that P300 amplitude rather than latency is associated with speed of reaction times. P300 amplitudes and latencies are interdependent factors reflecting a relative modulation in attentional processing.

The N400 and Cognitive Anticipation

The N400 is commonly associated with high-order cognitive processing,[36,63] and has previously been linked to modulated cognitive readiness in the current brain vital signs framework.[33] While most studies traditionally connect the N400 to semantic language processing,[64] Kitade et al[65] concluded that N400 effects are sensitive to cognitive processing beyond language comprehension. Indeed, Kutas et al[36] emphasized that the N400 ERP component does not end with connections to language, but also may extend to memory and attention.[36,48] The current N400 latency differences, with faster N400 responses in forwards selectively during All-Star combine evaluation suggests that contextual factors such as a highly competitive environment may drive dynamic changes in cognitive anticipation.

Consistent with this, our group has demonstrated that the N400 can be modulated through neuromodulation.[33] Specifically, translingual neurostimulation to improve attentional processing[66] during cognitive training resulted in a significant N400 amplitude constancy over the duration of training. Interestingly in the current study, there were significant N400 latency differences during the All-Star combine event and not in the league-wide evaluation (which had a higher sample size). The All-Star combine event was a higher-pressure competitive environment, suggesting that N400 cognitive anticipation differences may be situation-specific. This finding aligns with the concept that high performance athletes are required to shift cognitive/mental performance into a "performance-ready mode", optimizing relative performance strengths and abilities. If trackable by an objective neurophysiological measure, then everyday factors such as fatigue and cognitive readiness training become increasingly accessible as manageable performance factors. To this end, both the attentional P300 and the cognitive N400 have recently demonstrated significant impairments during sleep deprivation,[49] suggesting quick real-world applications for cognitive performance in athletes.[67–72]

Caveats

The current study was a large analysis of a Junior-A league-wide mandated brain vital signs assessment to evaluate cognitive performance optimization in elite sport. There are a number of caveats when interpreting results. First, the number of scans needed along with differing team schedules necessarily meant that scans were acquired at differing points in the season. As we have shown, brain vital sign responses are sensitive to subconcussive impact exposure across a season of contact sport.[29,30] Accordingly, the data in this study cannot be assumed to reflect a baseline, but rather a benchmark with relative difference existing despite this uncontrolled factor. Further work is needed to better control for the effects of subconcussive impacts over the season. Secondly, this was a real-world retrospective study that looked at a full league of high-level ice hockey players, therefore, grouping players by their positions will not be evenly weighted because of the number of positions in a typical line-up (12 forwards, 6 defense, and 2 goaltenders in an ice hockey game line-up). In particular, this meant that it was not possible to examine goaltender data in the All-Star combine event, as the sample size was prohibitively low. Future work will continue to scan more high-level players to increase group numbers for more in-depth analyses. It is additionally noted that some players may have switched positions throughout the season, that the positional categories are an initial general separation not reflecting differences within these categories, and that other uncontrolled factors in real-world studies likely contributed uncontrolled variability between positional average results. Nonetheless, the robustness of the current findings across the two comparisons strongly indicates the additional studies that incorporate increased experimentally controlled comparisons are warranted.

Conclusion

The current analysis investigated cognitive performance differences in brain vital signs in 348 elite Junior-A ice hockey players. Across the whole league, forwards showed faster auditory sensory processing relative to defense and goalies, goalies showed enhanced attentional processing relative to forwards and defense, and top-ranked forwards in the All-Star combine event showed faster cognitive processing relative to defense. These results highlight cognitive differences with rapid, objective measures of neurophysiology in elite athletes. Optimizing cognitive performance for these athletes may not only have direct benefits, but also indirect benefits in terms of reduced subconcussive impact risk in contact sports, as measured by objective neurophysiological impairments.

Data Sharing Statement

Sharing of this data, supporting the conclusions of this article, will be made available by the authors, without undue reservation, to any qualified researcher. However, it is not currently available in any publicly accessible source. Any interest in receiving the data should be expressed to the corresponding author.

Ethics Statement

This retrospective study was reviewed and approved by the Advarra IRB (Pro00071356) and complies with the Declaration of Helsinki.

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Disclosure

EDK, SDF, RCND have financial and/or business interests in HealthTech Connex Inc., which may be affected by the research reported in this paper. The authors report no other conflicts of interest in this work.

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