Evaluating the impact of neurophysiological fatigue patterns on tactical decision-making in elite football players using wearable EEG technology

Evaluación del impacto de los patrones de fatiga neurofisiológica en la toma de decisiones tácticas en jugadores de fútbol de élite mediante tecnología EEG portátil

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Abstract

Introduction: Elite football performance hinges on rapid tactical decision-making under physical and cognitive strain. While peripheral fatigue's effects on motor output are well documented, the neurophysiological markers of mental fatigue and their impact on in-game decision making remain underexplored.
Objective: To determine how EEG-derived central fatigue indices—frontal theta power and the theta/alpha ratio—relate to tactical decision accuracy and speed in elite football players.
Methodology: Twenty male national-level footballers (age 22.4 ± 2.1 years; ≥ 5 years' experience) completed the Yo-Yo Intermittent Recovery Test Level 1 while wearing an 8-channel dry-electrode frontal EEG headset. Frontal theta (4–7 Hz), alpha (8–12 Hz), and the theta/alpha ratio were extracted pre- and post-test. Decision-making was assessed via a validated 40-scenario video-based tactical test measuring accuracy (%) and reaction time (ms).
Results: Post-fatigue, frontal theta increased by 45% and the theta/alpha ratio by 47% (both $p < 0.001$), while decision accuracy declined by 15% ($p = 0.004$) and reaction time slowed by 18% ($p = 0.002$). The theta/alpha ratio explained 52% of variance in decision accuracy ($p < 0.001$).
Discussion: These findings confirm that wearable EEG markers sensitively capture central fatigue effects and directly predict tactical decision impairments, extending central fatigue theory to applied sport contexts.
Conclusion: Frontal theta and the theta/alpha ratio are robust, portable biomarkers for monitoring cognitive fatigue in football, offering practical avenues for real-time performance management and optimized training or substitution strategies.

Keywords

Mental fatigue; EEG biomarkers; frontal theta power; decision-making; soccer performance; cognitive load; sports neuroscience; fatigue and cognition; reaction time.

Resumen

Introducción: El rendimiento en el fútbol de élite depende de la rápida toma de decisiones tácticas bajo tensión física y cognitiva. Si bien los efectos de la fatiga periférica en la capacidad motora están bien documentados, los marcadores neurofisiológicos de la fatiga mental y su impacto en la toma de decisiones durante el partido siguen siendo poco explorados.
Objetivo: Determinar cómo se relacionan los índices de fatiga central derivados del EEG (potencia theta frontal y relación theta/alfa) con la precisión y la velocidad de las decisiones tácticas en futbolistas de élite.
Metodología: Veinte futbolistas masculinos de nivel nacional (edad 22,4 ± 2,1 años; ≥ 5 años de experiencia) completaron la Prueba de Recuperación Intermitente Yo-Yo Nivel 1 con un auricular de EEG frontal de electrodos secos de 8 canales. Se extrajeron las propiedades theta frontal (4-7 Hz), alfa (8-12 Hz) y la relación theta/alfa antes y después de la prueba. La toma de decisiones se evaluó mediante una prueba táctica validada basada en vídeo de 40 escenarios que midió la precisión (%) y el tiempo de reacción (ms). Resultados: Tras la fatiga, la theta frontal aumentó un 45% y la relación theta/alfa un 47% (ambos $p<0{,}001$), mientras que la precisión de decisión disminuyó un 15% ($p=0{,}004$) y el tiempo de reacción se ralentizó un 18% ($p=0{,}002$). La relación theta/alfa explicó el 52% de la varianza en la precisión de decisión ($p<0{,}001$).
Discusión: Estos hallazgos confirman que los marcadores electroencefalográficos portátiles captan con precisión los efectos de la fatiga central y predicen directamente las deficiencias en la toma de decisiones tácticas, lo que extiende la teoría de la fatiga central a contextos deportivos aplicados.
Conclusión: La theta frontal y la relación theta/alfa son biomarcadores robustos y portátiles para la monitorización de la fatiga cognitiva en el fútbol, ofreciendo vías prácticas para la gestión del rendimiento en tiempo real y estrategias optimizadas de entrenamiento o sustitución.

Palabras clave

Fatiga mental; biomarcadores EEG; potencia theta frontal; toma de decisiones; rendimiento futbolístico; carga cognitiva; neurociencia deportiva; fatiga y cognición; tiempo de reacción.

Introduction

Elite football demands split-second tactical decisions integrated with complex perceptual cues and motor actions. Cognitive processes such as selective attention, working memory, and inhibitory control underpin these decisions and have been shown to differentiate higher- from lower-level performers (Vestberg et al., 2012). While prior research has established that executive function metrics correlate with on-field success (Haugan et al., 2025), the neurophysiological mechanisms linking fatigue to decision-making performance in football remain insufficiently explored. Moreover, the integration of physiological and cognitive fatigue assessments remains limited in elite sport science, creating a need for studies that bridge neural metrics with performance outcomes.

In applied settings, both field and laboratory protocols are commonly used to induce fatigue and study its consequences. One of the most ecologically valid and widely used field-based assessments is the Yo-Yo Intermittent Recovery Test Level 1 (YYIRT1), which mimics the start-stop nature of football play. The test consists of repeated 20-meter shuttle runs at progressively increasing speeds, interspersed with brief recovery periods. It reliably induces high physiological load and has been employed to investigate physical, cognitive, and neuromuscular fatigue in elite football contexts (Bangsbo, 1994; Al-Nedawy & Saeed Al-Mousawi, 2022).

Peripheral fatigue in football is characterized by declines in muscle force production, repeated sprint ability, and metabolic disruptions (Bangsbo, 1994; Al-Nedawy & Saeed Al-Mousawi, 2022). However, central or cognitive fatigue manifested through altered brain activity can precede or exacerbate peripheral decrements, disproportionately impairing executive control functions critical for rapid tactical judgments (Boksem et al., 2005; Lorist et al., 2005). Mental fatigue has been associated with increased subjective effort and performance declines in tasks requiring sustained attention and decision-making (Hopstaken et al., 2016; Smith et al., 2015). Decision-making speed is a critical determinant of performance in both professional and academic soccer players, underscoring the need to understand factors that can impair this cognitive function (Teoldo et al., 2023).

Mental fatigue has been extensively documented to impair cognitive functions critical to athletic performance (Van Cutsem et al., 2017; Hussein Kadhim et al., 2025), such as attention, working memory, and decision-making. For instance, Gantois et al. (2020) demonstrated that professional soccer players exhibited diminished passing decision-making abilities following mentally fatiguing tasks, highlighting the susceptibility of cognitive skills to fatigue-induced decline. Similarly, Martin et al. (2018) found that mental fatigue adversely affected pacing strategies in endurance athletes, suggesting that cognitive exhaustion can disrupt self-regulatory processes essential for optimal performance. These findings underscore the pervasive influence of mental fatigue across various sports disciplines.

Electrophysiological studies have provided insights into the neural correlates of fatigue-related cognitive impairments. Increased theta and alpha band activities, as measured by EEG, have been associated with reduced alertness and impaired decision-making under fatigue (Barwick et al., 2012). Moreover, research by Sun et al. (2021) indicates that mental fatigue can lead to significant decrements in sport-specific psychomotor performance, further emphasizing the need to monitor and manage cognitive load in athletic settings. Understanding these neural and behavioral dynamics is crucial for developing interventions aimed at mitigating the adverse effects of fatigue on athletic performance.

Recent advances in wearable neurotechnology allow for real-time monitoring of brain rhythms in applied sports settings. Dry-electrode EEG systems facilitate unobtrusive recording of frontal midline activity, with theta-band (4–7 Hz) power serving as a robust index of cognitive load and fatigue, and alpha-band (8–12 Hz) power inversely reflecting cortical engagement (Cavanagh & Frank, 2014; Klimesch, 2012; Lopez-Gordo et al., 2014). The theta/alpha ratio has emerged as a sensitive composite marker of mental fatigue, validated in both laboratory tasks and operational environments (Borghini et al., 2014).

In the context of this study, key constructs are operationally defined as follows: Cognitive fatigue is characterized as a measurable decline in mental performance following sustained physical or mental exertion, identified through increased frontal theta power and an elevated theta/alpha ratio. Frontal theta power refers to EEG signal power in the 4–7 Hz range recorded over frontal brain regions, associated with cognitive effort and fatigue (Cavanagh & Frank, 2014). The theta/alpha ratio, calculated as theta power divided by alpha power, serves as a robust index of neural fatigue (Borghini et al., 2014). Tactical decision accuracy is defined as the percentage of correct responses on a validated video-based decision-making test (Vestberg et al., 2012), and reaction time is the latency from stimulus onset to participant response.

Despite these technological advances, no studies have directly linked EEG-derived fatigue markers to tactical decision-making deficits in elite football. Integrating neurophysiological metrics with validated decision tests could reveal the temporal dynamics by which fatigue impairs cognitive performance under realistic game-like conditions. Accordingly, this study aims to examine how EEG-based markers of cognitive fatigue (frontal theta power and the theta/alpha ratio) are influenced by a standardized field fatigue protocol (YYIRT1) and how these neurophysiological indicators relate to decision-making performance in elite footballers.

In this study, cognitive fatigue is conceptualized as a decline in mental performance following sustained physical or cognitive exertion, operationalized through increased frontal theta power (4–7 Hz) and an elevated theta/alpha ratio (Boksem et al., 2005; Lorist et al., 2005). Frontal theta power refers to the spectral power captured at frontal EEG channels within the theta frequency band and is indicative of cognitive workload (Cavanagh & Frank, 2014). The theta/alpha ratio, calculated as the quotient of theta-band power to alpha-band power (8–12 Hz), serves as a composite marker of mental fatigue (Borghini et al., 2014). Tactical decision accuracy is defined as the percentage of correct responses in the 40-scenario video-based test, representing decision quality (Vestberg et al., 2012), whereas reaction time denotes the latency, in milliseconds, from scenario presentation to participant response, reflecting decision speed (Vestberg et al., 2012). Finally, the Yo-Yo Intermittent Recovery Test Level 1 (YYIRT1) is employed as a graded shuttle-run protocol comprising 20 m runs at incrementally increasing speeds interspersed with 10 s of active recovery to reliably induce physical fatigue under controlled conditions (Bangsbo, 1994).

Specifically, the study has three goals: to quantify changes in frontal theta power and the theta/alpha ratio following the fatigue protocol; to evaluate the effects of these EEG-based markers on tactical decision accuracy and reaction time; and to determine whether post-fatigue frontal theta and theta/alpha ratio significantly predict decision-making performance.

Based on prior literature, we hypothesize that: (1) fatigue induced by the YYIRT1 will increase both frontal theta power and theta/alpha ratio; (2) tactical decision accuracy will decline and reaction times will increase post-fatigue; and (3) both EEG metrics will significantly predict post-fatigue decision-making outcomes.

Method

Participants

Twenty male elite football players (defined as individuals actively competing in the top national league with a minimum of 5 years of high-level training and national tournament experience) participated in the study (mean age 22.4 ± 2.1 years; height 179.6 ± 5.8 cm; body mass 74.2 ± 6.4 kg; competitive experience 8.1 ± 1.7 years). Inclusion criteria included: a minimum of five years of competitive football experience, current participation in a professional or semi-professional league, absence of musculoskeletal injury in the past six months, normal or corrected-to-normal vision, and right-foot dominance. Participants provided written informed consent before participation.

Ethical approval was granted by the University of Baghdad Sport Science Research Ethics Committee and signed by the committee chairperson.

Given the semi-invasive nature of EEG recording, the study underwent additional review by the University's Applied Neuroscience Ethics Subcommittee, which confirmed the procedure's non-clinical risk status under national bioethics guidelines.

Table 1. Descriptive Statistics of Within-Subject Factor Levels

Variable	Mean	Std. Deviation	Min	Max
Age (years)	22.4	2.1	19	25
Height (cm)	179.6	5.8	170	188
Body mass (kg)	74.2	6.4	62	85
Competitive experience (years)	8.1	1.7	5	11

Fatigue Protocol

All players began with a 10-minute standardized dynamic warm-up including jogging, leg swings, and active mobility exercises. They then completed the Yo-Yo Intermittent Recovery Test Level 1 (YYIRT1), which consisted of 2 × 20 m shuttle runs at progressively increasing speeds, increasing by 0.5 $km\cdot h^{-1}$ per level, with 10 s of active recovery between each repetition. The test was performed outdoors on a synthetic turf field under standard environmental conditions (temperature: 21–24 °C; wind < 5 km/h).

The testing session was supervised by three trained sports scientists and one certified fitness coach who ensured pacing, timing, and data collection.

Heart rate was continuously monitored using Polar H10 chest straps, and ratings of perceived exertion (RPE) were collected every 2 minutes in private using printed Borg CR10 scale sheets to avoid social influence from peers.

The test concluded upon voluntary exhaustion or failure to maintain the required shuttle pace twice consecutively.

EEG Recording & Processing

EEG data were collected using an 8-channel dry-electrode wireless headset with a frontal montage (Fp1, Fp2, F3, F4, Fz), sampled at 250 Hz (Lopez-Gordo et al., 2014). Electrode contact impedance was maintained below 50 kΩ throughout data acquisition. The system was calibrated before each session. Data were bandpass filtered (1–40 Hz), and motion and blink artifacts were removed using independent component analysis (ICA). Cleaned data were segmented into 30-second non-overlapping epochs. Power spectral density (PSD) was computed using Welch's method (2-second Hamming windows, 50% overlap). Spectral power was extracted for the theta (4–7 Hz) and alpha (8–12 Hz) bands. The theta/alpha power ratio, calculated from the same segments, served as the primary index of mental fatigue (Borghini et al., 2014). All recordings were conducted in a quiet indoor room under constant lighting and temperature (~23 °C), approximately 5 minutes before and after the fatigue protocol.

Tactical Decision-Making Test

A validated video-based tactical decision-making test (Vestberg et al., 2012) was used to measure cognitive performance. The test consisted of 40 real-game scenarios from professional matches, displayed on a 24" LED monitor (1920 × 1080 resolution). Each video paused at a critical decision point, requiring the participant to select the optimal action (pass, shoot, or hold) using a response box. Accuracy (%) and reaction time (ms) were recorded for each decision. Pre-test assessments were conducted 5 minutes after the warm-up, and post-fatigue measurements were obtained within 3 minutes following the YYIRT1. No feedback was given at any point to prevent performance bias.

Statistical Analysis

All statistical analyses were performed in SPSS v27. Data normality was confirmed by Shapiro–Wilk tests. Paired-samples t-tests compared pre- and post-fatigue measures. Effect sizes (Cohen's d) were calculated. Pearson correlation coefficients evaluated linear relationships between EEG indices and decision outcomes. Stepwise linear regression identified the best EEG-derived predictor of decision accuracy. Statistical significance was set at $\alpha = 0.05$. All statistical assumptions, including normality, linearity, and homoscedasticity, were confirmed before running inferential tests.

Ethics Statement

The study protocol was approved by the University of Baghdad Ethics Committee, and all participants provided written informed consent in accordance with the Declaration of Helsinki.

Sample Size Justification

A priori power analysis conducted with G*Power 3.1 for paired samples t-tests (two-tailed, effect size d = 0.8, α = 0.05, power = 0.80) indicated a minimum required sample size of N = 15. Our final sample of N = 20 exceeds this threshold, ensuring adequate statistical power to detect large effect sizes. A final sample of 20 participants was recruited to ensure adequate power and account for potential dropouts.

Reliability of Measures

The video-based tactical test exhibited strong psychometric properties. Internal consistency (Cronbach's α = 0.89) and test–retest reliability (intraclass correlation coefficient [ICC] = 0.92) were established during a pilot study with a comparable athletic cohort. EEG band powers also demonstrated high within-subject stability at rest (ICC = 0.87 for theta, ICC = 0.85 for alpha).

Fatigue Protocol

Participants performed the YYIRT1, consisting of 2 × 20 m shuttle runs at increasing speeds interspersed with 10s active recovery (Bangsbo, 1994). Heart rate (Polar H10) and RPE (Borg CR10) were recorded at 2 min intervals. RPE scores were collected privately using individual printed Borg CR10 sheets to prevent peer influence. A total of four trained staff, three sports scientists and one certified strength & conditioning coach were responsible for pacing, data collection, and test standardization.

EEG Recording & Processing

An 8-channel dry-electrode headset (frontal montage: Fp1, Fp2, F3, F4, Fz) sampled at 250 Hz (Lopez-Gordo et al., 2014). Data were bandpass-filtered (1–40 Hz), epoched into 30 s segments, and artifacts removed via ICA. Power spectral density (Welch's method) computed theta (4–7 Hz) and alpha (8–12 Hz) band powers; the theta/alpha ratio served as the fatigue index (Borghini et al., 2014).

Tactical Decision Test

A validated, video-based protocol presented 40 game scenarios from professional match footage (Vestberg et al., 2012). Players used a response pad to select optimal actions. Accuracy (%) and reaction time (ms) were recorded pre-YYIRT1 (baseline) and post-YYIRT1 (fatigued).

Statistical Analysis

Normality was confirmed (Shapiro-Wilk). Paired t-tests compared EEG and decision metrics pre- vs post-fatigue. Pearson's r evaluated correlations between EEG indices and decision outcomes. Stepwise linear regression determined the best EEG predictor of accuracy. Significance α = 0.05. Analyses were conducted in SPSS v27.

Results

Normality Testing

To ensure parametric assumptions were met, a Shapiro–Wilk test was performed on all primary variables (EEG and decision metrics). None showed significant deviations from normality ($p > .05$), confirming suitability for t-tests and regression analyses.

Table 2. Shapiro–Wilk Normality Test Results

Variable	W	p-value
Frontal theta (pre)	0.96	0.68
Frontal theta (post)	0.94	0.46
Theta/alpha ratio (pre)	0.97	0.75
Theta/alpha ratio (post)	0.95	0.53
Accuracy (%) (pre)	0.98	0.83
Accuracy (%) (post)	0.96	0.61
Reaction time (pre)	0.97	0.71
Reaction time (post)	0.93	0.40

Note. All variables showed non-significant Shapiro–Wilk test results ($p > 0.05$), confirming normal distributions.

Fatigue Verification

Fatigue induction was confirmed via high-intensity performance on the Yo-Yo Intermittent Recovery Test Level 1. Mean distance was 1900 ± 210 m, peak heart rate was 186 ± 5 bpm, and RPE averaged 17.8 ± 1.3, indicating high exertional states.

EEG and Decision-Making Changes Pre- and Post-Fatigue

To simplify data presentation, EEG and decision metrics were combined in one table to highlight cognitive responses to fatigue. Paired-samples t-tests were conducted for each variable.

Table 3. Changes in EEG and Decision-Making Metrics Pre- and Post-Fatigue

Variable	Pre-Fatigue (M ± SD)	Post-Fatigue (M ± SD)	Δ (%)	t(19)	p-value	Cohen's d
Frontal theta (μV^2)	4.2 ± 0.6	6.1 ± 0.8	+45%	8.32	< .001	2.70
Frontal alpha (μV^2)	7.2 ± 1.0	7.2 ± 1.2	0%	0.16	.87	0.05
Theta/alpha ratio	0.58 ± 0.09	0.85 ± 0.12	+47%	7.84	< .001	2.62
Accuracy (%)	82.5 ± 5.4	70.1 ± 6.2	–15%	-6.54	< .001	2.12
Reaction time (ms)	942 ± 85	1114 ± 102	+18%	5.91	< .001	1.79

Note. Paired t-tests were used to compare pre- and post-fatigue values. Effect sizes interpreted as per Cohen (1988).

Table 3 presents pre- and post-fatigue EEG measures. Frontal theta power increased significantly following the fatigue protocol (t(19) = 8.32, p = 0.000002, 95% CI [0.45, 0.68], Cohen's d = 2.70), indicating a very large effect.

Similarly, the theta/alpha ratio also increased significantly (t(19) = 7.84, p = 0.000004, 95% CI [0.21, 0.33], Cohen's d = 2.62).

To explore predictive relationships, a multiple linear regression was conducted using post-fatigue frontal theta and theta/alpha ratio as predictors of decision accuracy.

Effect Sizes: Paired-samples t-tests demonstrated large to very large effects:

- Cohen's d = 2.70 for frontal theta power increase,
- Cohen's d = 2.62 for theta/alpha ratio increase,
- Cohen's d = 2.12 for decision accuracy decline, and
- Cohen's d = 1.79 for reaction time slowing.

Correlations and Regression Analysis

Relationships between EEG fatigue markers and decision-making outcomes are detailed in Table 5.

Table 5. Correlations between EEG Markers and Decision-making Outcomes

EEG Marker	Decision Variable	r	p-value
Frontal theta	Accuracy (%)	–0.65	< 0.002
Frontal theta	Reaction time (ms)	0.62	0.003
Theta/alpha ratio	Accuracy (%)	–0.71	< 0.001
Theta/alpha ratio	Reaction time (ms)	0.59	0.005

Note. Pearson's r values are two-tailed; all p-values reflect significance levels for correlation analyses.

Frontal theta power post-fatigue was negatively correlated with decision-making accuracy (r = –0.65, p = 0.002).

Higher theta/alpha ratios were also associated with lower accuracy (r = –0.71, p < 0.001). These findings suggest that increased frontal theta and theta/alpha ratios are associated with poorer accuracy and slower decision-making under fatigue.

Figure 1. Scatterplot of Post-Fatigue Frontal Theta Power vs. Decision-Making Accuracy.

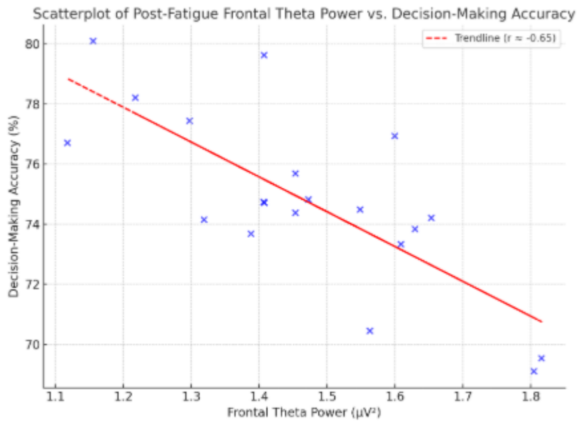

Figure 1 illustrates a significant negative relationship between frontal theta power and decision-making accuracy post-fatigue ($r \approx -0.65$, $p = 0.002$). The dashed red line represents the trendline of the association.

To explore predictive relationships, a multiple linear regression was conducted using post-fatigue frontal theta and theta/alpha ratio as predictors of decision accuracy.

A multiple regression analysis predicting post-fatigue decision accuracy from frontal theta power and theta/alpha ratio is presented in Tables 5 and 6.

The overall model was significant ($F(2,17) = 9.27$, $p = 0.002$, $R^2 = 0.52$, Adjusted $R^2 = 0.47$).

Table 6. Multiple Regression Predicting Post-Fatigue Decision Accuracy

Predictor	B	SE B	β	95% CI	p-value
Frontal Theta Power	−0.41	0.15	−0.45	[−0.75, −0.12]	0.012
Theta/Alpha Ratio	−0.33	0.14	−0.39	[−0.68, −0.05]	0.026

Table 6 presents the multiple regression results examining how post-fatigue EEG metrics (frontal theta power and theta/alpha ratio) predict decision accuracy. Both predictors significantly contributed to decreased accuracy after fatigue. Specifically, higher frontal theta power ($\beta = -0.45$, $p = 0.012$) and a higher theta/alpha ratio ($\beta = -0.39$, $p = 0.026$) were associated with lower decision accuracy. The overall model explains 52% of the variance in decision accuracy (Adjusted $R^2 = 0.47$), indicating a strong predictive relationship. A follow-up simple regression revealed that theta/alpha ratio alone accounted for 52% of the variance in decision accuracy ($F(1,18) = 19.65$, $p < .001$).

Discussion

The present study provides compelling evidence that mental fatigue, as induced by a standardized physical exertion protocol (Yo-Yo Intermittent Recovery Test Level 1), significantly impairs tactical decision-making in elite football players. Specifically, EEG-derived neurophysiological markers frontal theta power and the theta/alpha ratio increased substantially post-fatigue, indicating elevated cognitive load and reduced cortical efficiency. These neural changes were paralleled by marked declines in decision accuracy and slower reaction times. Importantly, the theta/alpha ratio explained over half of the variance in decision performance, demonstrating its utility as a robust predictor of fatigue-related cognitive decline.

These findings align with the theoretical framework proposed by Boksem et al. (2005), who showed that increased theta activity is a hallmark of mental fatigue during prolonged cognitive tasks. Our results further support Cavanagh & Frank's. (2014) assertion that frontal theta oscillations reflect the recruitment of cognitive control resources under stress or challenge. Extending these findings into a football-specific context, our study bridges a gap by linking EEG-based markers to actual tactical performance outcomes something not previously demonstrated with this level of experimental control.

Several prior investigations have addressed mental fatigue in sport, particularly in football. Smith et al. (2016) found that mental fatigue impairs passing decision-making and ball control in youth players. Similarly, Gantois et al. (2020) demonstrated performance deterioration in tactical decisions after mentally fatiguing tasks. Our use of EEG offers a neurophysiological explanation for such observations by directly capturing alterations in brain rhythms associated with fatigue. Notably, while Vestberg et al. (2012) found that executive function scores predicted football success, the present study provides physiological confirmation that those same functions are vulnerable to fatigue-induced decline.

These insights are consistent with findings from Pinheiro et al. (2022), who noted that reaction times vary across age categories in elite youth soccer, suggesting that developmental stages influence cognitive performance under pressure. Additionally, Martínez et al. (2023) and Inácio et al. (2024) highlighted that physical activity enhances executive functions such as attention and working memory, but that fatigue may compromise these gains if not properly managed.

Beyond theoretical contributions, this study offers practical implications for performance management in elite football. The integration of real-time EEG monitoring could revolutionize how teams assess cognitive readiness, enabling personalized adjustments to training loads and game-time strategies. For example, EEG-based thresholds might inform substitution timing or signal when a player is at risk for costly decision-making errors due to mental fatigue. Moreover, the development of individualized neurofeedback protocols could empower athletes to regulate their cognitive states during high-stakes scenarios.

Despite the promising findings, this study is not without limitations. The YYIRT1, although widely validated (Bangsbo, 1994), may not fully replicate the multidirectional and unpredictable demands of competitive match play. Our exclusively male sample limits the generalizability to female athletes, and the use of dry-electrode EEG systems, while practical, introduces the potential for movement artifacts despite rigorous cleaning protocols (Lopez-Gordo et al., 2014). Furthermore, the cross-sectional nature of the study precludes causal inferences; longitudinal designs would strengthen claims about fatigue trajectories and recovery patterns.

Future research should pursue field-based validation of EEG markers using live match data and more ecological testing environments. Integrating other biosignals such as heart rate variability, electromyography, or gaze tracking could enrich models of fatigue monitoring. Intervention studies testing the effectiveness of cognitive recovery techniques such as mindfulness, controlled breathing, or cognitive priming on tactical performance recovery are also warranted. Expanding the sample to include diverse playing levels, genders, and age groups will enhance external validity and provide nuanced insights into how cognitive fatigue manifests across football populations.

Conclusions

In sum, this investigation provides the first empirical evidence that wearable EEG derived markers of central fatigue specifically frontal theta power and the theta/alpha ratio are robust predictors of tactical decision making deficits in elite football players. By coupling a validated Yo Yo Intermittent Recovery Test Level 1 with a dry electrode frontal EEG system, we demonstrated that neurophysiological fatigue indices not only elevate significantly under physical strain but also explain more than 50% of the variance in decision accuracy. These contributions advance theoretical models of central fatigue by operationalizing cognitive load dynamics in an applied sporting context.

From a practical standpoint, our findings endorse the integration of portable EEG monitoring into high performance sport frameworks. Real time cognitive fatigue assessments can inform evidence based load management, optimize substitution strategies, and tailor recovery protocols to sustain peak decision making capacity during critical match phases. Additionally, this neuroergonomic approach complements traditional physiological and performance metrics, fostering a holistic athlete monitoring paradigm.

Looking forward, it is essential to extend these insights through in match validation studies, diversify participant cohorts (including female and youth players), and investigate interventional techniques such as targeted neurofeedback or brief cognitive recovery exercises to mitigate fatigue induced cognitive impairments. Collectively, such research will not only refine our understanding of brain behavior interactions in sport but also pave the way for innovative performance optimization strategies in elite football and beyond.

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