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EEG differences in competitive female gymnastics, soccer, and esports athletes between resting states with eyes closed and open

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Athletes heavily rely on visual perception for performance. This study delves into electroencephalographic (EEG) brain activity among gymnastics, soccer, and esports athletes during resting states with eyes closed (REC) and open (REO) and compares differences in EEG alpha power from REC to REO (Δ EC-EO ^{Alpha}) across athlete groups. Forty-two female participants, including 14 from each athletic discipline, underwent two 5-minute EEG recordings, first during REC and then during REO conditions. Absolute EEG power was analyzed for delta (δ), theta (θ), alpha (α), and beta (β) frequency bands across various brain regions, and Δ EC-EO ^{Alpha} values were computed. During REC, soccer players exhibited heightened α power at the midline frontopolar (Fpz) and β power at the midline occipital (Oz). Conversely, during REO, soccer players displayed increased δ power at Fpz and midline frontal (Fz) and reduced α power at the midline central (Cz) compared to gymnasts, along with elevated θ power at Fpz. Esports athletes demonstrated higher δ power and decreased α power at Fpz and Cz compared to gymnasts. Gymnasts exhibited distinct cortical activation patterns characterized by lower Δ EC-EO ^{Alpha} at multiple electrode sites. These findings highlight sport-specific cortical activation patterns linked to visual attention among athletes. Understanding these neural adaptations could refine training methods and enhance performance outcomes in sports.

Keywords Cortical activation, Visual attention, Sport-specific adaptations, Brain activity

The visual system plays a pivotal role in human perception, particularly in athletes whose performance relies heavily on perceiving, interpreting, and processing visual stimuli[1–6]. Visual skills enable athletes to gather crucial information from their environment, anticipate movements, make rapid decisions, and execute precise motor actions during training and competition[7]. Notably, the demands placed on visual skills vary across different sports disciplines, with individual and team sports presenting distinct challenges[8,9].

Gymnastics, as an individual sport, requires athletes to possess specific visual acuity, coordination, and visualization abilities to execute complex movements with precision and grace[10,11]. In contrast, dynamic, reactive team sports like soccer require robust visual skills to interact effectively with teammates and opponents, anticipate their actions, and make split-second decisions[12,13]. The emergence of esports, characterized by virtual gaming environments, further underscores the importance of visual skills, as players navigate digital landscapes and communicate with teammates while maintaining focus on screens[14,15].

Recent electroencephalographic (EEG) studies have unveiled differential cortical activation patterns between athletes and non-athletes, suggesting sport-specific neural adaptations[16–20]. To explore these adaptations, five midline electrode sites were selected: frontopolar (Fpz), frontal (Fz), central (Cz), parietal (Pz), and occipital (Oz), covering key brain regions involved in visual processing, attention, and cognitive control[21–28]. The Fpz and Fz regions are associated with higher-order cognitive functions[22], while the Oz region is crucial for visual processing[23,24]. The Cz and Pz regions are involved in visuospatial sensorimotor integration and attention[25,26]. Furthermore, delta (δ), theta (θ), alpha (α), and beta (β) frequency bands were analyzed to gain insights into

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brain activity. The δ and θ bands are associated with attentional processes and cognitive control[22]; the α band indicates visual attention and inhibition control[23,28,29]; and the β band is linked to active cognitive processing and motor planning[30].

Previous studies reported changes in EEG band activity (δ, θ, α, and β) across the scalp during resting eyes-closed (REC) and eyes-open (REO) conditions highlighting differences in cortical processing of visual input. While these differences are documented in both healthy[6,21,27,31] and unhealthy populations[32,33], it remains ambiguous if highly skilled athletes from different sports, such as individual and team sports, exhibit distinct cortical activations during REC and REO due to their unique visual demands. The current study, therefore, investigates whether the specific visual demands of team sports (e.g., soccer and esports) and individual sports (e.g., gymnastics) influence intrinsic brain activity, particularly during the transition from REC to REO conditions. Investigating this could highlight sport-specific neural adaptations and reveal how prolonged training and experience shape intrinsic brain activity.

Furthermore, transitioning from REC to REO reveals observable changes in EEG patterns, reflecting brain activity reorganization in response to visual stimuli[34]. The α power, predominantly observed during REC and suppressed upon REO, indicates a shift from internally directed attention to externally directed attention. Differences in EEG α power from eyes closed to open (Δ EC-EO $^{\text{Alpha}}$) reflect visuospatial attention inhibition and potentially serve as a marker of visual processing efficiency in athletes[35,36]. Del Percio et al.[37] provided evidence that elite karate athletes exhibit a decrease in Δ EC-EO $^{\text{Alpha}}$, suggesting potential spatially selective cortical activation (referred to as “neural efficiency”) in athletes’ brains compared to non-athletes. This raises the research problem of how different sports, each with unique visual and attentional demands, shape distinct neural efficiency profiles. Accordingly, the study further explores variations in visual processing efficiency, indicated by Δ EC-EO $^{\text{Alpha}}$, among athletes from soccer, esports, and gymnastics.

Therefore, this study aims to explore EEG brain activity among competitive athletes from soccer, esports, and gymnastics backgrounds during REC and REO, and to compare differences in EEG alpha power from REC to REO across these athlete groups. We hypothesize that soccer players will show greater increases in EEG δ and θ power during REO, reflecting their reliance on quick decision-making and visual tracking. Esports athletes, with their focus on fast-paced visual stimuli, are expected to exhibit increased EEG β power in both conditions. In contrast, gymnasts, due to their heightened need for body coordination and spatial awareness, are predicted to display higher EEG α power during REC. Additionally, gymnasts are anticipated to exhibit a smaller Δ EC-EO $^{\text{Alpha}}$, indicating more efficient visual processing. By examining how brain activity adapts to visual stimuli in diverse sports disciplines, this research contributes to our understanding of the neural adaptations underlying athletic performance.

Methods

Participants

Sample size estimates were calculated using G*Power 3.1.9.2 based on partial eta squared (ηp^2) of EEG delta power during the EC condition from a previous study[38]. The calculations used a Cohen’s effect size of 0.5 derived from $\eta p^2 = 0.2$, an α level of 0.05, and aimed for a statistical power (1-β) of 0.8. A total of 42 female participants (14 gymnasts, 14 soccer players, and 14 esports athletes) were recruited for the study. All participants had over three years of experience in their respective sports and actively participated in competitive national tournaments. Their ages ranged from 18 to 25 years, and they all had normal or corrected-to-normal vision and were right-hand dominant. Physical attributes such as age, weight, height, and body mass index (BMI) were comparable across the three athlete groups. Controlling for BMI helps ensure that any observed differences in EEG patterns are attributable to the type of sport rather than variations in body weight[39]. Moreover, recruiting only female athletes controlled for potential gender-related differences in cortical activation[38], reducing variability and enhancing the reliability of our findings. Prior to participation, all individuals provided informed consent approved by the Mahidol University Ethics Committee (MU-CIRB 2021/485.2311). The study adhered strictly to the ethical guidelines of the Helsinki Declaration and those outlined by the International Journal of Exercise Science[40].

Experimental procedure

To minimize external influences on resting-state alpha power, participants were instructed to abstain from caffeine for 24 h and alcohol for 48 h before testing and to ensure normal sleep the night before data collection. They were advised to avoid excessive eye strain the day before the test. All recordings were conducted at the same time of day to control for circadian variations, and the room temperature, light, and sound were controlled to minimize their effects. Participants were also instructed to wash their hair without conditioner before arriving at the laboratory. They arrived at the laboratory at 9:00 a.m., where physical characteristics such as age, body weight, and height were measured. Height and body weight were measured without footwear, using a precisely calibrated stadiometer. Body mass index (BMI) was calculated using the formula: body weight (kg) divided by the square of height (m^2). Participants sat comfortably on a chair in an isolated dark room with minimal external interference, light levels below 150 lx, and a room temperature maintained between 22 and 24 °C. After relaxing for two minutes, they then underwent EEG recordings for two 5-minute conditions that began with eyes closed and followed by eyes open at rest. During the REO condition, participants were instructed to fixate visually on a small marker displayed on a computer screen in front of them.

Electroencephalography (EEG) assessments

EEG equipment and preparation

EEG recordings were obtained using the eegosports system (eegosports™, ANT Neuro, Germany) which includes software (asa $^{\text{TM}}$ erp) for EEG analysis. Scalp electrodes were applied using a thirty-two-channel electrode cap (waveguard™ original, 32 channels, Germany) with sintered Ag/AgCl electrodes, following the international

10–20 placement system[41]. Before application, electrode sites were prepared and cleaned with skin preparation gel (Nuprep$^{®}$). The vertex of each participant's head was located at the intersection of the anteroposterior and left-to-right lines and marked for the midline central (Cz) electrode site on the cap. EEG gel was inserted into all cap sites to maintain impedance below 5 kΩ. Two electrooculogram (EOG) electrodes were placed above and below the left eye, and two EOG electrodes were placed at the outer canthus of each eye to monitor eye movements. All electrodes were referenced to the average value of both reference electrodes over the mastoid regions (A1 + A2 / 2).

EEG data acquisition

Each participant was seated in a comfortable chair during the EEG measurements, which consisted of 5-minute sessions for both the REC and REO conditions. EEG data were recorded from 32 electrode sites, focusing on six midline electrode sites: frontopolar (Fpz), frontal (Fz), central (Cz), parietal (Pz), parieto-occipital (POz), and occipital (Oz)[42]. Artifacts from eye movements, muscle activity, or electrode shifts were automatically cleaned using the artifact correction function of the asa ^{TM} erp software program. Pre-recording parameters were set to a bandpass frequency of 0.1–60 Hz, with a 50 Hz notch filter to remove noise. Post-recording parameters were set to a bandpass between 0.3 Hz (slope 12 dB/oct) and 30 Hz (slope 24 dB/oct). The absolute power (μV^2) of the respective frequency bands, derived by fast-Fourier transforms (FFTs), was defined for the delta (0.5–4 Hz), theta (4.5–8 Hz), alpha (8.5–13 Hz), and beta (13.5–29.5 Hz) wave ranges. For FFT analysis, the software program used the time window of recording without overlapping and set a block length of 2 s[43].

Statistical analysis

Statistical analyses were performed using GraphPad Prism 9 software version 9.5.1. Participant characteristics were presented as mean ± standard deviations (SD), with normal distribution assessed using the Shapiro-Wilk test. Data were presented as mean ± standard error of the mean (SEM). One-way ANOVA was used to compare data among gymnasts, soccer players, and esports athletes. Differences in EEG α between eyes-closed and eyes-open recording (Δ EC-EO $^{\text{Alpha}}$) were also calculated and analyzed. Statistical significance was accepted at $p < 0.05$.

Results

Participant characteristics

Participant characteristics are summarized in Table 1, with no significant differences observed among the three athlete groups. The mean age, height, weight, and BMI were comparable across the gymnasts, soccer players, and esports athletes.

During the eye-closed condition (REC), significant differences in EEG α power were found at the Fpz site ($F_{(2,39)} = 5.99$, $p = 0.01$, $R^2 = 0.23$). Post hoc analysis revealed that soccer players exhibited higher α power than esports ($p = 0.03$) and gymnasts ($p = 0.01$). Similarly, significant differences in EEG β power were observed at the Oz site ($F_{(2,39)} = 6.46$, $p < 0.01$, $R^2 = 0.25$) ,with soccer players showing higher beta power compared to esports ($p = 0.02$) and gymnasts ($p = 0.01$). No significant differences were observed at other electrode sites (Fz, Cz, Pz, and POz) for any frequency band (Table 2; Figs. 1 and 2).

During the eye-open condition (REO), a significant difference was observed in δ power between groups ($F_{(2,39)} = 22.21$, $p < 0.0001$, $R^2 = 0.53$). Post hoc analysis revealed that both esports ($p < 0.01$) and soccer ($p < 0.01$) exhibited higher δ power at Fpz than gymnasts. Additionally, soccer ($p < 0.01$) exhibited higher δ power at Fz than gymnasts. A significant difference between groups in θ power at Fpz was identified ($F_{(2,39)=}5.57$, $p = 0.01$, $R^2 = 0.22$), with soccer players exhibiting higher theta power compared to esports ($p = 0.02$) and gymnasts ($p = 0.01$). Regarding α power, a statistically significant difference between groups was observed ($F_{(2,39)} = 7.71$, $p = 0.00$, $R^2 = 0.28$). Post hoc analysis revealed gymnasts had lower α power at Fpz than both esports ($p < 0.01$) and gymnasts ($p = 0.01$). Additionally, a significant difference between groups in α power at Cz was identified ($F_{(2,39)} = 8.62$, $p = 0.00$, $R^2 = 0.31$). Post hoc analysis showed that gymnasts exhibited higher α power than both esports ($p < 0.01$) and soccer ($p = 0.01$). No significant differences were observed at other electrode sites (Fz, Cz, Pz, POz, and Oz) for β band (Table 2; Figs. 1 and 2).

Moreover, significant group differences were observed in Δ EC-EO $^{\text{Alpha}}$ across multiple electrode sites: Fpz ($F_{(2,45)} = 7.61$, $p < 0.01$, $R^2 = 0.25$), Fz ($F_{(2,45)} = 5.14$, $p < 0.01$ $R^2 = 0.19$), Cz site ($F_{(2,45)} = 4.96$, $p = 0.01$, $R^2 = 0.18$), Pz ($F_{(2,45)} = 3.85$, $p = 0.03$ $R^2 = 0.15$), and POz ($F_{(2,45)} = 4.82$, $p = 0.01$, $R^2 = 0.18$). Post hoc analysis revealed that gymnasts showed the lowest value of Δ EC-EO $^{\text{Alpha}}$ compared to esports and soccer players at Fpz (esports: $p < 0.01$, soccer players: $p = 0.01$), Fz (esports: $p = 0.03$, soccer players: $p = 0.02$), and Cz (esports: $p = 0.03$, soccer players: $p = 0.01$). At Pz, gymnasts exhibited lower value of Δ EC-EO $^{\text{Alpha}}$ than esports players ($p = 0.03$).

Variable	Gymnasts ($n = 14$)	Soccer ($n = 14$)	Esports ($n = 14$)
Age (yrs)	20 ± 1	21 ± 1	21 ± 2
Height (m)	1.62 ± 0.02	1.60 ± 0.06	1.62 ± 0.06
Body weight (kg)	57.6 ± 4.0	53.4 ± 7.3	56.8 ± 10.6
BMI (kg/m^2)	22.0 ± 1.46	20.8 ± 2.5	21.5 ± 3.3

Table 1. Participant characteristics Note: data presented as mean ± standard deviation; p-values not significant for group comparisons.

The mean power (μV^2)		EC			EO		
		Esports	Gymnasts	Soccer	Esports	Gymnasts	Soccer
Delta	Fpz	92.5 ± 15.7	95.0 ± 15.7	97.5 ± 8.1	**219.8 ± 8.1**[c]	143.4 ± 15.9	**240.5 ± 5.7**[a]
	Fz	63.2 ± 10.6	57.8 ± 5.2	60.2 ± 4.9	84.6 ± 7.7	64.4 ± 7.2	**97.1 ± 6.8**[a]
	Cz	54.6 ± 8.8	53.1 ± 5.3	51.9 ± 5.4	74.5 ± 9.9	54.3 ± 6.5	69.9 ± 8.1
	Pz	59.2 ± 8.9	50.5 ± 4.4	55.1 ± 5.7	76.4 ± 12.2	53.9 ± 7.1	72.5 ± 6.8
	POz	59.9 ± 9.7	50.7 ± 5.5	52.8 ± 5.1	72.1 ± 11.1	57.6 ± 7.1	62.4 ± 7.0
	Oz	48.4 ± 8.3	48.6 ± 5.3	45.9 ± 4.7	68.0 ± 9.8	51.2 ± 6.7	63.3 ± 8.4
Theta	Fpz	10.9 ± 1.9	10.7 ± 0.8	13.4 ± 1.6	11.5 ± 0.5	10.9 ± 0.8	**21.0 ± 4.1**[a, b]
	Fz	14.9 ± 2.4	15.1 ± 0.9	18.2 ± 2.6	18.5 ± 6.1	11.2 ± 0.5	11.0 ± 0.9
	Cz	14.9 ± 2.6	14.0 ± 0.9	16.0 ± 2.4	13.5 ± 3.6	8.9 ± 0.5	9.7 ± 1.1
	Pz	13.4 ± 2.8	11.7 ± 0.9	14.2 ± 2.3	14.1 ± 5.2	6.8 ± 0.4	8.3 ± 0.7
	POz	12.1 ± 2.2	10.9 ± 0.9	13.3 ± 2.3	10.3 ± 2.9	6.5 ± 0.5	6.8 ± 0.8
	Oz	7.4 ± 1.2	8.6 ± 0.7	9.3 ± 1.6	9.0 ± 3.3	4.8 ± 0.4	5.6 ± 0.6
Alpha	Fpz	20.4 ± 3.2	17.4 ± 2.7	**36.5 ± 5.9**[a, b]	**7.5 ± 0.5**[c]	17.6 ± 2.7	11.4 ± 1.6
	Fz	28.3 ± 4.5	24.2 ± 3.4	36.9 ± 6.1	13.2 ± 2.6	22.8 ± 3.7	18.1 ± 4.3
	Cz	32.7 ± 5.8	28.3 ± 4.0	39.7 ± 7.4	**10.1 ± 1.3**[c]	24.9 ± 4.0	**13.1 ± 1.8**[a]
	Pz	50.5 ± 11.4	37.6 ± 5.7	34.5 ± 5.9	14.1 ± 2.9	27.9 ± 4.8	20.7 ± 5.9
	POz	50.4 ± 10.5	33.8 ± 4.4	31.5 ± 4.5	12.8 ± 2.7	25.3 ± 3.9	23.0 ± 7.7
	Oz	34.4 ± 6.8	26.1 ± 3.8	39.9 ± 8.5	12.0 ± 2.8	16.8 ± 2.5	22.7 ± 8.3
Beta	Fpz	7.4 ± 0.8	7.4 ± 0.8	8.6 ± 0.8	15.3 ± 3.4	11.1 ± 1.5	12.5 ± 1.6
	Fz	8.3 ± 0.8	7.7 ± 0.47	10.5 ± 1.2	7.6 ± 0.7	8.9 ± 1.1	8.8 ± 0.9
	Cz	8.7 ± 1.0	8.9 ± 1.1	10.2 ± 1.3	6.8 ± 0.6	8.6 ± 1.0	7.8 ± 0.8
	Pz	9.8 ± 1.4	9.0 ± 1.0	10.8 ± 1.2	6.5 ± 0.6	7.8 ± 0.8	8.4 ± 1.0
	POz	9.2 ± 1.1	9.3 ± 0.9	11.7 ± 1.2	7.6 ± 1.0	8.0 ± 0.7	8.4 ± 0.9
	Oz	8.4 ± 0.7	8.0 ± 0.8	**11.8 ± 0 . 9**[a,b]	7.0 ± 0.7	7.3 ± 0.8	8.3 ± 0.9

Table 2. The average power of brain waves during rest with eye-closed (EC) and eyes-open (EO) recording in esports, gymnasts, and soccer groups. Note: Data are presented as means ± SEM; $n = 14$ for each group. Fpz = the midline frontopolar, Fz = the midline frontal, Cz = the midline central, Pz = the midline parietal, POz = the midline parieto-occipital, and Oz = the midline occipital. [a], different between Gymnasts and Soccer groups; [b], different between Esports and Soccer groups, [c], different between Gymnasts and Esports groups. One-way ANOVA, $p < 0.05$.

Moreover, at POz, esports players had the highest value of Δ EC-EO $^{\text{Alpha}}$ than soccer players ($p = 0.02$) and gymnasts ($p = 0.03$) (Table 3; Fig. 3).

Discussion

The findings of this study provide novel insights into the differential cortical activation patterns observed among competitive athletes from team sports like soccer, and esports and individual sports like gymnastics. During both REC and REO, significant differences in EEG α power were evident among athlete groups, reflecting distinct neural adaptations associated with visual attention and cognitive processing[35–37]. Soccer players exhibited higher α power during REC conditions, potentially indicating enhanced internally oriented attention and cognitive control mechanisms[44]. Conversely, esports athletes demonstrated reduced α power during REO conditions, suggesting heightened arousal levels and attention associated with rapid decision-making requirements[45,46]. Gymnasts displayed unique cortical activation patterns characterized by lower Δ EC-EO $^{\text{Alpha}}$, indicative of heightened internal attentional control and focus on internalized imagery or motor planning processes[37,46,47].

In the eyes-closed condition, soccer players exhibited higher EEG α power at the frontoparietal and EEG β power at the occipital areas of the brain compared to esports players and gymnasts. The increased EEG α-power at the frontal electrode site or higher frontal α synchronization may reflect a state of enhanced internally oriented attention and creative ideation[44]. Moreover, the elevated β power detected in soccer players during REC across the occipital cortex corresponds with earlier findings by Barry et al.[21,31] and Geller et al.[48]. These studies suggest that soccer players might exhibit heightened attentional focus or cognitive control mechanisms during resting periods with eyes closed, possibly indicating their internal attentional engagement in sustaining vigilance and anticipation on the field.

In the eyes-open condition, soccer players demonstrated heightened EEG δ power across the frontal brain regions (at Fpz and Fz sites) compared to gymnasts. Additionally, they exhibited elevated EEG θ power at the Fpz site compared to both esports players and gymnasts. This increase in EEG δ and θ powers in the frontal pole during REO may indicate robust engagement of brain processes associated with the processing of visual sensory information[27,49]. Notably, frontal θ has been identified as a marker of cognitive control processes[28,50] particularly during heightened attention demands[51,52]. These observations collectively suggest that soccer players are more

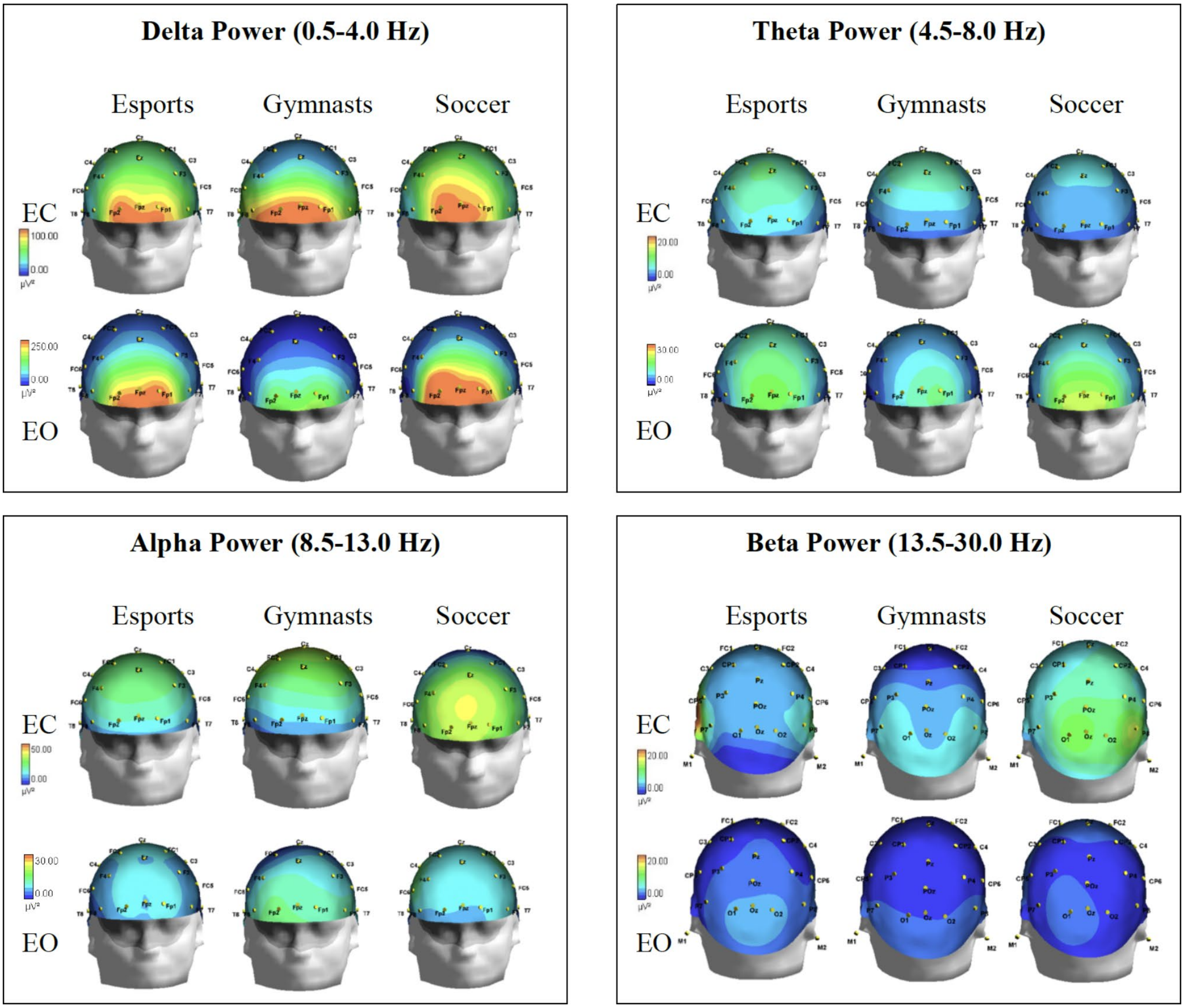

Fig. 1. Topographic EEG maps of spectral power density for the delta, theta, alpha and beta band during the resting state with eyes- closed (EC) and eyes- open (EO) in esports, gymnasts, and soccer players. The red color represents the maximum and blue represents the minimum values.

deeply involved in cognitive processes linked to spatial navigation, decision-making, and strategic planning, reflecting the intricate perceptual-cognitive demands inherent in soccer gameplay.

For another team sport like esports, athletes demonstrated reduced EEG α power at the Fpz and Cz sites, along with increased EEG δ power at the Fpz site during REO compared to gymnasts. Notably, overall EEG α values appeared lower in team sports such as esports and soccer, which demand visuospatial information processing and rapid decision-making in unpredictable scenarios, compared to individual sports like gymnastics. This decline in α power could be linked to heightened arousal levels and increased attention associated with processing visuospatial stimuli and making quick decisions[45,46,53]. Our findings suggest that exposure to prolonged screen time or interactions with teammates and opponents in esports may disrupt neural oscillatory patterns, leading to a desynchronization of neurons generating EEG α and subsequently resulting in decreased α power. This phenomenon aligns with the cortical neural efficiency hypothesis, which proposes reduced EEG α brain activation in experts compared to novices when exposed to external stimulation or performing tasks[54,55]. Moreover, esports athletes exhibited the most significant change in Δ EC-EO $^{\mathrm{Alpha}}$ at the parieto-occipital brain area compared to soccer players and gymnasts. This shift from higher alpha power during eye closure to lower alpha power during eyes open in competitive esports athletes may indicate a transition from a less to a more activated cortical state, consistent with their intense focus on gaming screens and the rapid decision-making demands during gameplay.

In contrast, gymnasts displayed heightened EEG α power at the frontopolar and central electrodes during REO compared to soccer and esports players, in opposition to the pattern observed during REC. Additionally, gymnasts exhibited the smallest change in Δ EC-EO $^{\mathrm{Alpha}}$ observed across various brain regions (i.e., Fpz, Fz, Cz, Pz, POz and Oz sites). These findings may reflect gymnasts' enhanced internal attentional control and emphasis

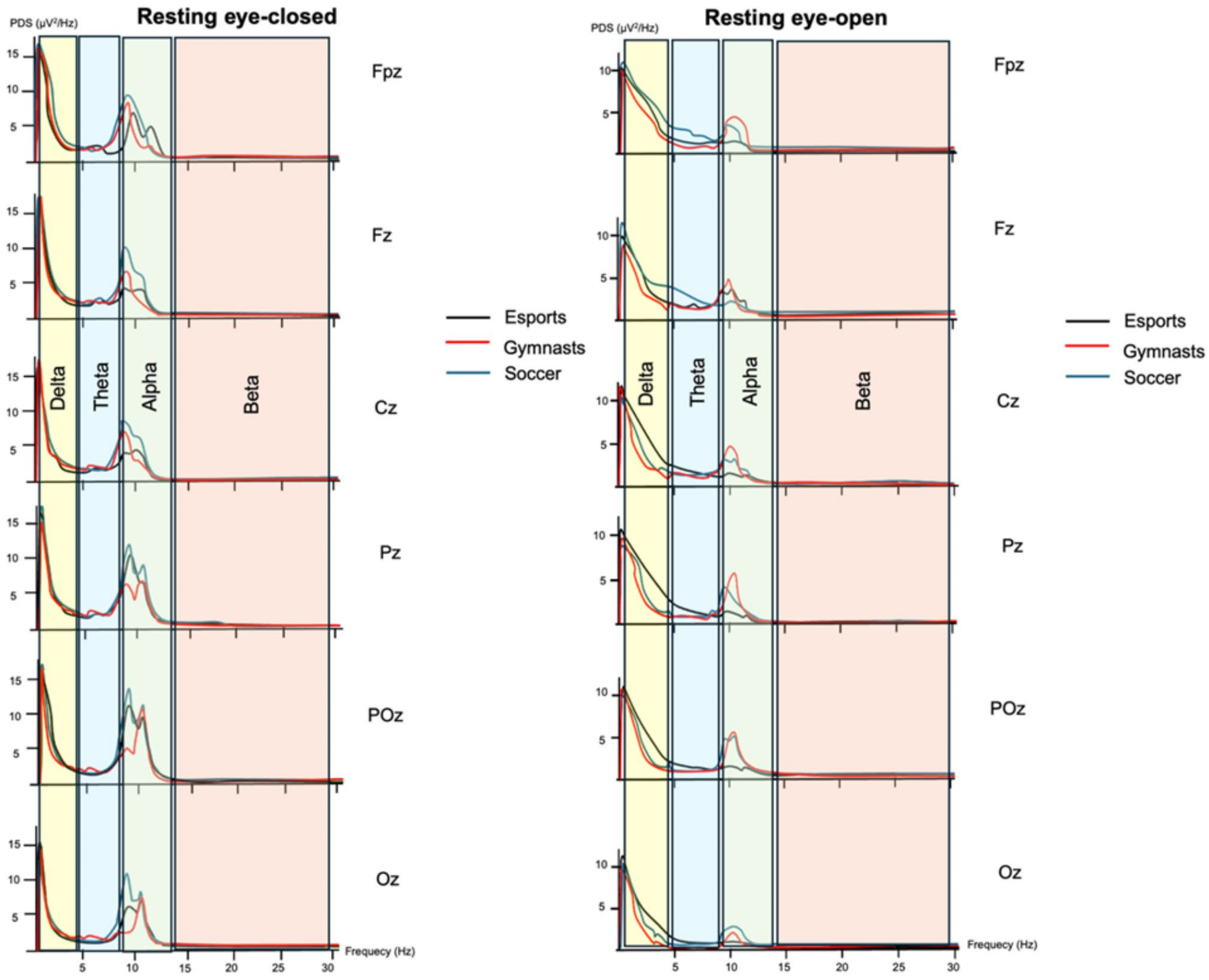

Fig. 2. The data as power spectral density (DPS) plots during rest with eye-closed (EC) and eye-open (EO) recording at six midline electrode sites: frontopolar (Fpz), frontal (Fz), central (Cz), parietal (Pz), parieto-occipital (POz), and occipital (Oz), in Esports (black line), Gymnasts (red line), and Soccer players (blue line). The shaded regions indicate the following frequency bands: delta (0.5–4 Hz) in yellow, theta (4.5–8 Hz) in blue, alpha (8.5–13 Hz) in green, and beta (13.5–29.5 Hz) in orange.

on internalized imagery or motor planning processes[37,46,47]. Research by White et al. highlighted that gymnasts primarily utilize imagery to enhance concentration, block out distractions, and review past performance in both competition and training scenarios[47]. Therefore, our result revealed the distinct cortical activation patterns underscore the unique visual and spatial demands inherent in individual sports like gymnastics, which require precise coordination, spatial awareness, and kinesthetic imagery.

Although our study offers valuable insights, several limitations should be acknowledged. Firstly, the cross-sectional design of the study excludes the establishment of causality or longitudinal changes in cortical activation patterns over time. Longitudinal studies tracking athletes' EEG responses throughout their training and competitive seasons would provide a more comprehensive understanding of the dynamic nature of neural adaptations to sport-specific visual demands. Secondly, while efforts were made to control for potential confounding factors such as age, gender, and experience, other variables such as individual differences in cognitive abilities, vigilance/arousal, attention, training intensity, and competition schedules may have influenced our results. Future research should include comprehensive measures of cognitive and perceptual abilities, physiological indicators (e.g., skin conductance, heart rate), and environmental factors to enhance the accuracy and reliability of the findings. Lastly, while our study focused on athletes from gymnastics, soccer, and esports backgrounds, other sports disciplines with distinct visual demands, such as combat sports or racquet sports, were not included. Future research comparing cortical activation patterns across a broader spectrum of sports disciplines would provide valuable insights into the specificity of neural adaptations to various athletic contexts.

Our research holds practical implications for athletes. Tailored neurofeedback and biofeedback training programs can enhance athletes' focus, decision-making, and overall performance by modulating specific brain

	Δ EC-EO ^{Alpha} (μV^2)		
Electrode sites	**Esports**	**Gymnasts**	**Soccer**
Fpz	12 ± 3	**-0 ± 2**$^{a, c}$	17 ± 4
Fz	15 ± 5	**1 ± 3**$^{a, c}$	19 ± 6
Cz	20 ± 5	**3 ± 3**$^{a, c}$	22 ± 6
Pz	36 ± 11	**9 ± 4**^{c}	14 ± 6
POz	**38 ± 7**$^{b, c}$	7 ± 5	7 ± 9
Oz	22 ± 7	8 ± 0	17 ± 10

Table 3. Differences in average power of EEG alpha power during rest between eye-closed and eye-open recordings (Δ EC-EO ^{Alpha}) in esports, gymnasts, and soccer groups. Data are presented as means ± SEM; $n = 14$ for each group. Note: Fpz = the midline frontopolar, Fz = the midline frontal, Cz = the midline central, Pz = the midline parietal, POz = the midline parieto-occipital, and Oz = the midline occipital. ^{a}, different between Gymnasts and Soccer groups; ^{b}, different between Esports and Soccer groups, ^{c}, different between Gymnasts and Esports groups. One-way ANOVA, $p < 0.05$.

waves and physiological responses identified in our study[56,57]. Moreover, personalized mental training programs incorporating visualization and mindfulness can reinforce neural pathways, fostering mental resilience and optimizing performance. By integrating these applications, athletes can gain a competitive edge, improve performance, and enhance overall well-being.

Conclusion

In conclusion, our study sheds light on the intricate neural dynamics underlying the performance of competitive athletes in gymnastics, soccer, and esports. Utilizing EEG recordings, we identified distinct cortical activation patterns during REC and REO, reflecting sport-specific neural adaptations. The observed differences Δ EC-EO ^{Alpha} values underscore the nuanced cognitive demands inherent in each sport. These findings contribute significantly to our understanding of sports neuroscience, emphasizing the need for further exploration into the neural mechanisms driving athletic performance. Moving forward, longitudinal studies, advanced neuroimaging techniques, and larger sample sizes will be crucial for validating and expanding upon our findings.

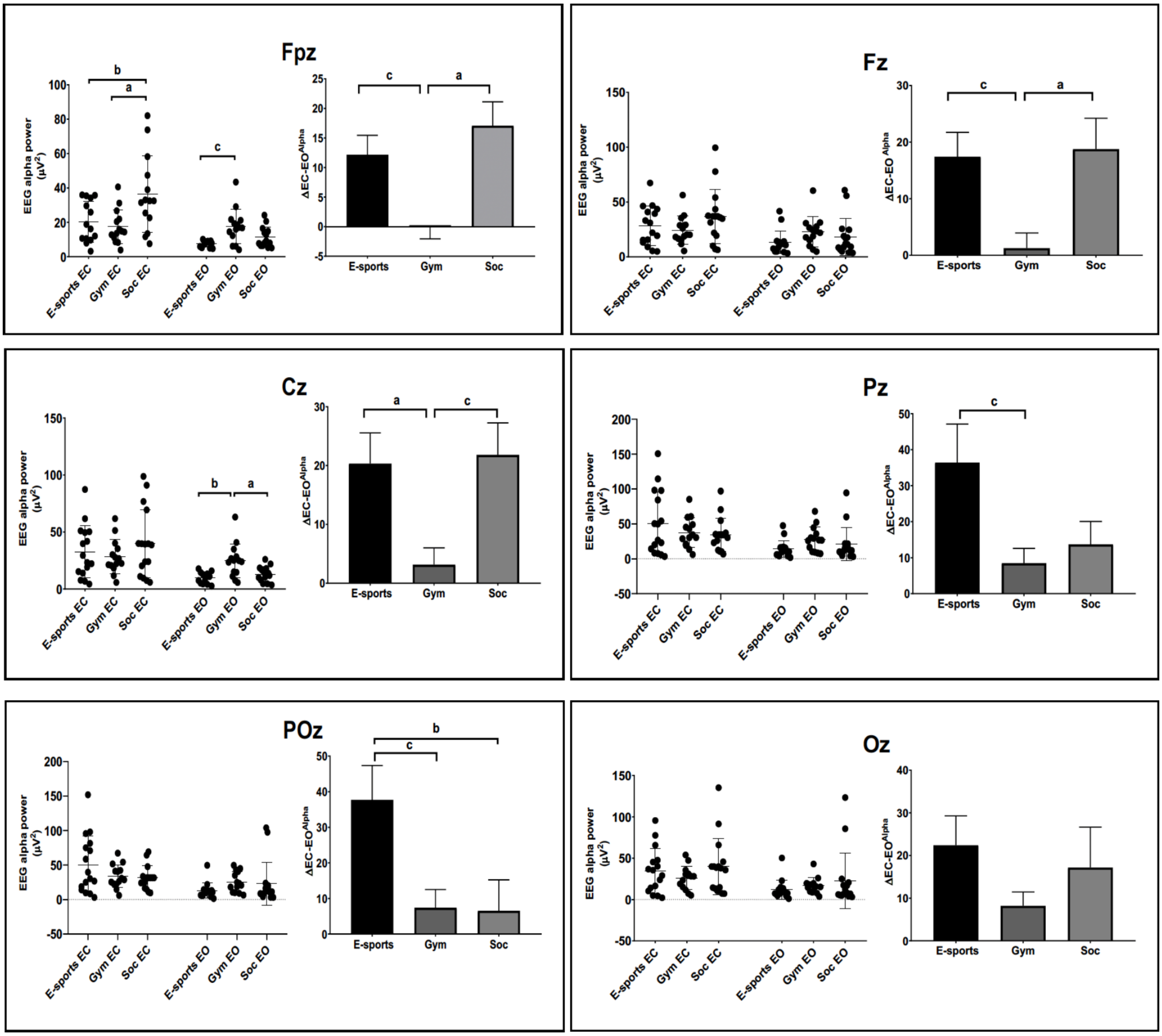

Fig. 3. Average alpha power of brain waves during rest with eye-closed (EC) and eye-open (EO) recording, and differences between eye-closed and eye-open (Δ EC-EO ^{Alpha}) in esports (E-sports), gymnasts (Gym), and soccer (Soc) groups. Data are presented as means ± SEM; $n = 14$ for each group. Fpz = the midline frontopolar, Fz = the midline frontal, Cz = the midline central, Pz = the midline parietal, POz = the midline parieto-occipital, and Oz = the midline occipital. [a], different between Gymnasts and Soccer groups; [b], different between Esports and Soccer groups, [c], different between Gymnasts and Esports groups. One-way ANOVA, $p < 0.05$.

Data availability

Data is provided within the manuscript.

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Author contributions

P.R. and A.A. conceptualized and designed the study, performed data collection, analyzed the data, interpreted the result, and wrote the main manuscript text; S.B., V.S., and A.N. contributed to supervise the study, and help revised the manuscript; A.P. and W.C. contributed to analyze the data and prepare Fig. 1. All authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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