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Dual-Task Performance and Prefrontal Cortex Hemodynamic Responses: A Pilot Study on Cognitive Load in Amateur Football Players

İkili-Görev Performansı ve Prefrontal Korteks Hemodinamik Yanıtları: Amatör Futbolcularda Bilişsel Yük Üzerine Bir Pilot Çalışma

Tugba Nalcacigil[1], Nazim Ata[2], Deniz Simsek[1]

[1]Faculty of Sports Sciences, Eskisehir Technical University, Eskisehir, Turkiye
[2]Aeromedical Research and Training Center, Eskisehir, Turkiye

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Sorumlu Yazar/Corresponding Author:
Tugba Nacacigil,
Faculty of Sports Sciences, Eskisehir Technical University, Eskisehir, Turkiye
e mail: tugbanalcacigil@gmail.com

ÖZET

Amaç: Bu çalışma, farklı zorluk seviyelerinde sunulan ikili görev paradigmalarının prefrontal korteksteki serebral hemodinamik parametreler üzerindeki etkilerini araştırmayı amaçlamaktadır.
Yöntem: Çalışmaya 14 erkek birey (ortalama ± SS: yaş = 12 ± 1.56 yıl) dahil edilmiştir. Katılımcılar "İkili Görev" paradigmasına tabi tutulmuştur (P1: motor görev; P2: ipucu görevi; P3: karmaşık ipucu görevi). Katılımcılar ikili görev aktivitelerini gerçekleştirirken prefrontal korteksin hemodinamik yanıtları (HbO: Oksihemoglobin; HbR: Deoksihemoglobin; HbT: Total Hemoglobin) yakın kızılötesi spektroskopi (fNIRS) kullanılarak değerlendirilmiştir.
Bulgular: Katılımcıların P1 ile P2 ($p < 0,001$) ve P1 ile P3 ($p < 0.001$) görevleri sırasında sergiledikleri testleri tamamlama süreleri arasında anlamlı farklılıklar olduğu ortaya çıkmıştır. fNIRS verileri, P3 görevi sırasında prefrontal kortekste diğer görevlere kıyasla daha yüksek düzeyde kortikal aktivasyon olduğunu göstermiştir; ancak bu fark istatistiksel olarak anlamlı bulunmamıştır ($p = 0,257$). P1, P2 ve P3 görevleri ile hemodinamik yanıtlar arasında istatistiksel olarak anlamlı olan güçlü, pozitif bir korelasyon olduğu saptanmıştır ($p < 0,001$).
Sonuç: Artan bilişsel yüke sahip görev protokolleri, prefrontal aktivasyonda görevin zorluğuyla orantılı olarak HbO, HbR ve HbT değerlerinde artış olduğunu göstermiştir.

Anahtar Kelimeler: İkili-görev, bilişsel yük, prefrontal korteks, fNIRS

ABSTRACT

Aim: This study aimed to investigate the effects of dual-task paradigms presented at different difficulty levels on cerebral hemodynamic parameters in the prefrontal cortex.
Methods: Fourteen male (mean ± SD: age= 12 ± 1.56 years) individuals were included in the present study. The individuals included in the study were subjected to the "Dual Task" paradigm (P1: motor task; P2: cue task; P3: mixed cue task). Hemodynamic responses in the prefrontal cortex (HbO, HbR, HbT) were assessed using fNIRS during task performance.
Results: Significant differences were observed in the competition time of the test between the P1 and P2 tasks ($p < 0.001$), as well as between the P1 and P3 tasks ($p < 0.001$). fNIRS data demonstrated a higher level of cortical activation in the prefrontal cortex during the P3 task compared to other tasks; however, this difference was not statistically significant ($p = 0.257$). A strong and statistically significant positive correlation was identified between the hemodynamic responses and the P1, P2, and P3 tasks ($p < 0.001$).
Conclusion: Task protocols with higher cognitive load resulted in an increase in HbO, HbR, and HbT values, which were proportional to task difficulty in prefrontal activation.

Key words: Dual-task, football, cognitive, prefrontal corteks, PFC

Açıklama/Disclosure: Yazarların hiçbiri, bu makalede bahsedilen herhangi bir ürün, aygıt veya ilaç ile ilgili maddi çıkar ilişkisine sahip değildir. Araştırma, herhangi bir dış organizasyon tarafından desteklenmedi. Yazarlar çalışmanın birincil verilerine tam erişim izni vermek ve derginin talep ettiği takdirde verileri incelemesine izin vermeyi kabul etmektedirler.

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INTRODUCTION

Children and adolescents frequently encounter challenging situations that require the simultaneous execution of motor and cognitive tasks during the learning of movement skills in daily life and sports. The challenging situation occurs when dual task interaction (cognitive+cognitive, motor+motor, or cognitive+motor tasks) is performed simultaneously, resulting in impaired performance of one or both tasks (1). The most important reason underlying this impairment in performance is thought to occur during the sharing of attentional resources required for the simultaneous completion of multiple tasks (2,3). Since limited resources have to be shared between tasks during this sharing, performing more than one task at the same time reduces the capacity to complete both tasks, and as a result, performance is negatively affected (3). The interruption in task processing is especially evident when the two tasks involve similar inputs or require similar responses (3). Cognitive workload and mental resources are critical concepts in understanding how individuals manage multiple tasks simultaneously. Due to the limited processing capacity of the brain, the need to coordinate various tasks creates a complex situation that increases cognitive workload, requiring additional executive processes (4). Paas and Van Merriënboer (1994) introduced the idea that an individual's attentional capacity is limited, depending on the components of mental load and mental effort (5). Mental load refers to the complexity of the task, the presentation of information, and the format of instructions, whereas mental effort involves the amount of cognitive resources allocated to completing the task (6).

Dual-task paradigms, which engage participants in simultaneous tasks, provide valuable insights into the executive functions needed to manage cognitive load and resource utilization (7). This approach has gained attention as an effective way to simulate the complexity of real-world sporting scenarios (8). In football, for instance, a player's expertise relies on their ability to manage both the ball's trajectory and the movements of other players. This requires the integration of perceptual abilities to analyze the changing game context, cognitive abilities to plan and execute actions, and technical and kinetic skills to carry out decisions (9). Consequently, successful athletes—particularly in sports with open motor skills like football—are expected to exhibit advanced cognitive abilities, often referred to as 'game intelligence,' which encompasses skills such as spatial attention, shared attention, working memory, and the ability to track and predict players' movements (9). In line with this, it has been suggested that dual-task training combinations lead to the development of new cognitive strategies by optimizing attentional focus towards relevant cues in the task (10,11). Peng et al. (2018) found that training involving dual tasks enhances both motor and cognitive performance (11). Similarly, Fleddermann et al. (2019) reported that dual-task training facilitates the optimization of attentional focus on task-relevant cues, thereby improving decision-making processes (10). Kreitz et al. (2016) emphasized the critical role of attentional control under increased cognitive load, highlighting that individuals with higher working memory capacity are better able to maintain focus on task-relevant information during dual-task conditions. In line with this, expert athletes have been shown to exhibit lower dual-task costs compared to novices, suggesting that the superior working memory capacity observed in experts supports more efficient attentional control processes (12). Supporting these findings, Lucia et al. (2023) reported that dual-task training in basketball players led to improvements in both athletic and cognitive performance (13).

Performing multiple tasks simultaneously requires the allocation of attentional resources across multiple concurrent processing systems, which can impair physical performance due to the cognitive load imposed by these tasks. The prefrontal cortex (PFC) is a complex neurological region where executive functions are highly localized, and it plays a central role in action-oriented attention (14). Because neurons in the PFC have a high metabolic rate associated with cognitive load, increased neuronal activation results in enhanced blood flow to the activated areas, a process mediated by metabolic and neuronally-induced vasodilation (15). Research suggests that regular physical activity can induce positive neuroplastic changes in the PFC (16,17). Cerebral oxygenation, specifically the levels of oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) in the PFC, can be measured using near-infrared spectroscopy (fNIRS), providing a reliable indicator of cortical activity (18). Consequently, as cognitive demands increase, there is a corresponding rise in cerebral blood flow (19). The involvement of the PFC in dual-task performance has been well-documented in the literature. Increased levels of HbO and HbR have been observed in the PFC in response to heightened attentional demands during cognitive tasks, compared to related single-task conditions (20). Mirelman et al. (2014) demonstrated that PFC activation increases proportionally with the difficulty of dual-task conditions (21). Similarly, Shaw et al. (2018) found that the dual-task paradigm activates the PFC, suggesting its involvement as part of a central bottleneck mechanism in task processing (22). Furthermore, Lucia et al. (2021) showed that dual-task training not only improved cognitive performance and sport-specific dribbling skills but also provided limited neurophysiological evidence, via electroencephalography, linking these improvements to PFC activity (23). However, these findings primarily reflect the effects of dual-task training, without addressing how task difficulty influences cortical responses. Although the effects of dual-task paradigms on PFC activation have been extensively studied, particularly in clinical and general cognitive research, there is still limited evidence regarding how varying levels of task difficulty modulate PFC activation in ecologically valid, sport-specific contexts involving time pressure and real-time decision-making. To our knowledge, no study has specifically investigated how increasing cognitive demands in reactive functions—such as perception, attention, and decision-making—impact PFC activity during motor-cognitive dual tasks performed under competitive, time-constrained conditions. Therefore, the present study aims to contribute to this gap by examining how motor-cognitive dual tasks of varying difficulty influence hemodynamic responses in the PFC of young football players.

The present study aims to investigate the effects of dual -task paradigm (cognitive+motor dual task) on prefrontal cortex haemodynamic responses of athletes. For this purpose, the hypotheses of the study were (i) 'athletes will show shorter performance times in cue and mixed cue tasks compared to random tasks and (ii) 'HbO and HbT values in the prefrontal cortex will increase with increasing cognitive load.

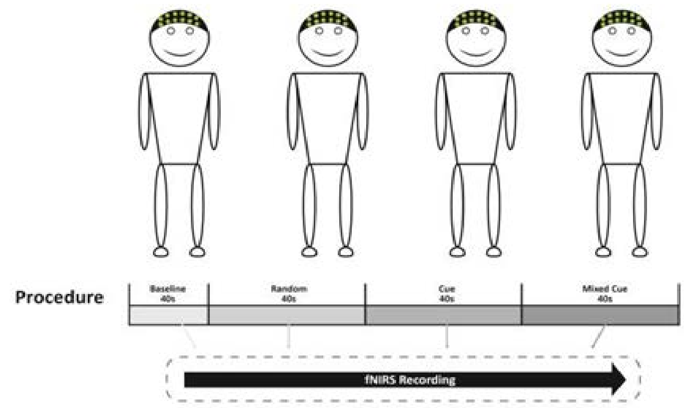

Figure 1. Dual task testing and fNIRS reccording procedure. Fitlight Trainer was used to determine dual task performances and fNIRS technology was used to detect real-time hemodynamic signals. Fitlight Trainer, dual task (motor, cue, mixed cue); fNIRS, functional near-infrared spectroscopy.

MATERIALS AND METHODS

Participants

The sample size for this study was determined by estimating the effect size f using the G*power software 3.1.9.2 (24). The sample size was determined based on data from previous studies (25) and effect size f at 0.25, the α level was set at 0.05, the desired power at 80%, and correlation between repeated measures at 0.5. In this calculation, the minimum sample size was estimated to be 32; however, since this study was a pilot study, 14 amateur football players (14 men, mean age 12 ± 1.56years, height = 155.66 ± 6.67 cm, body weight = 57.44 ± 8.83 kg) were included. Participants were selected based on the following inclusion criteria: they were naive to the study's purpose, had no history of neurological or psychiatric disorders, were not using any medications during the experimental sessions, had normal or corrected-to-normal vision, and were strictly right-handed, as assessed by the Edinburgh Handedness Inventory (26). Informed consent was obtained from the parents of all participants prior to their involvement in the study, in accordance with the Declaration of Helsinki, Informed consent was obtained from the parents of all participants prior to their involvement in the study, in accordance with the Declaration of Helsinki.

Experimental Design

A standardized 2-minute light stretching protocol was administered to all participants prior to the main task. Following the warm-up, participants sat quietly while fNIRS sensors were placed on their foreheads to measure changes in HbO, HbR, and HbT concentrations in the prefrontal cortex using the fNIRS system (fNIR Devices 1100, LLC, PA, USA). Baseline measurements were recorded for one minute, and data acquisition continued throughout the task. To minimize any residual physiological effects of the warm-up, the dual-task test began 4–5 minutes after its completion. Participants then performed a dual-task procedure with three different difficulty levels (P1: motor task; P2: cue task; P3: mixed cue task) using the FitLight Trainer system (FitLight Sports Corp, Ontario, Canada) (Figure 1). Participants were also asked to report their perceived exertion using the Borg CR-10 scale, and only those with ratings of ≤3 were included in the analysis.

Dual Task Recordings

Participants performed cognitive and motor dual-task tasks involving the extinguishing of 25 lights across three difficulty levels: P1 (motor task), P2 (cue task), and P3 (mixed cue task) (27,28). To minimize potential order effects, the sequence of tasks (P1, P2, and P3) was randomized for each participant, ensuring that task order did not influence the results (29). In P1, the lights were randomly activated, and no cognitive cues were provided, allowing the evaluation of participants' reaction times based solely on motor performance. In P2, the color of the light provided a cue indicating the region where the next light would be illuminated. For example, a green light signified that the next light would appear in the green region. In P3, a more complex cognitive task was introduced, with the color of the light offering a more intricate cue. In this protocol, if the green light was illuminated, it indicated that the next light would appear in the red region; if the red light was on, the next light would appear in the green region; and if

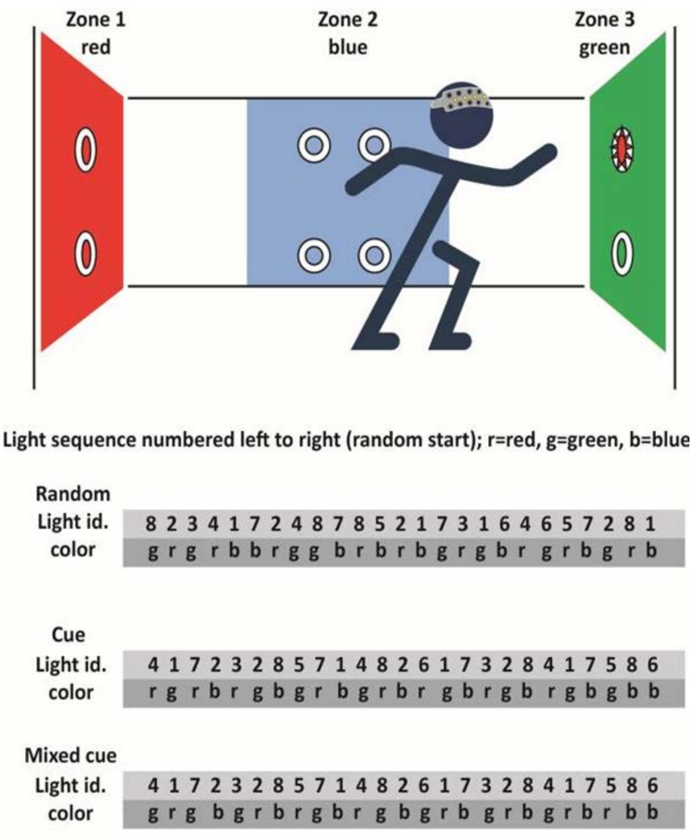

Figure 2. Installation. Lights/sensors are placed in three zones. Zones 1 and 3 represent red and green respectively, the middle zone is blue. The light sequence is different in three tests, but all lights are represented equally. In P2 and P3, the color of the light determines the position of the next light.

the blue light was on, the next light would remain in the blue region. For additional details, refer to (27,28) and Figure 2. To minimize carry-over effects between conditions, participants were given rest periods following each dual-task protocol (P1, P2, P3), each lasting as long as the average completion time for the specific task. These rest intervals were designed to ensure sufficient time for prefrontal hemodynamic signals to return to baseline before the subsequent task.

fNIRS Recordings

Prefrontal HbO, HbR and HbT measurements were performed with a wearable fNIRS device (Fnırs Devices 1100 LLC., PA, USA), The sensor pad was placed on the forehead area after cleaning the prefrontal area with alcohol (NuPrep EEG Skin Prepping Gel) and covered with a specially designed bandage for fixation (Figure 3). In addition, a black headband was placed over the participants' heads to eliminate potential environmental light effects. The data were visually inspected to ensure the presence of synchronized waveforms, with no abnormal spikes observed. Raw optical density signals were then converted into HbO, HbR, and HbT concentrations using the modified Beer–Lambert Law (DPF = 5.67). To minimize physiological and motion-related artifacts, a second-order Butterworth bandpass filter (0.01–0.14 Hz) was applied to remove low-frequency drift and high-frequency physiological noise, such as that caused by heartbeat and respiration. Epochs showing persistent signal disruptions were excluded from the statistical analysis. These preprocessing steps align with previous recommendations for motion artifact control in movement-related fNIRS studies (30,31).

Statistical Analysis

Data analysis was performed using IBM SPSS Statistics version 25.0 for Windows (SPSS, Inc., Chicago, IL, USA). The normality of the parameter distributions was assessed using the Shapiro-Wilk test. Performance times in P1, P2 and P3 tests and the change in haemodynamic responses (HbO, HbR and HbT) were compared by ANOVA and Friedman's ANOVA, respectively. Post hoc analysis with Wilcoxon signed rank tests was conducted with Bonferroni correction applied. Spearman correlation was performed to determine the relationship between HbO, HbR and HbT values at P1, P2 and P3 and reported using the r coefficient. Statistical significance was determined at $p < 0.05$.

RESULTS

Power Outputs

A repeated measures ANOVA was conducted on the completion times for the three dual-task conditions (P1, P2,

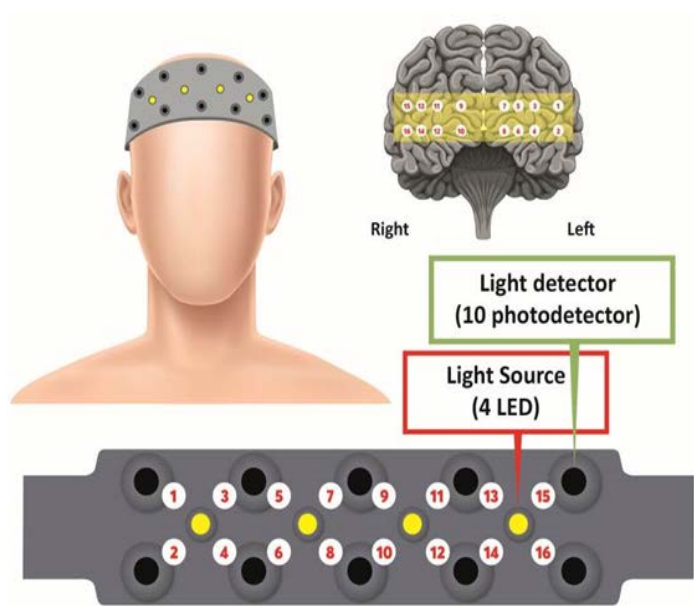

Figure 3. The demonstration of functional near infrared spectroscopy (fNIRS) sensor pad.

P3) with 14 participants. Mauchly's test confirmed sphericity ($\chi^2(2) = 5.923$, $p > .05$); therefore, no correction was applied. The resulting test statistic was $F(2, 26) = 43.903$, $p < .001$. No participants were excluded from this analysis. Following the repeated measures ANOVA, a post-hoc Bonferroni correction was carried out to examine pairwise differences. Significant differences were found between the P1 and P2 ($p < 0.001$), and between the P1 and P3 ($p < 0.001$). However, the P2 and P3 comparison was not significant. Figure 4 illustrates the performance times of the participants during dual-tasks of varying difficulty. An improvement in performance time was observed when comparing the P1 (42.81 s) test performance with the P2 (37.53 s) test performance. The reaction time was longer in the P3 (38.24 s) test due to the more complex cue compared to the P2 cue test.

Hemodynamic Parameters

Oxyhemoglobin Results

Research findings revealed a strong, statistically significant, positive correlation between P1HbO-P2HbO, P1HbO - P3Hbo and P2Hbo-P3HbO, respectively [(r s (8) = .859, p = .000), (r s (8) = .807, p = .000), (r s (8) = .921, p = .000)]. In addition, it was found that HbO values increased compared to baseline in each of the P1, P2 and P3 tasks. Athletes showed better values in P3 (Mdn = 0.812) and P2 (Mdn = 0.437) than in P1 (Mdn = 0.353) (Figure 5). However, there was an increase in HbO values in P1, P2 and P3 protocols, it was not statistically significant, $\chi2(2) = 8.143$ $p = 0.017$. Wilcoxon signed rank test showed that there was no significant difference between P1 and P2 tests ($Z = -1.789$, $p = 0.074$), P1 and P3 ($Z = -2.291$, $p = 0.022$) and P2 and P3 ($Z = -1.475$, $p = 0.140$).

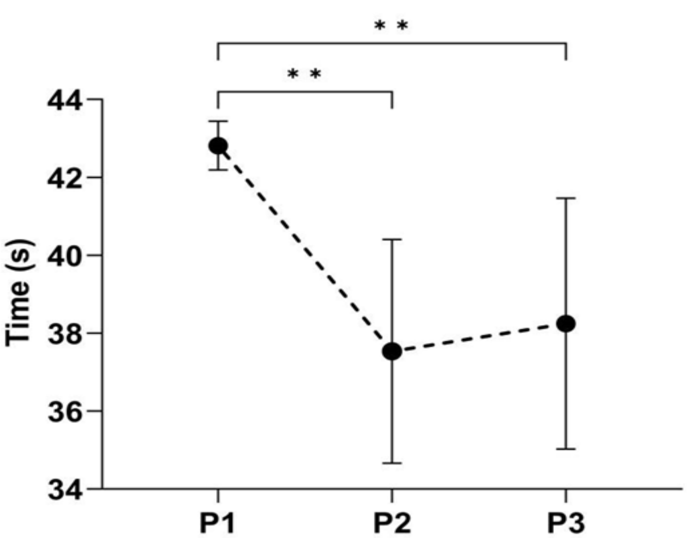

Figure 4. Performance Duration of the Participants During Dual Tasks of Different Difficulty
P1: motor task; P2: cue task; P3: mixed cue task. ** p < .001.

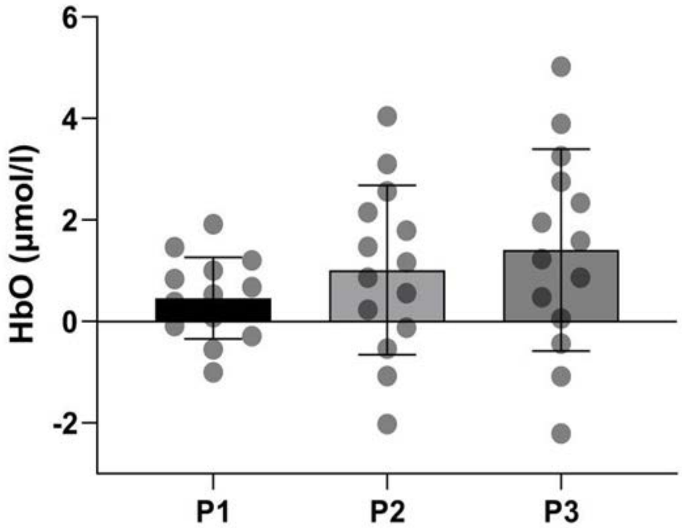

Figure 5. Changes in HbO levels during each tasks. P1: motor task; P2: cue task; P3: mixed cue task.

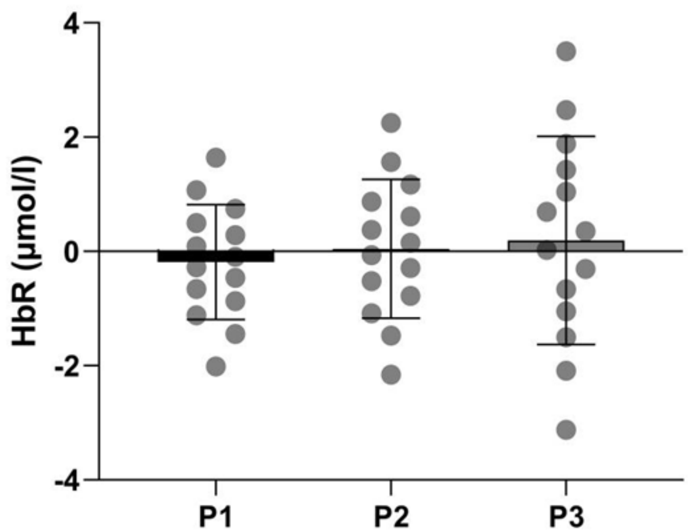

Figure 6. Changes in HbR levels during each tasks. P1: motor task; P2: cue task; P3: mixed cue task.

Deoxyhemoglobin Results

In the deoxygenation findings, there was a strong, statistically significant, positive correlation between P1HbR-P2HbR, P1HbR-P3HbR and P2HbR-P3HbR, respectively [(r s (8) = .881, p = .000), (r s (8) = .653, p = .011), (r s (8) = .842, p = .000)]. Furthermore, HbR concentrations increased as the test progressed and the task became more difficult in P2 and P3 tasks (0.05±0.03 and 0.19±0.49, respectively) (Fig. 6).

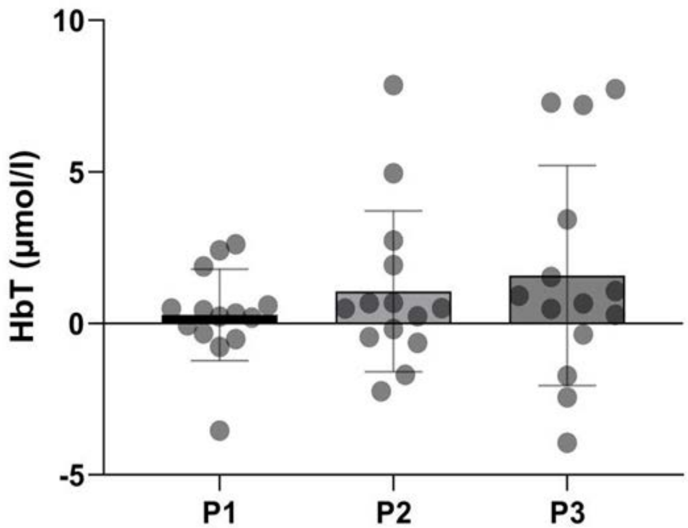

Figure 7. Changes in HbT levels during each tasks. P1: motor task; P2: cue task; P3: mixed cue task.

A decrease was detected in the P1 test (-0.19±0.27). However, although the athletes showed better values in P2 (Mdn = 0.084) and P3 (Mdn = 0.140) than in P1 (Mdn = 0.046), there was no statistically significant difference between P1, P2 and P3 tests, $\chi2$ (2) = 0.143 p = 0. 931. In the Wilcoxon signed rank test, we found no significant difference between P1 and P2 tests (Z = -0.534, p = 0.594), P1 and P3 (Z = -0.345, p = 0.730) and P2 and P3 (Z = -0.345, p = 0.730).

Total Hemoglobin Results

In total oxygenation findings, there was a strong, statistically significant, positive correlation between P1HbT-P2HbT, P1HbT - P3HbT and P2HbT-P3HbT [(r s (8) = .798, p = .001), (r s (8) = .618, p = .019), (r s (8) = .815, p = .000)]. In addition, the mean HbT during P1, P2 and P3 tests were higher than the previous test (0.28±0.4, 1.06±0.71 and 1.58± 0.97, respectively) (Figure 7). However, although the athletes showed better values in P3 (Mdn = 0.784) and P2 (Mdn = 0.491) than in P1 (Mdn = 0.272), no statistically significant difference was found between P1, P2 and P3 tests, $\chi2$ (2) = 0.2714 p = 0. 257. In the Wilcoxon signed rank test, we found that there was no significant difference between the P1 and P2 tests (Z = -1.538, p = 0.124), P1 and P3 (Z = -1.475, p = 0.140) and P2 and P3 (Z = -0.659, p = 0.510).

DISCUSSION

The present study aimed to examine hemodynamic changes (HbO, HbR, HbT) in the prefrontal cortex of amateur football athletes during dual-task (motor + cognitive) performances across varying levels of task difficulty. Grounded in the hypothesis of temporal and resource-sharing competition between motor and cognitive processes, it was hypothesized that the addition of a cognitive task would lead to shorter motor task completion times and heightened hemodynamic responses as task difficulty increased. The findings aligned with previous research (28, 34), indicating improved performance in the P2 and P3 conditions compared to P1. However, no statistically significant differences were observed between the P2 and P3 tasks.

During the P2 and P3 tasks, HbO, HbR, and HbT concentrations were higher than in the P1 task, with a strong positive correlation observed between these variables. These findings support the efficacy of motor-cognitive dual tasks in enhancing brain activity in amateur football athletes. However, contrary to expectations, the hypothesis that increasing the complexity of the cognitive task would lead to a further increase in cortical haemodynamic responses was not statistically supported. Potential explanations for this outcome include (1) inefficient utilization of attentional resources and (2) the cognitive tasks' difficulty levels potentially surpassing the athletes' attentional capacity. Interestingly, while the performance time for the P1 motor task was longer than for the P2 and P3 tasks, HbO levels—reflecting prefrontal cortical activation—demonstrated an increase with task complexity. The highest HbO concentrations were observed during the P3 task, followed by P2, with the lowest levels recorded in P1. These results suggest that although task complexity influenced performance time, it also induced heightened cortical activation, with P3 requiring the most cognitive resources. The faster performance times observed in the P2 and P3 tasks may be attributed to the cognitive cues provided, which enabled participants to anticipate the subsequent light location, thereby allowing for quicker responses despite the increased task complexity.

The findings of the present study are consistent with previous research demonstrating increased prefrontal cortex (PFC) activation during dual-task performance (16,17,32). Furthermore, no significant haemodynamic differences were observed between the two higher-difficulty conditions (P2 vs. P3), mirroring the results reported by Hoang et al. (2020) (6). This lack of differentiation may suggest that participants did not engage additional cognitive resources when performing the P3 task relative to P2. Alternatively, it is plausible that the P3 task exceeded the participants' attentional capacity, thereby limiting further cortical recruitment. Although HbO levels were elevated in P3 compared to P2, this difference did not reach statistical significance, possibly reflecting a ceiling effect in cognitive resource allocation. Carius et al. (2023) reported that during sport-specific dual-task training, amateur table tennis players exhibited greater HbO concentration changes in the dorsolateral PFC than expert players; however, no such difference was observed for HbR (20). In the current study, a similar pattern emerged: an increase in HbO concentration accompanied by a decrease in HbR concentration was observed during the P1 task. While HbO levels were higher during P2 and P3 relative to P1, no corresponding differences were detected in HbR concentrations. The inverse relationship between HbO and HbR observed during P1 may reflect heightened neural activation (30,31), whereas the concurrent increase in both HbO and HbR during P2 and P3 could be attributed to elevated cerebral oxygen consumption due to higher cognitive demands.

These findings highlight the complexity of interpreting haemodynamic responses in dual-task paradigms and emphasize the need for innovative approaches to reliably capture cortical dynamics across varying task difficulties. The observed increase in HbO levels with task complexity supports the hypothesis that greater cognitive load leads to enhanced prefrontal oxygenation. Despite longer reaction times in the relatively simple P1 motor task, the more cognitively demanding P2 and P3 tasks elicited higher HbO responses, indicating increased PFC involvement. The presence of visual cues in the P2 and P3 conditions may have facilitated anticipatory processing, allowing participants to respond more rapidly despite the increased cognitive demands. Research findings indicate that HbO and HbT values are elevated during cognitive and complex cognitive tasks compared to motor tasks. When the brain engages in a specific task, the demand for oxygen and glucose increases, leading to an oversupply of regional cerebral blood flow (CBF) to meet the heightened metabolic requirements. Regional brain activation is thus accompanied by increased CBF (33). While HbO changes are highly sensitive to fluctuations in regional CBF and may serve as reliable indicators of underlying neural activity (34), HbT may offer a broader index for mapping cerebral responses beyond localized assessments (35).

The current study revealed increased HbO and HbT levels during both the P2 and P3 tasks—characterized by higher cognitive load—compared to the motor-only P1 task. Interference arising from the concurrent execution of motor and cognitive tasks can negatively affect overall performance, and this detrimental effect tends to intensify with increasing cognitive load (36,37). The observed rise in PFC activity in this study suggests that cognitive resources are more extensively recruited during dual-task performance (21,22). These findings are consistent with prior research demonstrating elevated PFC activation in dual-task conditions (23,38).

However, relatively few studies have examined dual-task interactions across developmental stages—from childhood through adolescence—compared to adult populations. The available studies have predominantly involved basic cognitive tasks (e.g., digit recall, spatial orientation) performed alongside motor tasks such as walking or balance maintenance (21,39). In contrast, athletes are often required to manage complex motor actions under significant cognitive demands. In such sport-specific scenarios, efficient PFC functioning plays a crucial role in technical and tactical execution and is believed to enhance decision-making capacity during competitive performance. Nonetheless, the effects of motor-cognitive dual-task training on cerebral activation in athletes remain insufficiently explored in the current literature.

This study offers novel insights into haemodynamic responses (HbO, HbR, HbT) in the prefrontal cortex during motor-cognitive dual-task performance in amateur football players. The concurrent execution of motor and cognitive tasks may lead to performance decrements, particularly as task complexity increases and imposes a greater cognitive load. The elevated HbO and HbT levels observed during the P2 and P3 conditions, compared to the P1 condition, likely reflect increased cerebral resource demands associated with heightened task difficulty. Given the limited number of studies investigating cortical activation under dual-task conditions using fNIRS, the present findings contribute meaningfully to the literature by providing simultaneous assessment of multiple haemodynamic indicators (HbO, HbR, HbT) in response to varying cognitive demands in a sport-specific context. Although rest intervals matching task durations were applied between protocols to minimize hemodynamic overlap, future studies may consider using within-condition block designs with alternating rest and task segments to more clearly isolate task-specific cortical responses.

CONCLUSIONS

The findings of this study reveal a significant increase in HbO levels in the prefrontal cortex (PFC) of amateur football players during dual-task performance. This increase, particularly in the PFC, is important as it enhances key executive functions such as information processing speed, working memory, and response inhibition. These results suggest that dual-task training leads to greater cortical oxygenation compared to single-task training, potentially benefiting both motor development and cognitive functions, especially during the transition from childhood to young adulthood. Consequently, integrating dual-task training into athletes' training programs could be crucial for optimizing performance. While previous studies have investigated brain activation differences across age groups, genders, and sport-specific roles (40–42), further research is necessary to explore how these individual factors interact with task complexity in ecologically valid dual-task settings. Future studies should consider comparing cognitive load manipulation with real-time motor performance across diverse athlete populations to provide deeper insights into sport-specific neural adaptations.

Although this study contributes valuable insights into dual-task performance in amateur athletes, it is essential to extend the research by examining how age, gender, and sport-specific positions influence brain activation and performance. This approach will help to refine our understanding of the nuanced effects of these factors on cognitive and motor performance in competitive environments.

Limitations

One potential limitation of this study is the absence of statistically significant differences in cortical hemodynamic responses between tasks of varying difficulty, which may be explained by a ceiling effect caused by the preceding exercise session. Although the activity was light to moderate in intensity, it may have elevated baseline prefrontal activation, limiting the sensitivity of fNIRS to detect further increases in HbO during the more complex tasks. To better account for this, future studies could implement a passive baseline condition or a rest-only control group, providing a clearer baseline for comparison. Furthermore, the use of global PFC averages, rather than region-specific (e.g., right vs. left DLPFC) or channel-wise analysis, may have limited our ability to detect more nuanced spatial patterns of activation. Future research could benefit from focusing on region-specific or channel-wise analyses to gain a deeper understanding of the spatial dynamics of cortical activity during dual-task performance. Despite these limitations, the current study makes a valuable contribution to understanding prefrontal cortical activation in amateur football players during motor-cognitive dual tasks, providing a foundation for future studies to build upon.

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Sorumlu Yazar: Tugba Nacacigil, Faculty of Sports Sciences, Eskisehir Technical University, Eskisehir, Turkiye
e-mail: tugbanalcacigil@gmail.com

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