Acute associations between high-intensity cross-training and executive function in female athletes

Asociaciones agudas entre el cross training de alta intensidad y la función ejecutiva en atletas mujeres

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Abstract

Aim: This study explored the acute association between a high-intensity cross-training benchmark and executive function performance in female athletes.
Methodology: A convenience sample of trained female athletes (age: 29.17 ± 6.75 years; training experience: 29.83 ± 16.63 months) completed the Five-Digit Test (FDT) and underwent physiological assessments, including blood pressure, heart rate, and blood lactate concentration, before and immediately after the WOD Fran benchmark. A within-subject pre–post design was adopted. Paired Student's t-tests were used to compare cognitive and physiological variables between moments, with the level of statistical significance set at $p \leq 0.05$.
Results: Significant pre–post differences were observed in several executive function–related measures, including counting time, choice time, shifting time, inverse memory, inhibitory control, and cognitive flexibility.
Discussion: These findings indicate that acute exposure to a high-intensity functional exercise bout is associated with measurable changes in executive function performance and physiological responses in female athletes.
Conclusion: Although causality cannot be inferred due to the pre-experimental design and absence of a control condition, the results provide exploratory evidence supporting a link between acute cross-training exercise and executive function dynamics, contributing to the understanding of psychophysiological responses to high-intensity exercise in this population.

Keywords

Resistance training; inhibitory control; cognitive flexibility; processing speed; immediate memory

Resumen

Objectivo: Este estudio exploró la asociación aguda entre un benchmark de cross-training de alta intensidad y el rendimiento de la función ejecutiva en atletas mujeres.
Metodología: Una muestra por conveniencia de atletas mujeres entrenadas (edad: 29.17 ± 6.75 años; experiencia de entrenamiento: 29.83 ± 16.63 meses) completó el Test de Cinco Dígitos (FDT) y se sometió a evaluaciones fisiológicas, incluyendo presión arterial, frecuencia cardíaca y concentración de lactato sanguíneo, antes e inmediatamente después del benchmark WOD Fran. Se adoptó un diseño intra-sujeto pre–post. Se utilizaron pruebas t de Student pareadas para comparar las variables cognitivas y fisiológicas entre los momentos, estableciéndose el nivel de significación estadística en $p \leq 0.05$.
Resultados: Se observaron diferencias significativas pre–post en varias medidas relacionadas con la función ejecutiva, incluyendo tiempo de conteo, tiempo de elección, tiempo de cambio, memoria inversa, control inhibitorio y flexibilidad cognitiva.
Discussión: Estos hallazgos indican que la exposición aguda a un ejercicio funcional de alta intensidad se asocia con cambios medibles en el rendimiento de la función ejecutiva y en las respuestas fisiológicas en atletas mujeres.
Conclusión: Aunque no puede inferirse causalidad debido al diseño preexperimental y a la ausencia de un grupo control, los resultados aportan evidencia exploratoria que respalda una relación entre el ejercicio agudo de cross-training y la dinámica de la función ejecutiva, contribuyendo a la comprensión de las respuestas psicofisiológicas al ejercicio de alta intensidad en esta población.

Palabras clave

Entrenamiento de resistencia; control inhibitorio; flexibilidad cognitiva; belocidad de procesamiento; memoria inmediata.

Introduction

The longstanding interest in female characteristics within psychological and exercise sciences has highlighted a persistent gap in understanding their relevance to cognitive functioning, particularly in relation to physical training (Slimani et al., 2016). Although growing evidence suggests that biological sex may influence neurocognitive processes, the specific cognitive responses of female athletes to exercise-related physiological demands remain underrepresented in neuroscientific research (Coco, 2016). A clearer characterization of cognitive parameters in female athletes may contribute to a more accurate interpretation of psychophysiological responses to training and help contextualize observed sex-related differences in behavior and performance.

Although a growing body of literature has investigated the relationship between acute exercise and executive function, the majority of these studies have been conducted in male samples or have not accounted for sex-specific responses (Alves et al., 2014; Brito et al., 2023a; Kao et al., 2017; Tsukamoto et al., 2016). This represents a critical limitation, as neurocognitive and physiological responses to exercise may be modulated by sex-related factors, including hormonal regulation, metabolic differences, and variations in central nervous system activation Consequently, the extent to which findings derived from male-dominated samples can be generalized to female athletes remains unclear (Browne et al., 2016; Diamond & Ling, 2016). Addressing this gap is essential, particularly in high-intensity training modalities such as cross-training, where the interaction between physiological load and cognitive function may be influenced by sex-specific mechanisms.

In sport psychology, a central objective is to understand how physical training interacts with brain function, especially with respect to executive functions that regulate behavior, attention, and decision-making (Maerlender, 2017). Acute and chronic physical exercise have been associated with changes in central nervous system metabolism and cognitive performance, particularly in domains such as inhibitory control, working memory, and cognitive flexibility (Alves et al., 2014; Brito et al., 2023a; Kao et al., 2017; Tsukamoto et al., 2016). Cognition, defined as the set of processes responsible for behavioral regulation (Diamond, 2013), is therefore a relevant construct for understanding athletic performance in conjunction with physiological markers (MacDonald & Minahan, 2016). Previous investigations using neurocognitive assessments have demonstrated associations between athletic training and executive function performance across different sports contexts (Verburgh et al., 2014; Vestberg et al., 2012, 2017; Ade et al., 2016; Basso & Suzuki, 2017; Burr et al., 2019).

Executive functions are fundamental to processes such as response selection, reaction time, problem-solving, and decision-making, particularly in novel or cognitively demanding situations (Browne et al., 2016; Diamond & Ling, 2016). Evidence from cognitive training studies suggests that targeted interventions may support neural efficiency and plasticity (Brooks, 2016), and some experimental paradigms have demonstrated improvements in executive domains through structured cognitive or virtual task exposure (Cardoso et al., 2018). However, women remain underrepresented in these samples, and the extent to which physical training, rather than cognitive training, relates to executive function dynamics in female athletes remains insufficiently explored.

Athletic performance emerges from the interaction of physiological, psychological, and cognitive factors (Brito et al., 2023; Ferreira et al., 2020), all of which contribute to central nervous system functioning and overall health (Arena et al., 2022; Giles et al., 2014). While studies conducted predominantly in male samples have reported associations between high-intensity or resistance-based training and cognitive performance, neural plasticity, and learning processes (Griffin et al., 2011; Murawska-Cialowicz et al., 2015; Tomporowski & Pesce, 2019; Wang et al., 2013), it remains unclear whether similar associations occur in female athletes, particularly in the context of cross-training modalities.

Given the specific physiological demands and training characteristics of cross-training (Brito et al., 2023), there is limited empirical evidence examining its acute association with executive function and physiological responses in women.We hypothesize that acute exposure to a high-intensity cross-training bout (WOD) will lead to significant changes in executive function performance in female athletes, particularly in domains related to inhibitory control, cognitive flexibility, and working memory, due to transient increases in physiological arousal and metabolic demand. Therefore, the present study aimed to explore the association between an acute cross-training benchmark and executive function performance, alongside physiological parameters, in female athletes, adopting a pre–post exploratory approach.

Method

Participants

A convenience sample of twelve female cross-training athletes was recruited from a training facility in Governador Valadares, Minas Gerais, Brazil. Participants were selected from an initial pool of approximately 100 registered practitioners who met the eligibility criteria. The final sample consisted of twelve women (age: 29.17 ± 6.75 years; body mass: 32.0 ± 3.8 kg; height: 1.68 ± 0.08 m; training experience: 29.83 ± 16.63 months) who completed both pre- and post-intervention assessments.

The WOD Fran benchmark was selected based on its widespread use and reference performance times reported for female athletes participating in the CrossFit OPEN, with average execution times below 7 minutes (Glassman, 2015).

Given the exploratory nature of the study and the acute intervention design, no formal sample size calculation was performed. The sample size was considered adequate for preliminary analysis of within-subject changes in cognitive and physiological parameters.

Inclusion Criteria - Participants were eligible if they were between 22 and 39 years of age, engaged in regular cross-training practice at least three times per week for a minimum of 12 consecutive months, and under stable hormonal control through the use of a contraceptive method.

Exclusion Criteria - Participants were excluded if they reported the use of medications or substances known to affect psychophysiological responses within the three months preceding data collection. The list of substances prohibited by the World Anti-Doping Agency was used as a reference (Silveira, 2019). Individuals who failed to complete any stage of the experimental protocol or who were simultaneously engaged in another structured physical training program were also excluded.

Ethical Considerations - The study was conducted in accordance with Resolution No. 466/12 of the Brazilian National Health Council and was approved by the Research Ethics Committee for Human Research of the Federal University of Juiz de Fora (CAE: 13846919.8.0000.5257). All participants provided written informed consent prior to participation.

Instruments and Procedures

Data collection was conducted at the participants' affiliated training facility in a designated assessment area. All athletes were previously familiar with the WOD Fran protocol. Assessments were performed during the evening hours (between 18:00 and 21:00) to minimize variability related to training routines and daily activities.

Participants were instructed to perform the WOD until task completion at maximal voluntary effort, with continuous heart rate monitoring throughout the session. To reduce the influence of uncontrolled variables, participants were advised to maintain their habitual daily routines and dietary patterns during the study period and to continue their usual hormonal contraceptive use. These recommendations were intended to minimize acute behavioral changes rather than to strictly control lifestyle factors.

The mean execution time of the WOD Fran during the intervention was 6 minutes and 51 seconds. Each assessment domain was conducted by a single trained evaluator, and prior standardization training was performed to ensure consistency in test administration and data recording.

Assessments

Assessment of Cognitive Skills (Pre- and Post-WOD Fran) - Executive function was assessed using the Five Digits Test (FDT), adapted and validated for the Brazilian population (Sedó et al., 2015). The FDT evaluates components of executive function, including cognitive processing speed, direct and inverse immediate memory, inhibitory control, and cognitive flexibility (Diamond, 2013; Brito et al., 2023).

The test comprises tasks assessing automatic processes (reading and counting phases), controlled processes (inhibition and cognitive flexibility phases), and immediate memory (direct and inverse digit recall). Each phase is preceded by a practice trial. Execution time and number of errors are recorded for each task. Participants were instructed to perform all tasks as quickly and accurately as possible.

Primary outcome measures included execution times for reading, counting, choice, and shifting tasks, as well as derived executive indices. Inhibitory control was calculated as the difference between choice and reading times; cognitive flexibility as the difference between shifting and counting times; cognitive processing speed as the difference between choice and reading times; and immediate memory was assessed through performance in direct and inverse digit recall tasks.

Assessment of Physiological Parameters - Heart rate was continuously monitored using a chest strap and wrist receiver (Polar ProTrainer 5, USA) before, during, and after the intervention. Systolic and diastolic blood pressure were measured immediately before and immediately after the WOD using the auscultatory method with an aneroid sphygmomanometer (Premium, Duque de Caxias, Brazil). Blood lactate concentration was assessed at rest prior to the intervention and immediately upon completion of the WOD using a portable analyzer (Accutrend®, GC/GCT, USA).

Acute Cross-Training Intervention - The acute intervention consisted of the WOD Fran benchmark, performed as three rounds of 21, 15, and 9 repetitions of thrusters and pull-ups, respectively. Participants were instructed to complete the workout as quickly as possible. The thruster load was standardized at 29 kg for women, in accordance with established guidelines (Glassman, 2003, 2015). A standardized 5-minute warm-up preceded the intervention.

Post-WOD Cognitive Assessment - Immediately following completion of the WOD Fran (within the first minute post-exercise), the FDT was reapplied to assess acute changes in executive function. Physiological parameters were reassessed concurrently.

Statistical Analysis

Normality of data distribution and homogeneity of variances were assessed using the Shapiro–Wilk and Levene tests, respectively. Descriptive data are presented as mean (M) and standard deviation (SD). Paired Student's t-tests were used to compare cognitive and physiological variables between pre- and post-intervention moments, with statistical significance set at $p \leq 0.05$.

Pearson correlation coefficients were calculated to explore associations between cognitive and physiological variables and were interpreted as weak (r = 0.10–0.30), moderate (r = 0.40–0.60), or strong ($r \geq 0.70$) (Paranhos et al., 2014). Given the exploratory nature of the study and the small sample size, correlation analyses were interpreted descriptively. All analyses were performed using SPSS version 22.0 for Windows.

Results

Based on WOD Fran completion time, participants were descriptively classified according to reference performance categories: 25% of the sample was classified as elite (mean time = 212 s), 33.3% as advanced (mean time = 345 s), and 41.7% as intermediate (mean time = 585 s). These classifications were used for descriptive characterization of the sample and were not subjected to inferential statistical testing. Table 1 presents descriptive statistics (mean and standard deviation) for cognitive outcomes, including reading, counting, choice, and shifting times, as well as error rates. Derived executive indices, processing speed, direct and inverse memory, inhibitory control, and cognitive flexibility, are also reported.

Table 1.: Assessment of Cognitive Dimensions Pre- and Post-WOD Fran in Female Cross-Training Athletes.

Cognitive Variables	Pre WOD	Post WOD
	M±SD	M±SD
Rading time	26.56±3.59	33.15±13.84
Counting time	29.93±3.58*	33.83±11.19
Choice time	44.11±9.85	34.32±10.94*
Shifting time	50.77±17.36	49.59±9.98*
Direct Memory	10.92±2.74	11.25±2.59

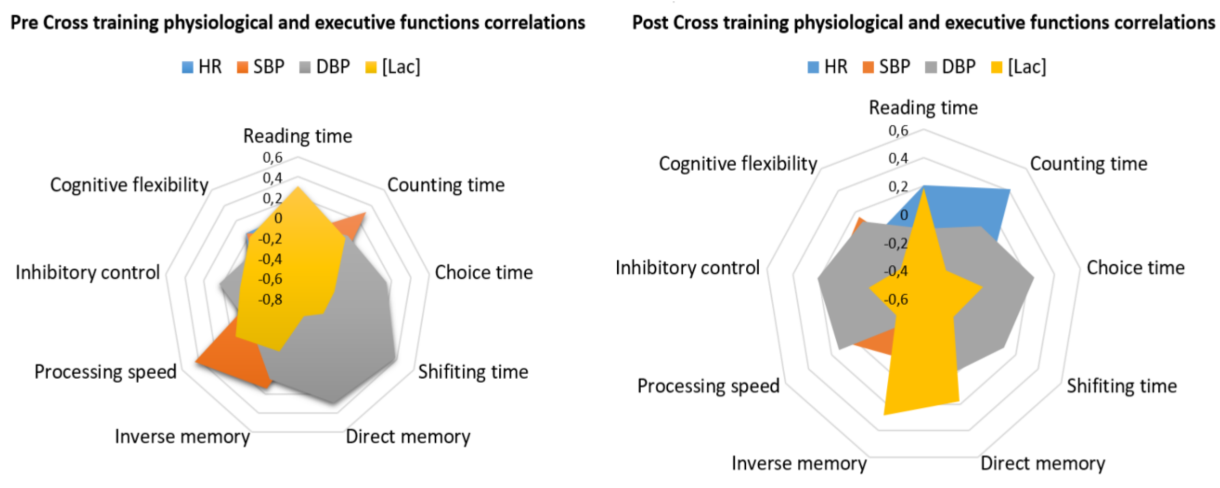
Inverse memory	5.50±1.93	6.33±1.96*
Processing speed	2.53±1.49	0.39±3.43*
Cognitive Flexibility	14.53±4.55	7.63±7.67*
Inhibitory Control	9.19±3.35	3.93±7.4*
Physiological Variables	Pre-WOD M±SD	Post WOD M±SD
Heart Rate	87.25±13.34	176.42±16.52*
Systolic Blood Pressure	127.33±7.25	147.67±9.09*
Diastolic Blood Pressure	83.00±3.56	73.83±8.28*
Blood Lactate	3.11±1.07	14.56±4.30*

Note: *= significant differences pre and post WOD moments. cognitive variables are measured in seconds, p≤0.05.

Comparisons between pre- and post-WOD Fran assessments revealed significant within-subject differences in several executive function measures. Specifically, significant differences were observed for counting time ($t(11) = 3.31$; $p = 0.007$), choice time ($t(11) = 2.72$; $p = 0.020$), shifting time ($t(11) = 2.99$; $p = 0.012$), inverse memory ($t(11) = 9.54$; $p \leq 0.001$), inhibitory control ($t(11) = 2.29$; $p = 0.043$), and cognitive flexibility ($t(11) = 2.62$; $p = 0.024$).

Significant pre- to post-exercise differences were also observed for physiological parameters, including heart rate ($t(11) = -19.77$; $p \leq 0.001$), systolic blood pressure ($t(11) = -7.70$; $p \leq 0.001$), diastolic blood pressure ($t(11) = -3.85$; $p = 0.003$), and blood lactate concentration ($t(11) = -8.92$; $p \leq 0.001$).

Figure 1.: Correlations Between Physiological Effects of Cross Training and Executive Functions, Separated by Pre- and Post-Moments.



Note: *significant correlation with DBP; #= significant correlation with [Lac], p ≤ 0.05.

Figure 1 illustrates exploratory associations between physiological variables and executive function measures at pre- and post-WOD moments. A moderate negative correlation was observed between training experience and diastolic blood pressure at baseline ($p = 0.048$). Additionally, moderate negative correlations were identified between baseline diastolic blood pressure and counting time ($p = 0.038$), as well as between baseline blood lactate concentration and counting time ($p = 0.032$). A further moderate negative association was found between post-WOD shifting time and baseline blood lactate concentration ($p = 0.033$). A strong positive association was observed between baseline processing speed and post-WOD diastolic blood pressure ($p = 0.011$).

Discussion

This study explored the acute association between a high-intensity cross-training benchmark and cognitive and physiological responses in a sample of trained female athletes. Participants exhibited a wide range of WOD Fran completion times, allowing for descriptive classification into elite, advanced, and intermediate performance categories. This variability likely reflects differences in technical proficiency and physical conditioning accumulated through training experience, as previously suggested in resistance and cross-training contexts (Bellar et al., 2015; Glassman, 2015). These classifications were used to characterize the sample rather than to infer performance determinants.

Within-subject comparisons indicated changes in several executive function–related measures following completion of the WOD Fran, including choice time, shifting time, inverse memory, inhibitory control, and cognitive flexibility. These findings suggest that acute exposure to a high-intensity functional exercise bout is associated with measurable alterations in executive function performance in female athletes. Similar associations between acute exercise and executive function have been reported in previous studies, particularly in relation to exercise intensity and task demands (Alves et al., 2014; Tsukamoto et al., 2016; Kao et al., 2017). However, due to the absence of a control condition, these results should be interpreted as exploratory and cannot be used to infer causality.

The observed associations are consistent with literature indicating that executive functions may be sensitive to acute physiological stress induced by high-intensity exercise (Li et al., 2014; Yanagisawa et al., 2010). It has been proposed that such responses may be related to transient changes in arousal, attentional allocation, or neurophysiological activation following exercise. Nevertheless, the present study did not directly assess neural or neurochemical mechanisms, and any interpretation regarding cerebral blood flow, neurotransmitter activity, or lactate-mediated cognitive modulation remains speculative.

Physiological variables, including heart rate, systolic and diastolic blood pressure, and blood lactate concentration, showed marked pre–post differences, reflecting the expected acute cardiovascular and metabolic demands of the WOD Fran. These responses are characteristic of high-intensity functional exercise and align with previous findings in cross-training populations (Brito et al., 2023; Materko et al., 2020). While elevated lactate levels have been hypothesized to relate to cognitive modulation during or after exercise (Coco et al., 2019; Perciavalle et al., 2016), the present data do not allow conclusions regarding whether lactate acts as a mediator, marker of intensity, or coincidental correlate of cognitive change.

Exploratory correlation analyses revealed moderate associations between training experience, baseline diastolic blood pressure, lactate concentration, and selected executive function measures. Given the small sample size, these associations should be interpreted with caution and viewed as hypothesis-generating rather than confirmatory. From a theoretical perspective, these findings may reflect the interaction between physiological stress and central cognitive processes, as cardiovascular and metabolic responses to exercise, such as changes in heart rate, blood pressure, and lactate concentration, are known to influence cerebral perfusion, arousal regulation, and neurochemical activity. In particular, acute increases in lactate have been proposed to act not only as a metabolic byproduct but also as a potential signaling molecule involved in brain energy metabolism and cognitive modulation. Similarly, variations in blood pressure may be associated with changes in cerebral blood flow, which can impact executive function performance. Similar relationships between physiological load and cognitive performance have been reported in prior work (Kao et al., 2017; Strömmer et al., 2020; Uehara et al., 2019), supporting the plausibility of interactions between physiological stress and executive function dynamics during high-intensity exercise.

Although this study contributes to the limited body of literature examining acute cognitive and physiological responses to cross-training in female athletes, several limitations must be acknowledged. The pre-experimental design, small sample size, absence of a non-exercise control condition, and lack of post-recovery assessments restrict the generalizability and causal interpretation of the findings. The pre–post within-subject design was selected to capture acute responses to a high-intensity functional training stimulus under ecologically valid conditions. While this approach allows for the detection of immediate changes in cognitive and physiological variables, it does not permit causal inference, as potential confounding factors such as learning effects, fatigue, or time-related influences cannot be fully disentangled. Additionally, potential learning effects from repeated cognitive testing and the absence of menstrual cycle phase control may have influenced the observed responses.

Future research should employ randomized controlled or crossover designs, include larger samples, and incorporate multiple post-exercise assessment time points to better characterize the temporal dynamics of cognitive recovery. Longitudinal studies examining chronic training adaptations may further clarify whether repeated exposure to high-intensity functional exercise is associated with sustained changes in executive function among female athletes.

Conclusions

This study explored the acute association between a high-intensity cross-training benchmark (WOD Fran) and cognitive and physiological responses in female athletes. Within-subject comparisons revealed changes in several executive function–related measures following exercise, including choice time, shifting time, inverse memory, inhibitory control, and cognitive flexibility. These findings indicate that acute exposure to a short-duration, high-intensity functional workout is associated with measurable alterations in executive function performance in this population.

Physiological parameters, including heart rate, blood pressure, and blood lactate concentration, also showed marked pre–post exercise changes, reflecting the expected cardiovascular and metabolic demands of the benchmark workout. While these physiological responses have been proposed in the literature as potential contributors to post-exercise cognitive modulation, the present study did not directly assess underlying neurophysiological mechanisms, and causal interpretations cannot be drawn.

The results contribute exploratory evidence to the growing body of literature examining the relationship between high-intensity functional exercise and executive function in female athletes. Given the pre-experimental design, small sample size, and absence of a control condition, the findings should be interpreted with caution. Future studies employing controlled and longitudinal designs are necessary to clarify the mechanisms, time course, and potential training-related adaptations linking high-intensity exercise to cognitive performance.

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