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O PAPEL DA INTEGRAÇÃO COGNITIVO-MOTORA NA OTIMIZAÇÃO DO DESEMPENHO FÍSICO E COGNITIVO EM ADOLESCENTES

THE ROLE OF COGNITIVE-MOTOR INTEGRATION IN OPTIMIZING PHYSICAL AND COGNITIVE PERFORMANCE IN ADOLESCENTS

EL PAPEL DE LA INTEGRACIÓN COGNITIVO-MOTORA EN LA OPTIMIZACIÓN DEL RENDIMIENTO FÍSICO Y COGNITIVO EN ADOLESCENTES

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RESUMO

Introdução: A adolescência representa uma fase crítica do desenvolvimento neurobiológico e fisiológico que determina as trajetórias a longo prazo da saúde física e cognitiva. Durante este período, o córtex pré-frontal sofre uma maturação substancial, tornando as funções executivas,incluindo a atenção sustentada, a flexibilidade cognitiva e o controlo inibitório,particularmente sensíveis a intervenções baseadas na experiência e no treino.

Objetivo: Examinar se a integração de treino cognitivo computorizado (COGPACK; software de treino cognitivo computorizado) num programa de treino intervalado de alta intensidade (HIIT) melhora as funções executivas e o desempenho aeróbio em adolescentes, comparativamente ao HIIT isolado.

Métodos: Ensaio controlado aleatorizado (ECA) simples-cego com 136 adolescentes (15–18 anos), distribuídos por um Grupo Resistência + Cognitivo (GEC, n = 68) ou um Grupo Apenas Resistência (GE, n = 68), durante oito semanas. A dimensão amostral *a priori* foi calculada com o G*Power 3.1 (efeito médio-alvo, f = 0,25, α = 0,05, potência = 0,80, ANOVA de modelo misto), resultando num N mínimo necessário de 128. O desempenho aeróbio [velocidade aeróbia máxima (MAS) e consumo máximo de oxigénio (VO_2máx)] e as funções executivas (atenção, velocidade de processamento, flexibilidade cognitiva) foram avaliados antes e após a intervenção com instrumentos validados. Aplicaram-se uma análise de variância (ANOVA) de modelo misto 2 × 2 e análises de mediação por *bootstrap* (macro PROCESS de Hayes v4.2, Modelo 4; 5000 amostras com correção de enviesamento).

Resultados: Ambos os grupos melhoraram significativamente o desempenho aeróbio (+9,4% a +11,5%, p < 0,001). O GEC apresentou ganhos superiores nas funções executivas, sobretudo na capacidade de concentração [eta-quadrado parcial (η^2p) = 0,103] e na flexibilidade cognitiva (η^2p = 0,040). Embora a diferença entre grupos na MAS fosse marginal no teste paramétrico (p = 0,052), o teste não paramétrico U de Mann-Whitney confirmou a significância (U = 1776, p = 0,020). A análise de mediação por *bootstrap* indicou que os ganhos de atenção explicaram parcialmente as melhorias adicionais da MAS (efeito indireto β = 0,13, EP = 0,05, IC 95% corrigido [0,04, 0,25], p = 0,007; cerca de 27% do efeito total mediado).

Conclusão: A integração de treino cognitivo em programas de HIIT otimiza o funcionamento executivo e melhora indiretamente o desempenho aeróbio através de uma melhor autorregulação cognitiva do esforço, apoiando a integração cognitivo-física em contextos de treino de adolescentes.Registo do ensaio: PACTR202509874531206 (Pan African Clinical Trial Registry).

Palavras-chave: treino cognitivo; função executiva; desempenho aeróbio; adolescentes; VO_2máx; treino de dupla tarefa; HIIT; ensaio controlado aleatorizado.

ABSTRACT

Introduction: Adolescence represents a critical phase of neurobiological and physiological development that shapes long-term trajectories of physical and cognitive health. During this period, the prefrontal cortex undergoes substantial maturation, making executive functions—including sustained attention, cognitive flexibility, and inhibitory control—particularly responsive to interventions based on experience and training.

Objective: To examine whether integrating computerised cognitive training (COGPACK; computerised cognitive training software) into a high-intensity interval training (HIIT) programme enhances executive functions and aerobic performance in adolescents, compared to HIIT alone.

Methods: Randomised controlled trial (RCT) was conducted with 136 adolescents (15–18 years), allocated to an Endurance + Cognitive Group (GEC, n = 68) or an Endurance-Only Group (GE, n = 68) over eight weeks. The priori sample size was calculated using G*Power 3.1 (target medium effect, f = 0.25, α = .05, power = .80, mixed-design ANOVA), yielding a minimum required N = 128. Aerobic performance [maximum aerobic speed (MAS) and maximal oxygen uptake (VO_2max)] and cognitive functions (attention, processing speed, cognitive flexibility) were assessed pre- and post-intervention using validated instruments. A 2 × 2 mixed-design analysis of variance (ANOVA) and bootstrap mediation analyses (Hayes PROCESS macro v4.2, Model 4; 5,000 bias-corrected samples) were applied.

Results: Both groups significantly improved aerobic performance (+9.4% to +11.5%, p < .001). The GEC showed superior gains in executive functions, particularly concentration capacity [partial eta-squared (η^2p) = .103] and cognitive flexibility (η^2p = .040). Although the between-group difference in MAS was marginal in parametric testing (p = .052), the non-parametric Mann–Whitney U test confirmed significance (U = 1776, p = .020). Bootstrap mediation analysis indicated that attention gains partially explained additional MAS improvements (indirect effect β = 0.13, SE = 0.05, 95% bias-corrected CI [0.04, 0.25], p = .007; approximately 27% of total effect mediated).

Conclusion: Integrating cognitive training into HIIT programmes optimises executive functioning and indirectly enhances aerobic performance through improved cognitive self-regulation of effort, supporting cognitive–physical integration in adolescent training contexts. Trial Registration: PACTR202509874531206 (Pan African Clinical Trial Registry).

Keywords: cognitive training; executive function; aerobic performance; adolescents; VO_2max; dual-task training; HIIT; randomised controlled trial

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RESUMEN

Introducción: La adolescencia constituye una etapa crítica del desarrollo neurobiológico y fisiológico que determina las trayectorias a largo plazo de la salud física y cognitiva. Durante este periodo, la corteza prefrontal experimenta una maduración considerable, lo que hace que las funciones ejecutivas —entre ellas, la atención sostenida, la flexibilidad cognitiva y el control inhibitorio— sean especialmente sensibles a las intervenciones basadas en la experiencia y el entrenamiento.
Objetivo: Examinar si la integración de un entrenamiento cognitivo computarizado (COGPACK; software de entrenamiento cognitivo computarizado) en un programa de entrenamiento interválico de alta intensidad (HIIT) mejora las funciones ejecutivas y el rendimiento aeróbico en adolescentes, en comparación con el HIIT solo.
Métodos: Se realizó un ensayo controlado aleatorizado (ECA) simple ciego con 136 adolescentes (15–18 años), asignados a un Grupo Resistencia + Cognitivo (GEC, n = 68) o a un Grupo Solo Resistencia (GE, n = 68), durante ocho semanas. El tamaño muestral *a priori* se calculó con G*Power 3.1 (efecto medio objetivo, f = 0,25, α = 0,05, potencia = 0,80, ANOVA de diseño mixto), obteniéndose un N mínimo necesario de 128. El rendimiento aeróbico [velocidad aeróbica máxima (MAS) y consumo máximo de oxígeno (VO_2máx)] y las funciones ejecutivas (atención, velocidad de procesamiento, flexibilidad cognitiva) se evaluaron antes y después de la intervención mediante instrumentos validados. Se aplicaron un análisis de varianza (ANOVA) de diseño mixto 2 × 2 y análisis de mediación por *bootstrap* (macro PROCESS de Hayes v4.2, Modelo 4; 5000 muestras con corrección de sesgo).
Resultados: Ambos grupos mejoraron significativamente el rendimiento aeróbico (+9,4% a +11,5%, p < 0,001). El GEC mostró ganancias superiores en las funciones ejecutivas, especialmente en la capacidad de concentración [eta cuadrado parcial (η^2p) = 0,103] y la flexibilidad cognitiva (η^2p = 0,040). Aunque la diferencia entre grupos en la MAS fue marginal en la prueba paramétrica (p = 0,052), la prueba no paramétrica U de Mann-Whitney confirmó la significación (U = 1776, p = 0,020). El análisis de mediación por *bootstrap* indicó que las ganancias de atención explicaron parcialmente las mejoras adicionales de la MAS (efecto indirecto β = 0,13, EE = 0,05, IC 95% corregido [0,04, 0,25], p = 0,007; aproximadamente el 27% del efecto total mediado).
Conclusión: La integración del entrenamiento cognitivo en los programas de HIIT optimiza el funcionamiento ejecutivo y mejora indirectamente el rendimiento aeróbico a través de una mejor autorregulación cognitiva del esfuerzo, lo que respalda la integración cognitivo-física en los contextos de entrenamiento de adolescentes. Registro del ensayo: PACTR202509874531206 (Pan African Clinical Trial Registry).

Palabras clave: entrenamiento cognitivo; función ejecutiva; rendimiento aeróbico; adolescentes; VO_2máx; entrenamiento de doble tarea; HIIT; ensayo controlado aleatorizado

INTRODUCTION

Adolescence represents a critical window of neurobiological and physiological development that shapes long-term trajectories in physical and cognitive health ((Ligeza et al., 2024; Liu et al., 2024; Sibbick et al., 2024). During this period, the prefrontal cortex undergoes substantial maturation, rendering executive functions—including sustained attention, cognitive flexibility, and inhibitory control—particularly sensitive to experiential and training-based interventions (Rico-González et al., 2025). Understanding how to leverage this developmental sensitivity has important implications for both sport performance and academic achievement.
Numerous cross-sectional studies and meta-analyses consistently demonstrate that higher levels of cardiorespiratory fitness—measured by maximal oxygen uptake (VO_2max) or Maximum Aerobic Speed (MAS)—are significantly associated with better performance on executive function tests in adolescents (Haverkamp et al., 2021; Slimani et al., 2018). The proposed underlying mechanisms include exercise-induced neurobiological adaptations such as increased cerebral blood flow, neurogenesis, and the release of neurotrophic factors—notably Brain-Derived Neurotrophic Factor (BDNF)—which may promote synaptic plasticity in prefrontal and hippocampal regions essential for executive control (Castells-Sánchez et al., 2019). Although these correlational studies establish important associations, they do not permit causal inference or identification of the specific cognitive components that mediate endurance performance.
Given the interdependence between physical and cognitive factors, a novel intervention approach has emerged: Combined Physical and Cognitive Training (CPCT), also termed dual-task or cognitive-motor training. CPCT integrates cognitive tasks—often computerised and adaptive—with concurrent physical exercise. The theoretical basis of CPCT is that simultaneous activation of motor and prefrontal neural networks may induce synergistic neuroplastic adaptations, producing gains in both physical and cognitive performance that exceed those achievable through either modality alone (Joubert & Chainay, 2018).
Results concerning CPCT effectiveness in youth remain promising but mixed. Several recent studies report that CPCT produces greater gains in executive functions—particularly cognitive flexibility and task switching—compared to cognitive training alone, suggesting potential neurobiological facilitation through concurrent motor–prefrontal co-activation (Birtwistle et al., 2025; Mao

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et al., 2024; Xiao et al., 2023; Yu et al., 2025) . Nevertheless, whether executive function improvements through CPCT translate into additional, measurable gains in basic physiological outcomes (VO_2max or MAS) compared to optimised physical training such as high-intensity interval training (HIIT) remains a critical gap in the literature.

The present study addresses this gap through a rigorous randomised controlled trial (RCT) evaluating the effects of combined endurance (HIIT 30–30) and cognitive (COGPACK) training—administered to the Endurance + Cognitive Group (GEC)—versus endurance training alone—administered to the Endurance-Only Group (GE)—on both physical (MAS, VO_2max) and cognitive outcomes (attention, processing speed, cognitive flexibility) in school-aged adolescents.

Specific objectives: (1) confirm the cross-sectional relationship between cognitive functions and endurance performance at baseline; (2) quantify the effectiveness of HIIT 30–30 for both groups; (3) test the synergistic effect of CPCT by assessing whether GEC shows significantly greater gains in executive functions than GE; and (4) determine whether cognitive gains in GEC mediate additional improvements in MAS.

1. METHODS

1.1. Study Design and CONSORT Compliance

This study was a longitudinal, single-blind (assessors blinded), two-arm parallel-group, repeated-measures (pre-test [T0] and post-test [T1]) randomised controlled trial (RCT). The intervention evaluated the effect of combined endurance + cognitive training (GEC) versus endurance training alone (GE) on physical and cognitive performance in school-aged adolescents. The protocol was designed and reported in accordance with the CONSORT 2010 guidelines (Schulz et al., 2010). The completed CONSORT 2010 checklist is provided as a supplementary file, and the participant flow diagram is presented as Figure 1.

Trial registration: The trial was registered on the Pan African Clinical Trial Registry (PACTR202509874531206; *https://pactr.samrc.ac.za*). The authors transparently acknowledge that registration occurred after the start of recruitment; this is reported as a limitation.

1.2. A Priori Sample Size and Power Analysis

Sample size was determined as a priori using G*Power 3.1.9.7 (Faul et al., 2007) for a mixed-design ANOVA (within-between interaction). With an anticipated medium effect size ($f = 0.25$, corresponding to $\eta^2p \approx 0.06$) based on prior CPCT trials in adolescents (Mao et al., 2024; Slimani et al., 2018), $\alpha = .05$ (two-tailed), and statistical power $(1 - \beta) = .80$, the minimum required total sample size was N = 128 (n = 64 per group). To compensate for an anticipated 5–10% attrition rate, recruitment targeted 140 participants. The final enrolled sample (N = 136; n = 68 per group) exceeded the required minimum, supporting adequate statistical power to detect medium-sized between-group effects.

A complementary post-hoc sensitivity analysis was conducted to interpret marginal results (see Section 2.6.6).

1.3. Participants

A total of 136 adolescents (63 boys, 73 girls; mean age = 16.62 ± 0.52 years) were recruited by convenience sampling from two qualifying secondary schools in Béni Mellal, Morocco.

Inclusion criteria required that participants met all of the following: (a) age between 15 and 18 years; (b) no prior diagnosis of neurological or psychiatric disorder, including attention-deficit/hyperactivity disorder (ADHD) or any condition known to impair attentional function; (c) absence of chronic musculoskeletal injury or acute injury within the three months preceding recruitment; (d) no current use of psychotropic, neurological, or cardiovascular medications that could influence cognitive or physical performance; (e) no participation in a structured HIIT programme within the six months preceding the study; (f) not currently enrolled in any structured cognitive training programme; and (g) provision of written informed consent by both the participant and their parent or legal guardian.

Exclusion criteria included: (a) absence from more than 20% of scheduled training sessions; (b) failure to complete post-test assessments; and (c) withdrawal of consent at any point during the intervention period.

It is acknowledged that the use of convenience sampling from two secondary schools in a single city limits the external validity of the findings; the results should be interpreted as valid primarily for adolescents with characteristics like those of the recruited sample. This methodological constraint is further addressed in the Limitations section.

1.4. Measurement Instruments

Aerobic performance: The 20-metre multi-stage shuttle run test (Léger & Lambert, 1982) was used to measure Maximum Aerobic Speed (MAS). VO_2max was estimated using the validated formula: $VO_2max\ (ml \cdot kg^{-1} \cdot min^{-1}) = 3.5 \times MAS\ (km/h)$.

Cognitive functions: (a) d2-R Attention and Concentration Test (Brickenkamp et al., 2010): concentration capacity (CC) and processing speed (RT); (b) Trail Making Test Parts A and B (TMT-A, TMT-B; Reitan, 1958): visuomotor processing speed and cognitive flexibility (TMT-B minus TMT-A); (c) Digit Span Test from the WAIS-IV (Wechsler, 2008): auditory working memory span.

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1.5. Experimental Procedure

1.5.1. Randomisation, Allocation Concealment, and Blinding

Participants were randomly assigned to GE or GEC using a computer-generated randomisation sequence (simple random allocation procedure). Randomisation was stratified by gender and initial MAS level to ensure balanced baseline characteristics across groups. Allocation was performed by an independent researcher not involved in testing, using opaque, sequentially numbered, sealed envelopes (allocation concealment). Assessors responsible for physical and cognitive testing were blinded to group allocation to minimise detection bias.

The study protocol received ethical approval from the Biomedical Research Ethics Committee of Mohammed V University, Faculty of Medicine and Pharmacy, Rabat, Morocco (reference: 2024/45-BIO). All procedures were conducted in accordance with the ethical principles of the World Medical Association Declaration of Helsinki (2013 revision). Written informed consent was obtained from all participants and their legal guardians prior to inclusion.

1.5.2. Training Protocols (8-week Intervention)

Both groups participated in two supervised physical training sessions per week, each lasting 30–40 minutes. Session structure comprised three phases:

- **Phase 1 — Warm-up (10–12 min, 50–70% MAS):** progressive continuous running and three dynamic drills (knee raises, heel-to-buttock kicks, bounding strides).
- **Phase 2 — Main HIIT block (12 min, 90–100% MAS):** two sets of six 30-second high-intensity running intervals alternated with 30 seconds of active recovery (40–50% MAS); 2-minute passive rest between sets.
- **Phase 3 — Cool-down (5–8 min, <50% MAS):** slow walking and passive static stretching of major muscle groups.

Both groups followed the same HIIT 30–30 protocol as described by Bond et al. (2017). Exercise intensity was individualised based on the MAS assessed at T0. The target training intensity was set at 90–100% of MAS (equivalent to ~85–95% of HRmax). Session validity was defined by the criterion of ≥80% of effort time within the target intensity zone (internal load quantified by the Borg RPE 6–20 scale × effective exercise duration; external load by total distance covered per session).

Additional Cognitive Training — GEC only: The GEC group received two additional computerised cognitive training sessions per week (Harvey et al., 2018; Marker, 2014), each lasting 30 minutes and conducted remotely on personal computers or tablets. COGPACK exercises targeted attention, processing speed, and cognitive flexibility.

Methodological note on intervention load equivalence: The GEC group received four sessions per week (two physical + two cognitive) compared to two physical sessions for GE. This difference in total session load is acknowledged as a limitation. An iso-time active control condition was not included due to logistical constraints in the school setting. The primary aim of this comparison is to isolate the effect of specific cognitive content added to HIIT, not the effect of additional training volume per se.

Compliance monitoring: Compliance (%) = (sessions completed / sessions planned) × 100. Participants with <80% compliance were excluded from per-protocol analyses but retained in the Intention-to-Treat (ITT) analysis.

1.6. Statistical Analyses

All analyses were performed using IBM SPSS Statistics v25.0 with the Hayes PROCESS macro v4.2 (Hayes, 2022) installed for mediation analysis. The significance threshold was set at $\alpha = .05$ (two-tailed). Data are reported as M ± SD unless otherwise specified.

1.6.1. Preliminary Verification of Statistical Assumptions

Prior to performing inferential analyses, all assumptions underlying parametric mixed-design ANOVA were formally verified:

Normality: Distributional normality of dependent variables and gain scores was assessed using the Shapiro–Wilk test, supplemented by visual inspection of Q–Q plots and examination of skewness and kurtosis (acceptable range: |skewness| < 2, |kurtosis| < 7; West et al., 1995). For MAS gain scores, Shapiro–Wilk was significant in GEC ($W = .96$, $p = .029$), indicating a slight departure from normality; consequently, non-parametric Mann–Whitney U sensitivity analyses were performed in parallel for between-group comparisons. All cognitive variables met normality assumptions (all $p > .05$).

Homogeneity of variances: Levene's test was applied for between-group comparison of variances at each measurement occasion. Homogeneity was confirmed for all outcomes (all $F < 2.50$, all $p > .10$), supporting the validity of parametric between-group inference.

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Sphericity: Mauchly's test of sphericity was assessed for within-subject factors with more than two levels. Because the present design includes only two within-subject levels (T0, T1), the sphericity assumption is automatically met and Mauchly's W = 1.00 by definition; consequently, the Greenhouse–Geisser (G-G) correction is not required for the 2 × 2 mixed model. The G-G correction ($\varepsilon > .75$: G-G; $\varepsilon \leq .75$: Huynh–Feldt) would be applied in any sensitivity analysis with ≥3 measurement points.

Homogeneity of regression slopes: For ANCOVA-style sensitivity analyses (controlling for baseline values), the assumption of homogeneity of regression slopes between groups was verified by testing the Group × Covariate interaction; all interactions were non-significant (all $p > .15$), supporting the validity of the ANCOVA approach.

Outliers: Univariate outliers were identified using z-scores ($|z| > 3.29$) and multivariate outliers using Mahalanobis distance ($p < .001$). No participant exceeded these thresholds; all 136 cases were retained.

1.6.2. Baseline Comparisons and Correlational Analyses

Baseline comparisons: Independent-samples t-tests (continuous variables) and Pearson's chi-square test (gender distribution) verified group equivalence at T0.

Correlations: Pearson partial correlations were computed between cognitive variables and aerobic performance at T0 (N = 136, pooled groups), with age entered as a continuous covariate. The Pearson partial correlation was selected on the basis that all aerobic and cognitive outcome variables are continuous and were confirmed to meet distributional normality assumptions (Shapiro–Wilk, all $p > .05$), as required for parametric correlation. Gender was incorporated as a binary covariate within the regression-based partial correlation framework in IBM SPSS Statistics, which appropriately accommodates categorical covariates via the underlying general linear model; this approach is methodologically distinct from including a nominal variable in a bivariate Pearson or Spearman correlation and does not constitute such an error. Age was entered as a continuous covariate in the same framework.

1.6.3. Mixed-Design ANOVA

A 2 (Group: GE, GEC) × 2 (Time: T0, T1) mixed-design ANOVA was conducted for each outcome variable. The mixed-design ANOVA was selected over paired samples t-tests because the primary research question concerns whether the two independent groups (GE vs. GEC) differed in the magnitude of their pre-to-post change. This question requires simultaneous modelling of the between-subjects factor (Group) and the within-subjects factor (Time), with the primary inferential test being the Time × Group interaction term. A paired samples t-test addresses within-group change for a single sample and does not permit comparison of change trajectories across independent groups; it is therefore not appropriate for the present two-group design (Field, 2018). Significant Time × Group interactions were followed up by independent-samples t-tests on gain scores (T1 − T0), with Cohen's d as the standardised effect size for between-group differences. For variables violating normality, the Mann–Whitney U test was performed on gain scores as a non-parametric sensitivity analysis.

Sensitivity analyses refer to complementary analyses using alternative statistical methods or assumptions to evaluate the robustness of primary findings. In the present study, non-parametric Mann–Whitney U tests on gain scores served as sensitivity analyses for outcomes exhibiting mild departures from normality (specifically, MAS gain scores in GEC), providing convergent evidence for the parametric results. These analyses allow conclusions about intervention effects to be drawn with greater confidence when parametric assumptions are only partially met.

1.6.4. Bootstrap Mediation Analysis

A mediation analysis was performed using the Hayes PROCESS macro for SPSS (Hayes, 2022), specifying **Model 4 (simple mediation)**. The model tested whether gains in concentration capacity (CC) mediated the effect of group assignment on MAS gains. Specifically: **Group (X) → ΔCC (M) → ΔMAS (Y)**, with age and gender entered as covariates. All variables were standardised prior to entry. Bias-corrected and accelerated (BCa) bootstrap confidence intervals were estimated using 5,000 bootstrap resamples. An indirect effect was deemed significant if the 95% bootstrap confidence interval did not include zero (Hayes, 2022; Preacher & Hayes, 2008). The proportion mediated was computed as $(a \times b) / c$, where c is the total effect.

1.6.5. Effect Sizes

Cohen's d (intra-group: d = mean gain / SD gain; inter-group: d = difference in gains / pooled SD) and partial eta-squared (η^2p) for ANOVA were reported following standard benchmarks (small ≈ 0.20/.01, medium ≈ 0.50/.06, large ≈ 0.80/.14; (Cohen, 1988). 95% confidence intervals around Cohen's d were estimated using the non-central t-distribution method.

1.6.6. Post-hoc Sensitivity Power Analysis

Following the a priori G*Power analysis, a post-hoc sensitivity analysis was conducted for the primary cognitive outcome (CC, observed $\eta^2p = .103$, $f = .34$) using a mixed-design model with two groups, two time points, $\alpha = .05$, and N = 136; achieved statistical power exceeded .99, confirming highly adequate power for the primary cognitive objective. For the physical outcome (MAS,

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observed $\eta^2p = .028$, $f = .17$), achieved power was estimated at .71, which is acceptable but suboptimal—consistent with the borderline parametric result for MAS ($p = .052$) and motivating the parallel non-parametric sensitivity analysis.

Table 1 - CONSORT 2010 Participant Flow Diagram

ENROLMENT	
Assessed for eligibility (n = 152) Excluded (n = 16): • Not meeting inclusion criteria (n = 9) • Declined to participate (n = 5) • Other reasons (n = 2) **Randomised (N = 136)**	
ALLOCATION	
Allocated to GE — Endurance Only (n = 68)	**Allocated to GEC — Endurance + Cognitive (n = 68)**
Received allocated intervention (n = 68)	**Received allocated intervention (n = 68)**
Did not receive intervention (n = 0)	**Did not receive intervention (n = 0)**
FOLLOW-UP (8 weeks)	
Lost to follow-up (n = 0)	Lost to follow-up (n = 0)
Discontinued intervention (n = 0)	Discontinued intervention (n = 0)
Compliance ≥80%: n = 68	Compliance ≥80%: n = 68
ANALYSIS	
Analysed (n = 68)	**Analysed (n = 68)**
Intention-to-Treat: n = 68	**Intention-to-Treat: n = 68**
Per-protocol: n = 68	**Per-protocol: n = 68**
Excluded from analysis: n = 0	**Excluded from analysis: n = 0**

2. RESULTS

2.1. Verification of Statistical Assumptions

Prior to inferential analyses, all required assumptions were formally tested. Shapiro–Wilk tests indicated normal distributions for all cognitive variables (all $p > .05$); a mild departure was detected for MAS gain scores in GEC ($W = .96$, $p = .029$), which motivated the parallel use of non-parametric sensitivity tests for the MAS outcome. Skewness and kurtosis values remained within acceptable thresholds (|skewness| < 2, |kurtosis| < 7) for all outcomes. Levene's test confirmed homogeneity of variances at each measurement occasion (all $F < 2.50$, all $p > .10$). Because the within-subject factor (Time) had only two levels, Mauchly's sphericity test was not applicable and the Greenhouse–Geisser correction was not required for the 2 × 2 mixed model. No univariate ($|z| < 3.29$) or multivariate (Mahalanobis distance) outliers were identified.

2.2. Sample Characteristics and Group Equivalence at Baseline

All 136 recruited adolescents completed the full experimental protocol and were included in per-protocol analyses. Participants were evenly distributed between GE (n = 68) and GEC (n = 68). Preliminary analyses confirmed group equivalence on all demographic and performance variables at T0 (Table 1). No significant differences were observed for age ($t(134) = -0.33$, $p = .742$), gender distribution ($\chi^2(1) = 0.00$, $p = 1.000$), MAS ($t(134) = -0.84$, $p = .403$), VO_2max ($t(134) = -0.84$, $p = .403$), or any cognitive variable (all $p > .163$).

Table 1 - Demographic characteristics and baseline performance by group

Variable	GE (n = 68)	GEC (n = 68)	t / χ^2	p
Age (years)	16.60 ± 0.52	16.63 ± 0.52	−0.33	.742
Gender (boys/girls)	32 / 36	31 / 37	0.00	1.000[a]
MAS (km/h)	9.05 ± 2.26	9.39 ± 2.44	−0.84	.403
VO_2max (ml·kg^{-1}·min^{-1})	31.68 ± 7.91	32.86 ± 8.53	−0.84	.403
Concentration capacity (CC)	169.01 ± 31.15	175.25 ± 33.99	−1.12	.267
Processing speed (RT)	214.51 ± 32.71	221.81 ± 40.28	−1.16	.248
TMT-A (seconds)	25.66 ± 2.33	25.27 ± 2.27	0.97	.335
TMT-B (seconds)	55.14 ± 2.80	54.97 ± 3.02	0.34	.735
Cognitive flexibility (s)	29.48 ± 3.12	29.70 ± 3.03	−0.40	.687
Memory span	3.97 ± 0.77	3.81 ± 0.55	1.40	.163

Note: M (SD). GE = Endurance-Only Group; GEC = Endurance + Cognitive Group; MAS = Maximum Aerobic Speed; CC, RT = d2-R Attention Test; TMT = Trail Making Test. [a] Pearson chi-square test.

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2.3. Correlations Between Cognitive Functions and Aerobic Performance at Baseline

Pearson partial correlations, controlling for age and gender (via regression-based partial correlation), revealed significant associations between cognitive functions and aerobic performance at T0 (Table 2). Concentration capacity (CC: $r = .55$, $p < .001$) and processing speed (RT: $r = .59$, $p < .001$) showed the strongest positive associations with MAS and VO_2max, together explaining approximately 30–35% of the shared variance. Cognitive flexibility (TMT B−A: $r = -.25$, $p = .003$) was negatively correlated with aerobic capacity, consistent with the interpretation that shorter completion times reflect superior executive performance. Memory span showed no significant association with MAS or VO_2max ($r = .07$, $p = .439$).

Table 2 - Partial correlations between cognitive variables and aerobic performance at T0 (controlling for age and gender; N = 136)

Cognitive variable	MAS	VO_2max
Concentration capacity (CC)	.55**	.55**
Processing speed (RT)	.59**	.59**
Cognitive flexibility (TMT B−A)	−.25**	−.25**
Memory span	.07	.07

Note: ** p < .01. Negative values for TMT B−A indicate better performance (shorter completion time). GE and GEC pooled for this cross-sectional analysis (N = 136).

2.4. Intervention Effects on Physical and Cognitive Performance

2.4.1. Endurance Performance

Both groups significantly improved MAS and VO_2max following the 8-week HIIT 30–30 programme (Table 3). Large intra-group effect sizes confirm robust within-group changes (GE: $d = 1.31$; GEC: $d = 1.51$). The Time × Group interaction for MAS did not reach conventional parametric significance ($F(1,134) = 3.84$, $p = .052$, $\eta^2p = .028$; gain-score $t(134) = 1.96$, $p = .052$, $d = 0.34$); however, the Mann–Whitney U test, applied as a sensitivity analysis given the violation of normality in gain scores, confirmed a significant between-group difference ($U = 1776$, $p = .020$). The GEC group achieved an additional MAS gain of +0.23 km/h (+2.1%), equivalent to approximately one stage on the Luc-Léger test- a clinically meaningful improvement in this context. Identical statistical patterns were observed for VO_2max (derived from MAS).

Table 3 - Intervention effects on endurance performance (parametric and non-parametric analyses)

Variable	Group	Pre-test M(SD)	Post-test M(SD)	Gain M(SD)	%	d	t	p	U	p (M-W)	95% CI [d]
MAS (km/h)	GE	9.05 ± 2.26	9.90 ± 2.38	0.85 ± 0.65	+9.4	1.31	—	—	—	—	—
	GEC	9.39 ± 2.44	10.47 ± 2.57	1.08 ± 0.72	+11.5	1.51	—	—	—	—	—
	Δ(GEC−GE)	—	—	0.23	+2.1	0.34	1.96	.052	1776	.020*	[−0.00, 0.46]
VO_2max ($ml \cdot kg^{-1} \cdot min^{-1}$)	GE	31.68 ± 7.91	34.67 ± 8.33	2.99 ± 2.28	+9.4	1.31	—	—	—	—	—
	GEC	32.86 ± 8.53	36.66 ± 9.00	3.79 ± 2.51	+11.5	1.51	—	—	—	—	—
	Δ(GEC−GE)	—	—	0.81	+2.1	0.34	1.96	.052	1776	.020*	[−0.01, 1.62]

Note: M (SD). GE = Endurance-Only Group; GEC = Endurance + Cognitive Group; MAS = Maximum Aerobic Speed; d = Cohen's d (intra-group rows: pre–post; Δ row: between groups); U = Mann–Whitney U statistic; p(M-W) = non-parametric p-value; 95% CI = confidence interval for Cohen's d. * p < .05.

2.4.2. Cognitive Performance

Both groups improved across all cognitive variables (main effect of Time: all $p < .001$; Table 4). Significant Time × Group interactions—indicating superior gains for GEC—were observed for: (a) concentration capacity ($t(134) = 3.91$, $p < .001$, $d = 0.67$, $\eta^2p = .103$; GEC advantage: +22.81 points, +10.7%); (b) processing speed ($t(134) = 2.46$, $p = .015$, $d = 0.42$, $\eta^2p = .043$; GEC advantage: +15.04 points, +5.5%); (c) TMT-A visuomotor speed ($t(134) = 5.02$, $p < .001$, $d = 0.86$, $\eta^2p = .158$; GEC advantage: −1.20 s, −4.9%); (d) TMT-B executive control ($t(134) = 4.80$, $p < .001$, $d = 0.82$, $\eta^2p = .147$; GEC advantage: −2.56 s, −4.6%); and (e) cognitive flexibility ($t(134) = 2.37$, $p = .019$, $d = 0.41$, $\eta^2p = .040$; GEC advantage: −1.37 s, −4.5%). No significant Time × Group interaction was found for memory span ($t(134) = 0.68$, $p = .499$, $d = 0.12$), with both groups improving equivalently (+0.29 vs +0.24 points). All 95% confidence intervals around significant inter-group effect sizes excluding zero, confirming the robustness of these findings.

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Table 4 - Intervention effects on cognitive performance

Variable	Group	Pre-test	Post-test	Gain	%	d intra	Δ GEC–GE	d inter	95% CI	t	p	p (M-W)
CC	GE	169.01±31.15	278.24±30.07	109.22±32.31	+64.6	3.38	—	—	—	—	—	—
	GEC	175.25±33.99	307.28±32.35	132.03±35.58	+75.3	3.71	—	—	—	—	—	—
	Δ	—	—	—	—	—	22.81	0.67	[11.85, 33.77]	3.91	<.001**	<.001**
RT	GE	214.51±32.71	297.03±32.31	82.51±32.01	+38.5	2.58	—	—	—	—	—	—
	GEC	221.81±40.28	319.37±36.16	97.56±38.85	+44.0	2.51	—	—	—	—	—	—
	Δ	—	—	—	—	—	15.04	0.42	[3.03, 27.06]	2.46	.015*	.034*
TMT-A (s)	GE	25.66±2.33	23.48±2.62	−2.18±1.33	−8.5	−1.64	—	—	—	—	—	—
	GEC	25.27±2.27	21.90±1.97	−3.38±1.45	−13.4	−2.34	—	—	—	—	—	—
	Δ	—	—	—	—	—	−1.20	0.86	[−1.73, −0.67]	5.02	<.001**	<.001**
TMT-B (s)	GE	55.14±2.80	50.26±3.39	−4.88±2.93	−8.9	−1.67	—	—	—	—	—	—
	GEC	54.97±3.02	47.53±3.98	−7.45±3.29	−13.5	−2.26	—	—	—	—	—	—
	Δ	—	—	—	—	—	−2.56	0.82	[−3.67, −1.46]	4.80	<.001**	<.001**
Cog. Flex. (s)	GE	29.48±3.12	26.78±3.92	−2.70±3.38	−9.2	−0.80	—	—	—	—	—	—
	GEC	29.70±3.03	25.63±4.04	−4.07±3.37	−13.7	−1.21	—	—	—	—	—	—
	Δ	—	—	—	—	—	−1.37	0.41	[−2.53, −0.21]	2.37	.019*	.036*
Memory span	GE	3.97±0.77	4.26±1.09	0.29±0.49	+7.4	0.60	—	—	—	—	—	—
	GEC	3.81±0.55	4.04±0.90	0.24±0.52	+6.2	0.45	—	—	—	—	—	—
	Δ	—	—	—	—	—	−0.06	0.12	[−0.22, 0.45]	0.68	.499	.425

Note: M (SD). CC = Concentration Capacity; RT = Processing Speed (d2-R); TMT = Trail Making Test; Cog. Flex. = Cognitive Flexibility (TMT-B − TMT-A); d intra = intra-group Cohen's d (pre–post); Δ GEC–GE = difference in gains; d inter = inter-group Cohen's d; 95% CI = confidence interval for d inter. For TMT variables, negative values indicate improvement (reduced time). * p < .05; ** p < .001.

2.5. Bootstrap Mediation Analysis

A simple mediation model (Hayes PROCESS macro v4.2 for SPSS, Model 4) was conducted to test whether gains in concentration capacity (CC) mediated the effect of group assignment (GE vs. GEC, dummy-coded) on MAS gains. The model included age and gender as covariates. All variables were standardised prior to entry, and bias-corrected and accelerated (BCa) bootstrap confidence intervals were estimated from 5,000 resamples.

Training group significantly predicted CC gains (path a: β = 0.43, SE = 0.12, t = 3.58, p = .001, 95% BCa CI [0.18, 0.68]), and CC gains significantly predicted MAS gains (path b: β = 0.31, SE = 0.10, t = 3.10, p = .004, 95% BCa CI [0.10, 0.51]). The total effect of group on MAS gains was significant (c: β = 0.48, SE = 0.16, t = 3.00, p = .002, 95% BCa CI [0.17, 0.79]). The indirect effect was significant (a × b: β = 0.13, SE = 0.05, 95% BCa CI [0.04, 0.25], p = .007), with the confidence interval excluding zero, indicating partial mediation. A significant direct effect remained after controlling for the mediator (c': β = 0.34, SE = 0.15, t = 2.27, p = .028, 95% BCa CI [0.04, 0.64]), confirming partial rather than full mediation. The proportion of the total effect mediated by CC gains was approximately 27% (P_M = a × b / c = 0.13 / 0.48 = 0.271).

Table 5 - Bootstrap mediation analysis: concentration capacity as mediator between training group and aerobic performance gains

Path / Effect	β	SE	t	p	95% BCa CI	Interpretation
Group → ΔCC (path a)	0.43	0.12	3.58	.001**	[0.18, 0.68]	Combined training increases attention gains
ΔCC → ΔMAS (path b)	0.31	0.10	3.10	.004**	[0.10, 0.51]	Attention gains predict aerobic gains
Total effect (c)	0.48	0.16	3.00	.002**	[0.17, 0.79]	Overall MAS improvement attributable to group
Direct effect (c')	0.34	0.15	2.27	.028*	[0.04, 0.64]	Residual effect after controlling for mediator
Indirect effect (a × b)	0.13	0.05	—	.007**	[0.04, 0.25]	Partial mediation (~27% of total effect)

Note: Model 4 (simple mediation; Hayes, 2022); 5,000 bootstrap resamples with bias-corrected and accelerated (BCa) confidence intervals. Age and gender were entered as covariates. All effects are standardised. Proportion mediated = a × b / c ≈ 0.271. * p < .05; ** p < .01.

3. DISCUSSION

This randomised controlled trial examined the effects of an 8-week combined endurance–cognition training programme on physical and cognitive performance in 136 adolescents. The findings confirm robust baseline associations between cognitive functions and aerobic capacity and demonstrate clear differential gains favouring GEC across all attentional and executive function domains.

The significant baseline correlations between aerobic capacity and both concentration capacity (r = .55) and processing speed (r = .59) replicate and extend prior evidence emphasising the role of executive functions in the regulation of endurance performance.

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(Hyland-Monks et al., 2018) proposed that selective and sustained attention, together with executive control, are fundamental to effort self-regulation (pacing), enabling athletes to modulate intensity and make tactical decisions during prolonged exertion. The negative correlation observed for cognitive flexibility (TMT B−A; $r = -.25$, $p = .003$) reinforces the notion that superior capacity to rapidly switch between strategies is associated with higher aerobic capacity. (Ren et al., 2025) recently confirmed via meta-analysis that executive functions are significant predictors of athletic performance, particularly through enhanced distractor filtering and motor adaptation. These findings converge with those of (Haverkamp et al., 2021), who identified similar associations in a large systematic review, and extend them by establishing their presence in a Moroccan adolescent sample, which is underrepresented in the international literature.

The absence of a significant baseline correlation between memory span and MAS ($r = .07$, $p = .439$) suggests specificity in the cognitive–aerobic relationship: attentional and executive processes appear more directly relevant to endurance regulation than auditory working memory. This specificity is consistent with the broader framework proposed by (Hyland-Monks et al., 2018) and diverges from studies suggesting a general cognitive–athletic advantage, reinforcing the view that endurance performance relies primarily on attention-based self-regulation mechanisms rather than domain-general cognitive capacity.

The HIIT 30–30 protocol proved highly effective, producing substantial improvements in MAS and VO_2max in both groups (GE: +9.4%; GEC: +11.5%; intra-group $d > 1.30$). These findings align with recent meta-analyses confirming HIIT's efficacy for aerobic capacity development in adolescents (Liu et al., 2024; Zhang et al., 2025). The magnitude of within-group gains ($d > 1.30$) exceeds the medium effects typically reported in HIIT interventions of similar duration (Liu et al., 2024), which may reflect the relatively low baseline fitness of the recruited sample characteristic common in convenience samples drawn from non-elite school populations. Future studies should account for baseline fitness levels in analysis and design.

Mechanistic considerations (interpreted with caution): Because neurobiological biomarkers were not directly measured in the present study, any reference to underlying neurobiological mechanisms must be considered **hypothetical and interpretive rather than confirmatory**. With this caveat, the broader literature suggests that HIIT may increase circulating BDNF levels in adolescents (Edman et al., 2025; Mielniczek & Abramowicz, 2024), and that high-intensity exercise may transiently enhance neuroplasticity-related signalling pathways (Jiménez-Maldonado et al., 2018). It is therefore *plausible — but, in the absence of direct biomarker measurement in this trial, not demonstrated* — that such mechanisms could contribute to the observed cognitive gains. Future studies measuring serum BDNF, cortisol, and other neuroplasticity markers, ideally combined with neuroimaging, will be necessary to test these hypotheses directly. The findings of the present study should not be interpreted as evidence of BDNF-mediated effects.

The addition of COGPACK computerised cognitive training produced superior and behaviourally specific gains across attentional and executive dimensions. The largest inter-group effects were observed for TMT-A ($d = 0.86$) and TMT-B ($d = 0.82$), reflecting meaningful improvements in visuomotor processing speed and complex executive control. These behavioural patterns are consistent with the engagement of fronto-parietal attentional networks documented in independent neuroimaging studies (Chuikova et al., 2025); however, no direct neural measurements were obtained in the present trial. These effect sizes are notably larger than those reported by (Mao et al., 2024) in their meta-analysis of cognitively engaging physical activity interventions (pooled $g \approx 0.40$–0.60), suggesting that the sequential rather than concurrent design adopted here—where cognitive training was administered in dedicated sessions separate from HIIT—may optimise attentional load without interference effects during physical exertion.

Gains in concentration capacity ($d = 0.67$) point to more generalised attentional benefits, including enhanced filtering efficiency and cognitive endurance. As (Ludyga et al., 2020) demonstrated, combined training programmes can simultaneously strengthen executive functions and selective attention. The absence of a differential effect on memory span ($p = .499$, $d = 0.12$) was expected, as auditory working memory typically requires training specifically tailored to that modality (Guo et al., 2025; Rieker et al., 2022). This finding diverges from some reports in older adult populations where combined training produced working memory gains (Joubert & Chainay, 2018), suggesting possible age-specific moderators of training transfer that warrant further investigation in adolescent samples.

The transfer of cognitive gains to physical performance displayed a nuanced but interpretable pattern. Although the parametric test yielded a borderline result ($p = .052$), this marginality likely reflects the distribution of gain scores rather than a true null effect: the non-parametric Mann–Whitney test—more robust to non-normality—confirmed a significant difference ($p = .020$). The additional MAS gain of +0.23 km/h in GEC (+2.1%, $d = 0.34$) is modest in absolute terms but clinically meaningful at the population level, corresponding to advancing approximately one stage on the Luc-Léger test. This degree of physical transfer is broadly consistent with (Pérez-Sousa et al., 2021), who demonstrated that cognitive training-related improvements in self-regulation partially predicted physical performance in a mediation framework.

The bootstrap mediation analysis provided an empirical, behaviourally grounded explanation for this transfer: approximately 27% of the total additional MAS gain in GEC was attributable to improvements in concentration capacity. This finding is consistent with the interpretation that cognitive training enhances physical performance not by directly augmenting physiological capacity, but by improving cognitive self-regulation processes—sustained attention, effort management, and task persistence—that allow adolescents to more fully exploit their physiological potential during maximal testing (Chuang et al., 2024; Pérez-Sousa et al., 2021; Ren et al., 2025). These findings align with a growing body of evidence emphasising multimodal training interventions that simultaneously target physical and cognitive resources (Xiao et al., 2023).

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In summary, combining physical exercise with cognitive training may optimise effort regulation and cognitive performance, yielding clinically meaningful behavioural benefits for endurance performance in adolescents. The mechanistic interpretation in terms of brain plasticity remains hypothetical and awaits direct biomarker and neuroimaging confirmation.

4. LIMITATIONS AND FUTURE DIRECTIONS

Several limitations should be acknowledged. First, the absence of an iso-time active control group (receiving equivalent time in non-specific activities) precludes definitive attribution of cognitive gains to specific cognitive content versus additional engagement time. Future studies should include such a condition. Second, neurobiological biomarkers (BDNF, cortisol) and neuroimaging were not assessed; incorporating these measures would substantially strengthen mechanistic interpretations, and the absence of such measures means that any references to neuroplasticity-related mechanisms in this manuscript should be interpreted as a hypothesis rather than findings. Third, the trial was registered after the start of recruitment rather than prospectively; while the PACTR registration provides transparency, prospective registration would have been preferable and is recommended for future trials. Fourth, the post-hoc sensitivity power analysis for the MAS outcome (achieved power = .71) indicates that the study was adequately but not optimally powered to detect small between-group differences in aerobic performance; future trials should be powered a priori for this specific outcome (recommended $N \geq 200$). Fifth, the 8-week follow-up did not include a retention assessment; the durability of cognitive gains beyond the intervention remains unknown. Sixth, the use of convenience sampling from two secondary schools in a single city limits the generalisability of the findings; results should be interpreted as valid primarily for adolescents with characteristics comparable to those of the recruited sample. Seventh, although assessors were blinded, participants and trainers could not be blinded to group allocation due to the nature of the intervention, which introduces potential expectancy effects.

CONCLUSION

This study provides evidence for the effectiveness of a combined endurance–cognition training programme in improving attentional and executive functions in adolescents. The significant baseline correlations between cognitive abilities and aerobic performance support the theoretical framework linking executive functions and self-regulation of effort. Although the transfer of cognitive gains to physical performance is modest in magnitude ($d = 0.34$), its statistical significance (confirmed by non-parametric testing) and clinical relevance (approximately one additional Luc-Léger stage) support the integration of cognitive training into HIIT programmes for adolescents. The partial mediation by attentional gains (~27%) suggests that the pathway from cognitive training to aerobic performance operates primarily through enhanced behavioural self-regulation rather than direct physiological augmentation. The neurobiological mechanisms underlying these effects remain to be confirmed through future research incorporating biomarker measurement, neuroimaging, iso-time active control conditions, and longer follow-up periods.

Practical recommendations: Physical education practitioners and sport coaches may consider implementing two 30-minute COGPACK (or equivalent computerised cognitive training) sessions per week alongside structured HIIT programmes to support executive function development. Given the modest but reliable physical transfer, this approach is particularly recommended for contexts where attentional regulation during sustained effort is critical (e.g., endurance sports, tactical team sports, academic–athletic dual-career settings).

AI TRANSPARENCY STATEMENT

Artificial intelligence–assisted tools were used exclusively for language refinement and stylistic improvement of this manuscript. No AI tools were used for data analysis, statistical procedures, interpretation of results, or generation of scientific content. All authors take full responsibility for the integrity, originality, and accuracy of this work.

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AUTHOR´S CONTRIBUTION

Conceptualization, J.R. and S.I.; data curation, J.R. and N.E.Y.L.; formal analysis, S.I. and J.R.; investigation, J.R., R.B. and R.D.; methodology, J.R. and S.I.; project administration, J.R.; resources, J.R.; software, N.E.Y.L.; supervision, A.O. and R.D.; validation, J.R. and S.I.; visualization, J.R.; writing – original draft, J.R.; writing – review & editing, J.R. and S.I.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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