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Multimodal Cognitive Training and Executive Functions in Public Managers: A Preregistered Randomized Controlled Trial Targeting Working Memory and Inhibitory Control

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Abstract

Executive functions (EF) are critical for adaptive performance in cognitively demanding occupational settings, yet evidence regarding their malleability in healthy working adults remains limited. This preregistered randomized controlled trial evaluated a 12-week multimodal cognitive training (CT) program targeting working memory (WM) and inhibitory control (IC) in 24 public managers randomized to intervention or active control groups. The intervention comprised 24 supervised sessions integrating adaptive computerized CT, mindfulness-based attentional practices, psychoeducation, and strategy coaching. Linear mixed-effects models revealed a significant Group × Time interaction for WM ($F(1, 21.35) = 17.52$, $p < .001$), reflecting marked improvement in the intervention group while active-control performance remained stable. This effect remained significant after adjustment for baseline age, perceived stress, and sleep duration. No significant intervention effect emerged for the composite IC outcome. Exploratory task-level analyses nevertheless indicated selective changes, including improved Go/No-Go hit rate and a nonsignificant tendency toward faster responses during incongruent Stroop trials. Training performance showed progressive nonlinear learning trajectories in both targeted domains, with substantial interindividual variability. Adherence was high across both conditions. These findings support the responsiveness of WM to targeted multimodal training while indicating greater heterogeneity and process specificity in IC-related effects among healthy working adults.

Introduction

Executive functions (EF), including working memory (WM) and inhibitory control (IC), support goal-directed behavior, decision-making, and self-regulation in complex environments (Diamond, 2013; Miyake et al., 2000). These functions are particularly relevant in managerial settings, where planning, information integration, behavioral regulation, and adaptive decision-making occur under uncertainty, high cognitive load, and interpersonal demands (Chan et al., 2021; Karatosidi & Iordanoglou, 2024; Percy & Butler, 2025). In public-sector environments, competing priorities, institutional constraints, and accountability pressures place particular demands on cognitive control and adaptive regulation (Huang & Villadsen, 2023; Tummers & Knies, 2016).

Despite their relevance, experimental evidence regarding the malleability of EF in healthy working populations remains limited, particularly within preregistered randomized controlled designs. Cognitive training (CT) provides a potential approach to addressing this gap through repeated engagement of specific executive processes. The present study therefore evaluated a 12-week multimodal CT program targeting WM and IC in public managers using a preregistered randomized controlled design. By combining adaptive computerized CT with mindfulness-based attentional practices and examining both pre–post outcomes and learning trajectories across training, the study aimed to investigate whether core EF can be modified in a cognitively demanding occupational population and how training-related performance develops over time.

Cognitive Training and Executive Function Plasticity

Recent evidence indicates that CT can improve WM and IC in healthy adults, with moderate-to-large effects and functional adaptations in prefrontal and frontoparietal networks (Neves-Teles, Lourenço, et al., 2026). These conclusions are reinforced by recent meta-analytic evidence demonstrating that computerized WM training produces robust near-transfer effects while highlighting the importance of adaptive task design and training specificity for EF improvement (Li et al., 2026).

An important limitation, however, concerns the restricted generalization of training effects. Recent network meta-analytic evidence indicates that the benefits of computerized CT are predominantly characterized by robust near-transfer effects, whereas broader cognitive improvements remain limited and largely dependent on the executive process being trained (Bai et al., 2026; Li et al., 2026). Accordingly, different intervention modalities appear to preferentially enhance specific executive components rather than producing generalized cognitive improvements.

These findings have motivated increasing emphasis on structured, theory-driven interventions targeting specific executive processes over sustained training periods (e.g., ≥ 8–12 weeks). Moreover, growing evidence suggests that multimodal approaches combining complementary intervention components may optimize executive outcomes beyond those achieved through unimodal training alone (Lee et al., 2024; Ludyga et al., 2023).

Multimodal Training and Learning Dynamics

Within this multimodal framework, mindfulness-based interventions have been proposed as a complementary strategy to enhance attentional regulation and reduce mind wandering during cognitive training (Bennike et al., 2017). Recent meta-analytic evidence indicates modest benefits of mindfulness-based interventions across selected cognitive outcomes, including executive attention, WM, IC, and sustained attention, although effects vary across outcomes and populations (Zainal & Newman, 2024). Neuroimaging evidence further suggests accompanying changes in intrinsic functional connectivity, particularly involving hippocampal and posteromedial networks (Sevinc et al., 2021). Accordingly, rather than being expected to produce broad EF improvements in isolation, mindfulness may complement the cognitive processes targeted during training.

Despite these advances, important gaps remain. Most CT studies focus on older adults or clinical populations, framing CT primarily as a strategy to mitigate cognitive decline rather than optimize executive performance in healthy working adults. Furthermore, many interventions rely on multidomain commercial programs, limiting the isolation of specific executive processes. Methodological constraints, including relatively small samples, short intervention periods, and the limited availability of preregistered randomized trials, further reduce the certainty of evidence.

Beyond these limitations, most intervention studies rely primarily on pre–post comparisons, providing limited insight into how cognitive improvements develop throughout training. Large-scale evidence

indicates that CT follows structured learning trajectories characterized by substantial interindividual variability in learning rates (Steyvers & Schafer, 2020). Understanding these learning dynamics may therefore provide complementary information beyond conventional pre–post analyses and contribute to optimizing future intervention protocols (Osman et al., 2023).

The Present Study

The present study addresses these limitations by evaluating a structured CT program targeting WM and IC in a sample of public managers using a preregistered randomized controlled design. The 12-week intervention combines adaptive computerized CT with mindfulness-based attentional practices, aiming to jointly engage executive control and attentional regulation. Participants were randomly assigned to either an intervention group or a low-intensity active control condition, and EF were assessed at baseline and post-intervention.

Two hypotheses were tested. First, cognitive training was expected to improve WM and IC from baseline to post-intervention. Second, a Group × Time interaction was expected, with greater gains in the intervention group than in the active control group. In addition, exploratory analyses examined learning trajectories across training sessions, given evidence that CT effects emerge as dynamic learning processes rather than solely as pre–post differences (Osman et al., 2023; Steyvers & Schafer, 2020).

By focusing on a managerial population and employing a theoretically grounded multimodal intervention within a preregistered RCT framework, this study aims to provide causal evidence regarding the malleability of core EF in healthy working adults while contributing to the development of scalable and ecologically valid strategies for cognitive optimization in real-world leadership contexts.

Methods

Study Design

This study employed a randomized controlled trial (RCT) with a longitudinal mixed design, comprising two parallel groups (intervention and active control) assessed at two time points (pre- and post-intervention). The design included one between-subject factor (Group) and one within-subject factor (Time), allowing the examination of both within-group changes and between-group differences over time.

Trial Registration

The study was prospectively preregistered on the Open Science Framework (OSF) before participant recruitment and data collection (OSF registration: 10.17605/OSF.IO/J93DK). The preregistration included the study hypotheses, experimental procedures, outcome measures, and statistical analysis plan.

Participants

Recruitment, Eligibility, and Sample Characteristics

Participants were public managers recruited from public institutions in the Brazilian states of Rio Grande do Sul and Santa Catarina through direct invitations distributed via institutional communication channels (e.g., e-mails). Eligibility criteria were: (a) being an adult currently employed in a managerial position within the public sector; (b) absence of self-reported neurological or psychiatric conditions likely to substantially affect cognitive functioning; and (c) meeting cognitive screening criteria on the Mini-Mental State Examination (MMSE), using a cutoff score of 24 or higher (Kochhann et al., 2010; sensitivity = 87%; specificity = 82%).

Of the 26 eligible participants, two withdrew before randomization, resulting in a final randomized sample of 24 participants. Detailed demographic, occupational, and baseline characteristics of the sample are presented in Table 1.

Table 1

Sample Size Determination

An a priori power analysis was conducted using G*Power (version 3.1.9.7) based on the preregistered repeated-measures ANOVA framework, with a within-between interaction (Group × Time). The analysis assumed a moderate-to-large effect size (f = 0.30), a significance level of α = .05, statistical power (1 − β) = .80, two parallel groups, and two measurement occasions. The selected effect size was informed by recent systematic reviews and meta-analyses of cognitive-training interventions targeting EF, which have reported effects of similar magnitude (e.g., (Neves-Teles, Lourenço, et al., 2026); Bai et al., 2026).

The estimated minimum sample size was 24 participants (approximately 12 per group), which met the prespecified power target and was considered operationally feasible given the challenges associated with recruiting public-sector managers.

Design and Randomization

The study employed a two-arm, preregistered randomized controlled design with assessments at baseline and post-intervention. Eligible participants were allocated to either the intervention group or the active control group in a 1:1 ratio using a computer-generated random-number procedure without replacement (4Devs Random Number Generator).

Prior to baseline assessment, three participants per group were reassigned because of previously scheduled travel commitments that would prevent adherence to the intervention schedule. These adjustments were made before any outcome assessment and therefore could not have been influenced by participant performance.

Measures

Executive Function Outcomes

EF were assessed using a standardized computerized cognitive test battery. For the purposes of the present trial, only measures of WM and IC were administered. These tasks represent well-established paradigms in EF research and have demonstrated adequate psychometric properties in previous work (Neves-Teles, Monticelli, et al., 2026). The assessment battery comprised four tests (two per EF domain) and required approximately 30 minutes to complete.

Working Memory

WM was assessed using two complementary tasks. The Digit Span task assessed the storage component of WM through total correct responses and maximum span achieved, whereas the 2-back task assessed the manipulation component through accuracy-based indices and signal detection sensitivity (d').

Inhibitory Control

IC was assessed using two complementary tasks. The Go/No-Go task indexed motor response inhibition through accuracy (ACC) and signal detection sensitivity (d'), whereas the Stroop task assessed interference control through reaction time (RT) and ACC interference effects (incongruent minus congruent conditions).

Composite Scores

Primary outcome analyses were conducted using composite scores representing overall performance in each EF domain. The WM composite score was calculated as the mean of standardized indices derived from Digit Span (storage) and 2-back (manipulation), whereas the IC composite score was calculated as the mean of standardized indices derived from Go/No-Go (motor inhibition) and Stroop (interference control).

To ensure comparability across assessments, all task-specific indices were standardized (z-scores) using the baseline mean and standard deviation. Standardized post-intervention scores were computed using these same reference parameters. RT variables were reverse-coded before standardization so that higher values consistently reflected better cognitive performance. Detailed definitions and score-computation procedures are provided in Online Resource 1.

Training-Related Learning Measures

Learning trajectories during the intervention were characterized using the Lumosity Performance Index (LPI), a standardized performance metric ranging from 0 to 2,000, with higher scores indicating better performance. Average LPI values were computed separately for the five WM training tasks and the four IC training tasks throughout the intervention. These aggregated scores constituted the longitudinal

learning measures used in subsequent analyses. Owing to the number of training tasks in each domain, the aggregation procedure yielded four intermediate learning cycles for WM and five for IC.

These measures were treated as secondary outcomes reflecting learning during the intervention itself rather than transfer to standardized cognitive assessments.

Participant-Reported Measures

Participant-reported measures were collected throughout the intervention to characterize adherence and engagement. For the intervention group, session-level measures included sleep duration before each training session, perceived engagement, and satisfaction with the training session. For the active control group, weekly measures included time spent using the mobile application, time devoted to the psychoeducational materials, and perceived engagement with the assigned activities. These measures were used to monitor adherence and provide contextual information for interpreting intervention effects.

Demographic and Covariate Measures

Baseline demographic and occupational measures included age, sex, educational attainment, marital status, employment type, income, tenure, and span of control. Sleep duration and perceived stress were also assessed and subsequently considered in adjusted analyses, as described below.

Procedures

All cognitive assessments were administered remotely at baseline and post-intervention using the same standardized computerized cognitive test battery with automated scoring. Before the baseline assessment, all participants received a standardized instructional video explaining the assessment procedures to minimize procedural variability across participants.

Intervention Group

The intervention was conducted over 12 weeks, from April to July 2026, in Porto Alegre, Rio Grande do Sul, Brazil. Participants completed 24 supervised face-to-face sessions delivered twice weekly, with each session lasting approximately 45 minutes.

Each session followed a standardized multimodal protocol comprising: (a) a brief opening segment including session orientation and psychoeducational guidance (~ 5 min); (b) a brief mindfulness exercise to prepare participants for training (~ 5 min); (c) computerized cognitive training using the Lumosity platform (~ 15 min); (d) a guided mindfulness practice (~ 15 min); and (e) a brief closing segment including progress monitoring, participant feedback, and clarification of questions (~ 5 min).

The computerized cognitive training component consisted of six training rounds per session, comprising three consecutive administrations of a single WM game followed by three administrations of a single IC game (or vice versa), with the order of the EF domains alternating across consecutive sessions. Five Lumosity tasks targeted WM through paradigms analogous to visual span, n-back, and backward spatial span, whereas four tasks targeted IC through motor response inhibition, interference control, and

suppression of prepotent responses. The specific games were systematically rotated between sessions to ensure exposure to all training tasks throughout the intervention. Detailed descriptions of the WM and IC games are provided in Online Resource 2.

Throughout the intervention, the opening and closing segments provided opportunities for brief psychoeducational guidance regarding EF, particularly WM and IC, including their cognitive and neural foundations and the rationale underlying the training activities. Participants also received brief strategy coaching on evidence-based cognitive strategies (e.g., chunking, semantic organization, and attentional control) intended to facilitate strategic engagement with the training tasks. These interactions were standardized across sessions while allowing participants to ask questions and receive clarification regarding the training process.

Active Control Group

Participants assigned to the active control group completed a low-intensity intervention designed to provide regular cognitive engagement without specifically training the targeted EF. An active control condition was adopted to address a recurrent methodological concern in cognitive-training research, as weak or insufficiently matched comparison conditions may complicate the attribution of observed effects to the intervention itself (Diamond & Ling, 2016; Gobet & Sala, 2023; Nguyen et al., 2019).

The control condition comprised two complementary activities: (a) self-directed use of a commercially available mobile application requiring attention and processing speed (*Vita Mahjong*); and (b) biweekly psychoeducational materials addressing mental health promotion, followed by brief comprehension questions. These activities provided an active comparison condition with substantially lower training intensity and without the structured WM- and IC-specific practice implemented in the intervention group.

Data Analysis

Outcome Processing and Data Quality

Outcome-specific data processing and quality-control procedures were prespecified and applied independently to each cognitive task. Consequently, failure to meet the validity criteria for one outcome resulted only in exclusion from analyses involving that specific outcome, rather than exclusion from the study as a whole. Task-specific temporal validity criteria were defined according to the temporal configuration of each computerized task and previously established procedures for the cognitive test battery (Neves-Teles, Monticelli, et al., 2026).

All randomized participants were retained in the analytical dataset and included in analyses whenever valid outcome data were available. Longitudinal analyses required valid data at both baseline and post-intervention; therefore, participants with invalid data at either assessment were excluded only from the corresponding longitudinal comparison. No missing values were imputed, and all analyses were conducted using the available valid observations for each outcome.

For the Digit Span task, no trial-level filtering or participant-level exclusion criteria were applied because the outcome measures were based on response ACC rather than RT. Unlike the standardized administration, the task was not discontinued after two consecutive failures at the same span length. Although the conventional span score was retained (i.e., the highest successfully completed span preceding the discontinuation criterion), administration continued until completion of all trials to allow calculation of a total-correct score across the entire task, thereby preserving additional performance information beyond the participant's maximum span.

For the 2-Back task, RT analyses included only correct responses with latencies between 200 and 2,000 ms. One post-intervention assessment was excluded because task performance indicated that the instructions had not been followed. No further participant-level exclusions were applied to the WM outcomes.

For the Stroop task, RT analyses included only correct-response trials with a registered response (i.e., excluding “none” responses) and RTs between 200 and 1,500 ms. ACC was calculated from all trials within the same temporal window, irrespective of response correctness. Participant-level Stroop data were excluded when 35 or fewer trials met the temporal validity criterion or when ACC on incongruent trials was 25% or lower. These exclusions affected only Stroop-derived outcomes and the IC composite whenever a valid Stroop score was required.

For the Go/No-Go task, RT was calculated exclusively from correct Go responses with latencies between 200 and 800 ms. Hit rate was calculated as the proportion of correct responses to all Go trials presented, whereas false-alarm rate was calculated as the proportion of responses to all NoGo trials presented. Temporal filtering was therefore applied only to RT and not to the calculation of hit or false-alarm rates. Sensitivity (d') was computed from the corrected hit and false-alarm rates using the log-linear adjustment for extreme proportions (0 or 1). Participant-level Go/No-Go data were excluded when 50 or fewer correct Go trials met the RT validity criterion, the hit rate was below 75%, or d' was below zero. These exclusions affected only Go/No-Go-derived outcomes and the IC composite whenever a valid Go/No-Go score was required.

Primary Analyses

Primary hypotheses were tested using Linear Mixed-effects Models (LMMs), with Group (intervention vs. control), Time (pre- vs. post-intervention), and their interaction (Group × Time) specified as fixed effects. Although the preregistered protocol proposed mixed-design analyses of variance (ANOVA), LMMs were adopted because they provide greater robustness for repeated-measures data in small samples while preserving the same inferential focus on the Group × Time interaction. Participant (ID) was included as a random intercept to account for the dependence of repeated observations within individuals. Fixed effects were evaluated using Type III tests with the Satterthwaite approximation for degrees of freedom. Separate models were estimated for the WM and IC composite scores.

Longitudinal learning trajectories were also analyzed using LMMs to evaluate changes in the domain-specific LPI measures across the intervention.

Sensitivity and Exploratory Analyses

To evaluate the robustness of the primary findings, adjusted LMMs were subsequently estimated by including age, baseline perceived stress, and sleep duration as covariates. Exploratory sensitivity analyses were conducted separately for the individual cognitive measures underlying each composite outcome to examine the consistency of the observed effects across their component tasks.

Model assumptions were evaluated through inspection of residual distributions and homoscedasticity. When indicated, robust LMMs were estimated as sensitivity analyses to assess the stability of the primary findings.

Statistical Inference

Statistical significance was determined using a two-tailed α level of .05. For the primary analyses, inference was based on fixed-effect estimates obtained from the LMMs, with Type III tests evaluated using the Satterthwaite approximation for degrees of freedom.

Fixed-effect estimates (β), standard errors (*SE*), 95% confidence intervals (95% CIs), *t* values, and associated *p* values were reported for all primary models. For pairwise comparisons, Cohen's *d* was reported and interpreted using conventional thresholds (small = 0.20, medium = 0.50, large = 0.80). When applicable, post hoc comparisons were adjusted using the Bonferroni correction.

Correlation analyses were conducted using Pearson's *r* for normally distributed continuous variables and Spearman's ρ when assumptions of normality were not met or when ordinal variables were analyzed. Correlation coefficients were interpreted according to conventional benchmarks (small = .10, medium = .30, large = .50). All statistical analyses were conducted using JASP (Version 0.96; JASP Team, 2026).

Results

Participant Flow

A total of 26 participants were assessed for eligibility. Of these, 24 met the inclusion criteria and were randomized, whereas two were excluded prior to randomization due to scheduling conflicts. Participants were equally allocated to the intervention group (n = 12) and the active control group (n = 12).

No dropouts were observed, and all randomized participants completed the intervention and were retained through post-intervention assessment. A detailed overview of participant flow is presented in Fig. 1.

Baseline Equivalence

Baseline equivalence between the intervention and active control groups was examined across sociodemographic, control, and cognitive variables (Table 2). No statistically significant group differences were observed for sociodemographic variables (all *ps* > .05).

Table 2

However, significant differences emerged for two control variables. The active control group was significantly older than the intervention group (*t = -2.81*, *p* = .010, *d* = − 1.15), and the intervention group reported higher levels of perceived stress compared to the active control group (Mann–Whitney, *p* = .047, *r* = − .45). No differences were observed for sleep duration, tenure, or span of control (all *ps* > .05).

Importantly, no significant differences were observed between groups in baseline EF measures, including WM and IC, with small effect sizes (all *ps* > .05), supporting comparability in the primary cognitive outcomes.

Data screening procedures confirmed the adequacy of the cognitive measures. Assumptions of normality were met, and task-specific validity criteria were systematically applied. Six Stroop assessments were excluded at baseline (three in each group) based on the predefined validity criteria, resulting in a refined IC measure. No participant-level exclusions were required for the remaining cognitive measures at baseline.

Correlational analyses indicated convergence between the component measures and their respective cognitive composites. The WM composite demonstrated strong internal convergence, with both storage and manipulation components showing high correlations with the overall WM index (*r* = .755, *p* < .001). Similarly, the IC composite showed moderate to high associations between its constituent indices (Go/No-Go and Stroop) and the overall IC measure (Go/No-Go: *r* = .677, *p* = .002; Stroop: *r* = .631, *p* = .005).

Relationships between EF dimensions were consistent with theoretical expectations. A moderate association was observed between WM manipulation and Stroop performance (*r* = − .601, *p* = .008), whereas the correlation between the overall WM and IC composites was low and non-significant (*r* = − .316), consistent with relative differentiation between these domains.

Overall, the results indicate that groups were comparable across demographic and cognitive variables at baseline, although differences in age and perceived stress were observed and considered in subsequent analyses.

Adherence and Engagement

Intervention Group

Adherence to the intervention protocol was high throughout the 12-week program (Table 3). Overall attendance exceeded 90%, with nearly half of the participants completing all scheduled training sessions

and only one participant attending fewer than 88% of the sessions.

Table 3

Descriptive indicators of adherence, sleep, engagement, and satisfaction are presented in Table 3. Pearson correlation analyses revealed no significant temporal changes in sleep duration, engagement, or satisfaction across the 24 training sessions (all *ps* > .05), showing that these indicators remained stable throughout the intervention. A moderate positive association was observed between engagement and satisfaction (r = .40, p = .052), whereas sleep duration was not significantly associated with engagement or satisfaction.

Active Control Group

Over the 12-week intervention, participants in the active control group demonstrated high adherence to the intervention protocol. Of the 144 expected weekly monitoring reports, 141 (97.9%) were completed. Mean weekly Vita Mahjong exposure was 88.2 min (*SD* = 47.9), whereas mean psychoeducational reading exposure was 14.0 min (*SD* = 15.5). Participants also reported consistently high engagement throughout the intervention (*M* = 3.77, *SD* = 0.94 on a 5-point scale). LMMs revealed no significant effect of week on weekly app usage time, reading time, or self-reported engagement (all *ps* > .05), indicating stable adherence throughout the intervention period (Table 4).

Table 4

Additional evidence of adherence was provided by participants' performance on the six psychoeducational modules. Mean accuracy on the multiple-choice comprehension questionnaires remained consistently high across modules, ranging from 93.3% to 100.0%, while all participants who completed the questionnaires also completed the reflective open-ended question (100% completion across all six modules). Together, these findings indicate sustained adherence to both the app-based and psychoeducational components of the active control protocol, with no evidence of declining engagement over the 12-week intervention.

Learning Trajectories (Intervention Group Only)

Learning trajectories were examined separately for the WM and IC training tasks using the Lumosity Performance Index (LPI). Because the intervention protocol included five WM games and four IC games, the resulting longitudinal summaries comprised four and five intermediate training cycles, respectively.

Working Memory Training

Performance on the WM training tasks improved markedly throughout the intervention. The LMM revealed a significant effect of training cycle on the LPI, $F(5, 53.04) = 90.73$, $p < .001$, with a very large effect (approximate partial $\eta^2 \approx .90$).

Pairwise comparisons indicated substantial gains from baseline to the initial training cycles, followed by further increases toward the end of the intervention. By the post-intervention assessment, participants had achieved considerably higher performance than at baseline, providing strong evidence of learning across the 12-week program.

The average learning trajectory followed a nonlinear pattern, characterized by rapid improvement during the early training cycles and progressively smaller gains thereafter (Fig. 2). A logarithmic function provided an excellent fit to the mean trajectory (R^2 = .98), suggesting diminishing incremental gains as participants reached higher levels of performance. Despite interindividual variability in baseline scores and learning magnitude, the participant-level trajectories showed a broadly consistent upward pattern.

Inhibitory Control Training

Consistent with the findings for WM, participants also exhibited progressive improvements in the IC training tasks throughout the intervention. The LMM revealed a significant effect of training cycle on the LPI, $F(6, 64.03) = 50.61$, $p < .001$, with a very large effect (approximate partial η^2 = .83). Pairwise comparisons indicated marked improvements from baseline to the early training cycles, followed by further gains toward the end of the intervention. By the post-training assessment, participants had achieved substantially higher performance than at baseline, providing strong evidence of learning throughout the 12-week program.

The average learning trajectory followed a nonlinear pattern, characterized by pronounced improvements during the initial training cycles and progressively smaller gains thereafter (Fig. 3). A logarithmic function provided an excellent fit to the mean trajectory (R^2 = .98), indicating that performance gains became progressively smaller as participants approached higher levels of proficiency. Despite substantial interindividual variability in baseline performance and learning magnitude, participant-level trajectories consistently exhibited an overall upward trend throughout the intervention.

Effects of Cognitive Training on Executive Functions

Working Memory Outcomes

Changes in WM performance across the intervention period were examined using an LMM. The analyses revealed a significant main effect of Time, whereas no significant main effect of Group was observed. Importantly, a significant Group × Time interaction demonstrated distinct longitudinal trajectories in WM performance between the intervention and active control groups (Table 5).

Table 5

As illustrated in Fig. 4, participants assigned to the intervention group exhibited a marked improvement in WM performance from baseline to post-intervention, whereas performance in the active control group remained essentially unchanged. The estimated marginal means indicated that the intervention group

increased from values close to the baseline reference mean to markedly higher standardized scores at post-intervention, whereas the active control group remained stable across assessments (Table 6).

Table 6

Inhibitory Control Outcomes

Changes in IC performance across the intervention period were examined using an LMM. The analyses revealed no significant main effects of Group or Time, and the Group × Time interaction was likewise non-significant, indicating that IC performance remained stable throughout the intervention period, with no evidence of differential longitudinal change between groups (Table 7).

Table 7

As illustrated in Fig. 5, IC performance remained relatively stable throughout the intervention period. Estimated marginal means showed only minimal changes from baseline to post-intervention in both groups, with substantial overlap of the corresponding 95% confidence intervals (Table 8).

Table 8

Sensitivity Analysis

Covariate-adjusted analyses

To evaluate the robustness of the primary findings, the LMMs were re-estimated after adjustment for baseline age, perceived stress, and sleep duration.

For the WM composite score, adjustment for baseline covariates did not alter the primary findings. The Group × Time interaction remained statistically significant ($F(1, 21.53) = 17.81$, $p < .001$), indicating that the superior improvement observed in the intervention group was robust to baseline differences in age, perceived stress, and sleep duration. A significant main effect of Time was also retained ($F(1, 21.53) = 12.60$, $p = .002$), whereas the main effect of Group remained non-significant ($p = .472$). Among the covariates, baseline perceived stress ($F(1, 19.02) = 6.47$, $p = .020$) and sleep duration ($F(1, 18.97) = 5.18$, $p = .035$) were significantly associated with WM performance, whereas age was not ($p = .252$).

In contrast, adjustment for the same baseline covariates did not modify the findings for the IC composite score. No significant main effects of Group, Time, or Group × Time were observed (all ps > .05), and none of the covariates showed significant associations with IC performance (all ps > .05). These findings indicate that the primary results for both EF composite scores were robust to adjustment for baseline age, perceived stress, and sleep duration.

Exploratory Analyses of Stroop Task Performance

Because the conventional Stroop outcome is derived from an interference score reflecting the relative cost of incongruent compared with congruent trials, additional exploratory analyses were conducted to examine performance during incongruent trials separately. Unlike the composite interference index, analyses of absolute RT and ACC may reveal improvements in conflict-processing efficiency that are not captured by the relative interference index. These analyses were exploratory and were not part of the preregistered primary hypotheses.

Reaction time during incongruent trials

LMMs adjusted for baseline age, perceived stress, and sleep duration revealed no significant effects of the covariates (all *p*s > .05). The Group × Time interaction did not reach statistical significance ($F(1, 15.64) = 4.23$, $p = .057$), although the estimated pattern indicated greater reductions in RT during incongruent trials in the intervention group than in the active control group. The main effect of Group was also non-significant ($F(1, 12.92) = 4.52$, $p = .053$). Estimated marginal means showed that RT decreased from 667.6 ms at baseline to 635.2 ms at post-intervention in the intervention group. In contrast, the active control group exhibited a slight increase over the same period (742.4 ms to 771.4 ms) (Fig. 6; Table 9).

Table 9

Accuracy during incongruent trials

For incongruent-trial ACC, the adjusted model revealed a significant main effect of Time ($F(1, 16.00) = 17.37$, $p < .001$), indicating that response ACC increased across assessments in both groups. No significant Group × Time interaction was observed ($p = .204$), suggesting that the magnitude of improvement was comparable between groups. Among the covariates, only baseline sleep duration was significantly associated with ACC ($F(1, 13.00) = 14.18$, $p = .002$), whereas age and perceived stress were not significant predictors ($p = .188$ and .382, respectively). Estimated marginal means indicated improvements from 72.2% to 77.9% in the intervention group and from 61.2% to 72.4% in the active control group (Fig. 7; Table 10).

Table 10

Taken together, these exploratory findings suggest a pattern potentially consistent with improved processing efficiency during conflict resolution. Although the conventional Stroop interference score did not demonstrate a significant intervention effect, participants in the intervention group exhibited a tendency toward faster responses during incongruent trials while maintaining response ACC, with both groups showing improvements in ACC over time. Because these analyses examined individual components of the Stroop task rather than the preregistered composite outcome, they should be interpreted as exploratory and with appropriate caution.

To examine whether the pattern observed for the Stroop task was also present in another measure of IC, additional exploratory analyses were conducted for individual Go/No-Go indices. Although the

composite Go/No-Go outcome remained nonsignificant, a significant Group × Time interaction was observed for hit rate, whereas RT, d', and false-alarm rate showed no significant interaction effects. These findings suggest that selective improvements may occur at the level of specific task components even when aggregate indices do not reach statistical significance.

Discussion

This preregistered randomized controlled trial evaluated the effects of a 12-week multimodal cognitive training (CT) program on executive functioning in public managers. Three main findings emerged. First, participants assigned to the intervention group exhibited significant improvements in WM compared with the active control group, supporting the efficacy of the multimodal intervention for this executive domain. Second, no significant effects were observed for the composite measure of IC, although exploratory task-level analyses suggested improvements in specific inhibitory processes. Third, longitudinal analyses revealed progressive learning trajectories across the intervention, indicating that cognitive gains developed gradually rather than emerging solely as pre–post differences.

Together, these findings extend current evidence on EF plasticity by demonstrating that targeted multimodal training can produce domain-specific cognitive gains in healthy, professionally active adults, a population that remains underrepresented in CT research. Importantly, the combination of significant WM improvement, more selective IC effects, and progressive learning trajectories provides a more differentiated account of training responsiveness than conventional pre–post comparisons alone. More broadly, these results highlight the importance of considering both intervention outcomes and learning dynamics when evaluating CT programs in occupational settings.

Working Memory

The primary finding of the present trial was the significant improvement in WM following the 12-week intervention. This result is consistent with converging evidence indicating that WM is one of the executive domains most responsive to adaptive computerized CT. In a recent meta-analysis including randomized controlled trials exclusively in adults, Li et al. (2026) demonstrated reliable near-transfer effects across verbal and visuospatial WM tasks, confirming that repeated adaptive practice selectively strengthens the cognitive processes directly engaged during training.

Similarly, a recent systematic review and meta-analysis focusing on the *Cogmed* program reported significant immediate improvements in verbal and visuospatial WM, although evidence for long-term maintenance remains more limited (Paradela et al., 2025). Together, these findings reinforce the view that adaptive WM training reliably produces near-transfer effects, while highlighting the need for interventions capable of enhancing the durability and broader applicability of these gains.

Our findings also converge with those of Neves-Teles et al. (2026), whose systematic review identified moderate-to-large improvements in WM following CT in healthy adults, accompanied by converging

evidence of functional adaptations within prefrontal and frontoparietal networks. This evidence further supports the substantial experience-dependent plasticity of WM and its responsiveness to interventions that repeatedly recruit executive updating, maintenance, and manipulation processes.

Recent mechanistic evidence further strengthens this interpretation. Using functional near-infrared spectroscopy, Gao et al. (2025) observed improved WM performance accompanied by reduced activation in prefrontal cortical regions following adaptive training, a pattern interpreted as increased neural efficiency. Although neurophysiological measures were not obtained in the present study, the behavioral improvements observed here are compatible with the hypothesis that adaptive CT may promote functional optimization of executive-control networks.

At the same time, the present intervention was multimodal, precluding attribution of the observed WM gains to adaptive CT alone. Recent network meta-analytic evidence indicates that different intervention modalities may preferentially benefit distinct executive components and that combined approaches integrating cognitive stimulation with complementary intervention components may provide additional benefits (Bai et al., 2026).

Accordingly, the present findings may reflect the selective responsiveness of WM within a multimodal intervention incorporating adaptive CT alongside complementary components. This domain-specific pattern provides an important framework for interpreting the absence of significant effects for the composite measure of IC, discussed in the following section.

Inhibitory Control

Unlike the robust improvement observed for WM, the findings for IC revealed a more differentiated pattern. Although the primary composite analysis did not demonstrate a significant Group × Time interaction, this result should be interpreted in light of the heterogeneous nature of inhibitory processes. Previous randomized controlled trials and systematic reviews consistently indicate that training-related improvements in IC are generally more variable than those observed for WM and often depend on the specific inhibitory component assessed rather than reflecting generalized enhancement across executive functioning (Harris et al., 2023; Maraver et al., 2016).

This interpretation is supported by the exploratory task-level analyses. Although the conventional Stroop interference score remained nonsignificant, exploratory analyses showed a nonsignificant pattern toward faster responses during incongruent trials in the intervention group, while response accuracy was maintained. This pattern may reflect improved efficiency in resolving cognitive interference rather than a speed–accuracy trade-off. Because the interference score reflects the relative difference between congruent and incongruent conditions, improvements occurring across both conditions may attenuate changes in the derived interference index, potentially obscuring condition-specific gains. Accordingly, the exploratory Stroop findings raise the possibility of changes in conflict-processing efficiency that were not captured by the conventional interference outcome.

Additional exploratory analyses further indicated that this pattern was not restricted to the Stroop task. Although the overall Go/No-Go composite remained stable, participants in the intervention group showed a significant improvement in hit rate, whereas RT, *d'*, and false alarm rate remained unchanged. Together, these findings suggest selective enhancement of specific task components rather than generalized improvement across all Go/No-Go indices. This pattern is conceptually consistent with the multidimensional nature of IC, as different paradigms recruit partially distinct executive operations, including interference resolution and motor response inhibition (Maraver et al., 2016).

Taken together, these findings converge with recent evidence indicating that CT effects are often process-specific rather than domain-general, with transfer more consistently observed for tasks sharing cognitive demands with the trained processes (Harris et al., 2023; Nguyen et al., 2026). Network meta-analytic evidence further indicates that different intervention modalities may preferentially benefit distinct executive components (Bai et al., 2026), reinforcing the importance of considering the specific processes captured by individual outcome measures.

Accordingly, although the present study did not provide evidence of an intervention effect on the composite IC outcome, the exploratory findings suggest that specific inhibitory processes may respond differently to training. These results underscore the value of examining task-level components alongside aggregate EF measures when evaluating intervention effects on multidimensional executive domains.

Potential Mechanisms Underlying the Observed Effects

The multimodal nature of the present intervention precludes attributing the observed effects to any single component. Rather, the observed cognitive effects likely emerged from the combined influence of adaptive computerized CT, mindfulness-based attentional practices, supervised face-to-face delivery, and brief psychoeducational guidance. Although the present design does not permit disentangling the specific contribution of each element, their theoretical complementarity provides a plausible framework for interpreting the intervention effects.

An aspect that distinguishes the present protocol from many computerized CT studies is the integration of brief psychoeducational discussions throughout the intervention. Beyond supervising task performance, participants were introduced to fundamental concepts of executive functioning and encouraged to apply evidence-based cognitive strategies, including chunking, semantic organization, and attentional monitoring. These interactions may have promoted a deeper understanding of the cognitive demands imposed by the training, facilitated the adoption of more efficient problem-solving strategies, and contributed to the high levels of adherence and engagement observed throughout the program.

Recent evidence further suggests that CT may be enhanced when participants actively engage with the executive processes targeted by the intervention rather than merely repeating task performance. Moreover, the coordinated recruitment of partially overlapping executive control networks may further enhance training effects, particularly given the functional interplay between WM and IC (Bounoua et al.,

2025). Accordingly, computerized training may benefit from integration with complementary intervention components (Bai et al., 2026; Li et al., 2026; Paradela et al., 2025).

Mindfulness may also have complemented the intervention through two functionally distinct mechanisms. The brief practice at the beginning of each session may have facilitated the transition from participants' occupational demands to the training context, potentially reducing residual cognitive load and improving attentional readiness. The longer practice, in turn, emphasized sustained attention and monitoring of mind wandering, processes closely related to attentional regulation and IC.

Although mindfulness alone generally produces modest effects on executive functioning, recent meta-analytic evidence indicates benefits across selected cognitive outcomes, including executive attention, WM accuracy, inhibition accuracy, and sustained attention, with effects varying across outcomes and populations (Zainal & Newman, 2024). Previous evidence further suggests that mindfulness may reduce mind wandering and promote greater attentional stability, while neuroimaging findings indicate accompanying changes in intrinsic functional connectivity (Bennike et al., 2017; Sevinc et al., 2021).

Taken together, these complementary components may have enhanced the overall effectiveness of the intervention by increasing participants' readiness to engage with the training tasks, encouraging the use of adaptive cognitive strategies, and promoting sustained attentional regulation throughout the 12-week program. Future dismantling trials comparing isolated and combined intervention components will be necessary to determine the specific contribution of computerized training, psychoeducation, strategy coaching, and mindfulness to EF improvement.

Learning Trajectories

Beyond the pre–post comparisons, the longitudinal analysis of performance across training sessions provided additional insight into how learning developed over time. Rather than emerging abruptly at the end of the intervention, participants demonstrated progressive improvements throughout the training period, supporting the view that CT should be understood as a dynamic learning process. This finding is consistent with large-scale evidence indicating that cognitive performance typically follows structured learning trajectories characterized by gradual improvement and substantial interindividual variability, rather than uniform gains across participants (Steyvers & Schafer, 2020). Accordingly, examining repeated performance throughout the intervention may provide complementary information that cannot be captured by conventional pre–post assessments alone.

From a practical perspective, these findings suggest that evaluating learning trajectories may help identify differences in responsiveness to CT and inform the personalization of future interventions. Recent studies have argued that understanding how participants learn during training may be as informative as evaluating whether they improve at the end of the intervention, particularly when adaptive protocols are employed (Osman et al., 2023). Future randomized trials should therefore incorporate

longitudinal performance metrics to investigate predictors of learning rate, maintenance of cognitive gains, and individual variability in responsiveness to EF training.

Practical Implications

The present findings have practical implications for leadership development and occupational health programs targeting healthy working adults. Although CT has traditionally been investigated in older populations or clinical settings, the present results suggest that structured interventions may also enhance specific EF in professionally active individuals exposed to sustained cognitive demands. This perspective is particularly relevant for managerial occupations, where WM and IC support planning, information integration, decision-making, and behavioral self-regulation under conditions of uncertainty and high cognitive load.

From an organizational perspective, the feasibility and high adherence observed throughout the intervention suggest that supervised multimodal CT may represent a promising complementary strategy within broader leadership-development and workplace well-being initiatives. While the present findings should be replicated in larger and more diverse occupational samples, they are consistent with the broader view that preserving and optimizing executive functioning may contribute to adaptive performance in cognitively demanding work environments.

Strengths and Limitations

The present study has several strengths that enhance the interpretability of its findings. To our knowledge, this is among the first preregistered randomized controlled trials to evaluate a supervised multimodal CT program specifically in healthy public managers. Additional methodological strengths include the use of an active control group, standardized intervention procedures, longitudinal mixed-effects modeling, high participant adherence, and the assessment of both composite executive-function outcomes and task-level performance indicators. Together, these design features strengthen the interpretation of the observed improvements as intervention-related changes while reducing the likelihood that they reflect nonspecific practice or expectancy effects alone.

Several limitations should nevertheless be acknowledged. First, the relatively small sample size may have limited statistical power to detect modest intervention effects, particularly for heterogeneous EF outcomes. Second, the absence of follow-up assessments precludes conclusions regarding the long-term maintenance of cognitive gains. Third, although the multimodal nature of the intervention represents a practical strength, it also prevents isolating the individual contribution of computerized CT, mindfulness, psychoeducational guidance, and strategy coaching.

Finally, the study relied exclusively on behavioral measures, precluding direct examination of the neurobiological mechanisms underlying the observed cognitive changes. Future randomized trials employing larger samples, longer follow-up periods, dismantling designs, and multimodal

neurophysiological assessments will be important for clarifying both the durability and mechanisms of training-induced EF plasticity.

Conclusion

The present study provides evidence that EF remain amenable to targeted intervention in healthy working adults, while also demonstrating differential responsiveness across executive domains. The multimodal CT program produced robust improvements in WM, whereas no significant improvement was observed for the composite measure of IC; exploratory task-level analyses nevertheless indicated more selective changes in specific inhibitory processes. Beyond the primary outcomes, the findings also highlight the value of combining composite and task-level outcome measures, as well as longitudinal analyses of training performance, to better characterize how cognitive improvements emerge during the intervention.

Although the multimodal design precludes identifying the contribution of individual intervention components, the combination of adaptive computerized CT, mindfulness-based attentional practices, supervised face-to-face delivery, and psychoeducational guidance proved feasible and was associated with high participant adherence. Together, these findings contribute to the growing evidence supporting EF plasticity in healthy working adults and provide a foundation for future randomized trials aimed at clarifying the mechanisms, durability, and practical applicability of multimodal CT in cognitively demanding occupational settings.

Declarations

Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

Ethics approval

The study was approved by the Research Ethics Committee of the Institute of Psychology of the Federal University of Rio Grande do Sul (Protocol No. 7.274.390; CAAE No. 84134724.5.0000.5334) and was conducted in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments.

Consent to participate

Written informed consent was obtained from all participants prior to participation.

Author Contribution

T.N.T.: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Writing – Original Draft, Project Administration. G.S.F.: Writing – Review & Editing. C.Z.: Validation, Supervision, Writing – Review & Editing. R.M.M.A.: Validation, Supervision, Writing – Review & Editing. All authors have read and approved the final version of the manuscript.

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Data Availability

The data supporting the findings of this study will be made publicly available in a suitable repository upon acceptance for publication, in a de-identified form designed to protect participant confidentiality.

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Tables

Table 1 *Sample Characteristics by Group*

Variable	Category	Total (*N* = 24)	Intervention (*n* = 12)	Active control (*n* = 12)
Sex	Male	14 (58.3%)	6 (50.0%)	8 (66.7%)
	Female	10 (41.7%)	6 (50.0%)	4 (33.3%)
Education	Bachelor's degree	1 (4.2%)	1 (8.3%)	0 (0.0%)
	Postgraduate specialization	10 (41.7%)	4 (33.3%)	6 (50.0%)
	Master's degree	6 (25.0%)	5 (41.7%)	1 (8.3%)
	Doctoral degree	7 (29.1%)	2 (16.7%)	5 (41.7%)
Marital status	Married	21 (87.5%)	10 (83.3%)	11 (91.7%)
	Separated	2 (8.3%)	1 (8.3%)	1 (8.3%)
	Single	1 (4.2%)	1 (8.3%)	0 (0.0%)
Employment type	Career civil servant	23 (95.8%)	12 (100.0%)	11 (91.7%)
	Comissioned position	1 (4.2%)	0 (0.0%)	1 (8.3%)
Income	R$ 4,0001 – R$ 8,000	2 (8.3%)	2 (16.7%)	0 (0.0%)
	R$ 8,001 – R$ 12,000	6 (25.0%)	4 (33.3%)	2 (16.7%)
	R$ 12,001 – R$ 16,000	2 (8.3%)	1 (8.3%)	1 (8.3%)
	R$ 16,001 – R$ 20,000	2 (8.3%)	1 (8.3%)	1 (8.3%)
	> R$ 20,000	11 (45.9%)	3 (25.0%)	8 (66.7%)
	Not reported	1 (4.2%)	1 (8.3%)	0 (0.0%)
Age (years)	□	50.5 (7.2)	46.9 (7.1)	54.2 (5.5)
Sleep duration (hours)	□	7.0 (0.8)	6.8 (0.9)	7.0 (0.7)
Perceived stress	□	4.0 (1.0)	4.0 (0.0)	3.0 (1.0)
Tenure (years)	□	3.0 (2.0)	3.0 (2.0)	3.0 (2.0)
Span of control	□	2.0 (3.0)	3.0 (2.0)	2.0 (3.0)

Note. Values are presented as n (%) for categorical variables, mean (SD) for continuous variables, and median (IQR) for ordinal variables. Percentages are calculated within each group.

Table 2 *Baseline Equivalence Between Intervention and Active Control Groups*

Variable	Intervention (n = 12)	Active Control (n = 12)	Test	p-value	Effect size
Demographic variables:					
Sex	□	□	χ^2	.408	0.17
Education	□	□	χ^2	.148	0.47
Marital status	□	□	χ^2	.592	0.21
Employment type	□	□	χ^2	.307	0.21
Income	□	□	χ^2	.297	0.46
Control variables:					
Age (years), *M* (*SD*)	46.9 (7.1)	54.2 (5.5)	*t*	.010*	-1.15
Sleep duration (hours), *M* (*SD*)	6.8 (0.9)	6.9 (0.7)	Mann-Whitney	.925	-0.03
Perceived stress, *Median* (*IQR*)	4.0 (0.0)	3.0 (1.0)	Mann-Whitney	.047*	-0.45
Tenure, *Median* (*IQR*)	3.0 (2.0)	3.0 (2.0)	Mann-Whitney	.976	-0.01
Span of control, *Median* (*IQR*)	3.0 (2.0)	2.0 (3.0)	Mann-Whitney	.214	-0.30
Cognitive variables (EF):					
WM composite, *M* (*SD*)	-0.02 (0.90)	0.02 (0.62)	*t*	.890	-0.06
IC composite, *M* (*SD*)	-0.02 (0.43)	0.09 (0.90)	Welch *t*	.743	-0.16

Note. Detailed distributions for categorical variables are presented in Table 1. χ^2 tests assess overall group differences across all categories. Values are presented as *mean* (*SD*) for continuous variables and *median* (*IQR*) for ordinal variables. χ^2 = chi-square test; *t* = independent-samples *t*-test; Welch *t* = Welch's *t*-test; Mann–Whitney = nonparametric test. Effect sizes are reported as Cramér's *V* for χ^2 tests, Cohen's *d* for independent-samples *t*-tests, and rank-biserial correlation (*r*) for Mann–Whitney tests. *p < .05.

Table 3 *Adherence and Engagement Outcomes in the Intervention Group*

Indicator	Value
Participants	12
Sessions completed (0-24), *mean* ± *SD*	22.4 ± 2.3
Overall attendance rate	93.4%
Participants completing all sessions	5 (41.7%)
Participants attending ≥ 88% of sessions	11 (91.7%)
Sleep duration (hours), *mean* ± *SD*	6.8 ± 0.3
Session engagement (1–5), *mean* ± *SD*	4.5 ± 0.2
Session satisfaction (1–5), *mean* ± *SD*	4.7 ± 0.3

Note. Overall attendance rate was calculated as the proportion of completed attendances (269) relative to the total of 288 possible attendances (12 participants × 24 scheduled training sessions).

Table 4 *Adherence and Engagement Outcomes in the Active Control Group*

Indicator	**Value**
Weekly monitoring completion	141/144 (97.9%)
Weekly Vita Mahjong exposure (min), *M* ± *SD*	88.23 ± 47.87
Weekly psychoeducational reading (min), *M* ± *SD*	14.01 ± 15.51
Weekly engagement (1–5), *M* ± *SD*	3.77 ± 0.94
LMM – App time	$F(11,118.02) = 1.53$, $p = .130$
LMM – Reading time	$F(11,118.21) = 1.17$, $p = .317$
LMM – Engagement	$F(11,118.07) = 1.26$, $p = .260$
Quiz accuracy (%)	93.3 – 100.0
Reflective completion (%)	100.0

Note. LMM = linear mixed effects model; App: application (Vita Mahjong). The 144 expected weekly monitoring reports correspond to 12 participants monitored weekly over the 12-week intervention period (12 × 12).

Table 5 *Linear Mixed-Effects Model for WM Performance*

Effect	df	F	p	Estimate	SE	t
Group	1, 22.08	2.60	.121	0.209	0.129	1.61
Time	1, 21.35	12.37	.002	−0.189	0.054	−3.52
Group × Time	1, 21.35	17.52	< .001	−0.224	0.054	−4.19

Note. WM = working memory; *df* = degrees of freedom; *F* = F statistic; SE = standard error; *t* = *t* statistic. Results are based on an LMM with participant included as a random intercept. Degrees of freedom were estimated using the Satterthwaite approximation. One post-intervention WM observation was excluded because one participant's 2-Back performance indicated that the task instructions had not been followed.

As illustrated in Fig. 4, participants assigned to the intervention group exhibited a marked improvement in WM performance from baseline to post-intervention, whereas performance in the active control group remained essentially unchanged. The estimated marginal means indicated that the intervention group increased from values close to the baseline reference mean to markedly higher standardized scores at post-intervention, whereas the active control group remained stable across assessments (Table 6).

Table 6 *Estimated Marginal Means for WM Performance*

Group	Time	Estimate	SE	95% CI	
				Lower	Upper
Intervention	Baseline	-0.016	0.197	-0.402	0.370
Active Control	Baseline	0.016	0.197	-0.370	0.402
Intervention	Post-Intervention	0.810	0.201	0.416	1.204
Active Control	Post-Intervention	-0.056	0.197	-0.442	0.330

Note. WM = working memory.

Table 7 *Linear Mixed-Effects Model for IC Performance*

Effect	*df*	*F*	*p*	Estimate	*SE*	*t*
Group	1, 16	0.84	.374	−0.081	0.089	-0.91
Time	1, 16.00	0.05	.833	−0.016	0.075	−0.22
Group × Time	1, 16.00	0.33	.572	0.043	0.075	0.58

Note. IC = inhibitory control; *df* = degrees of freedom; *F* = F statistic; SE = standard error; *t* = *t* statistic. Results are based on an LMM with participant included as a random intercept. Degrees of freedom were estimated using the Satterthwaite approximation. Six baseline Stroop observations (three per group) were excluded because they did not meet the predefined validity criteria; consequently, the corresponding participants could not be included in the longitudinal IC composite analysis.

Table 8 *Estimated Marginal Means for IC Performance*

Group	Time	Estimate	*SE*	95% CI	
				Lower	Upper
Intervention	Baseline	-0.011	0.164	-0.333	0.311
Active Control	Baseline	0.064	0.164	-0.258	0.387
Intervention	Post-Intervention	-0.066	0.164	-0.388	0.257
Active Control	Post-Intervention	0.183	0.164	-0.139	0.506

Note. IC = inhibitory control.

Table 9 *Estimated Marginal Means for RT during Incongruent Stroop Trials*

Group	Time	Estimate	SE	95% CI	
				Lower	Upper
Intervention	Baseline	667.620	30.339	608.156	727.084
Active Control	Baseline	742.386	29.473	684.620	800.153
Intervention	Post-Intervention	635.210	30.976	574.499	695.921
Active Control	Post-Intervention	771.386	29.473	713.620	829.153

Note. RT = reaction time.

Table 10 *Estimated Marginal Means for ACC during Incongruent Stroop Trials*

Group	Time	Estimate	SE	95% CI	
				Lower	Upper
Intervention	Baseline	72.171	3.445	65.418	78.923
Active Control	Baseline	61.241	3.445	54.488	67.993
Intervention	Post-Intervention	77.926	3.445	71.174	84.678
Active Control	Post-Intervention	72.352	3.445	65.599	79.104

Note. ACC = accuracy.

Figures

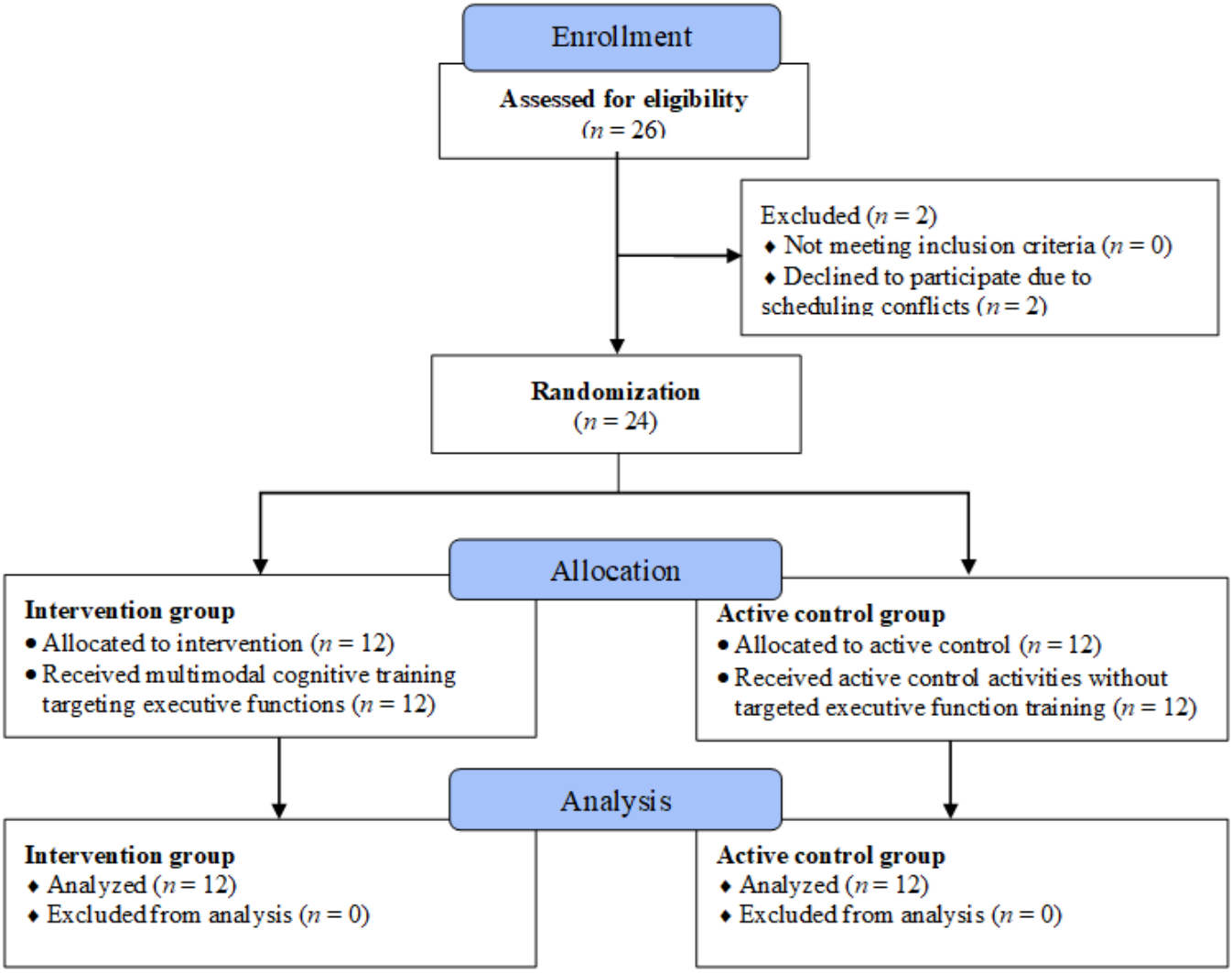


Figure 1

CONSORT flow diagram of participant progression through the study

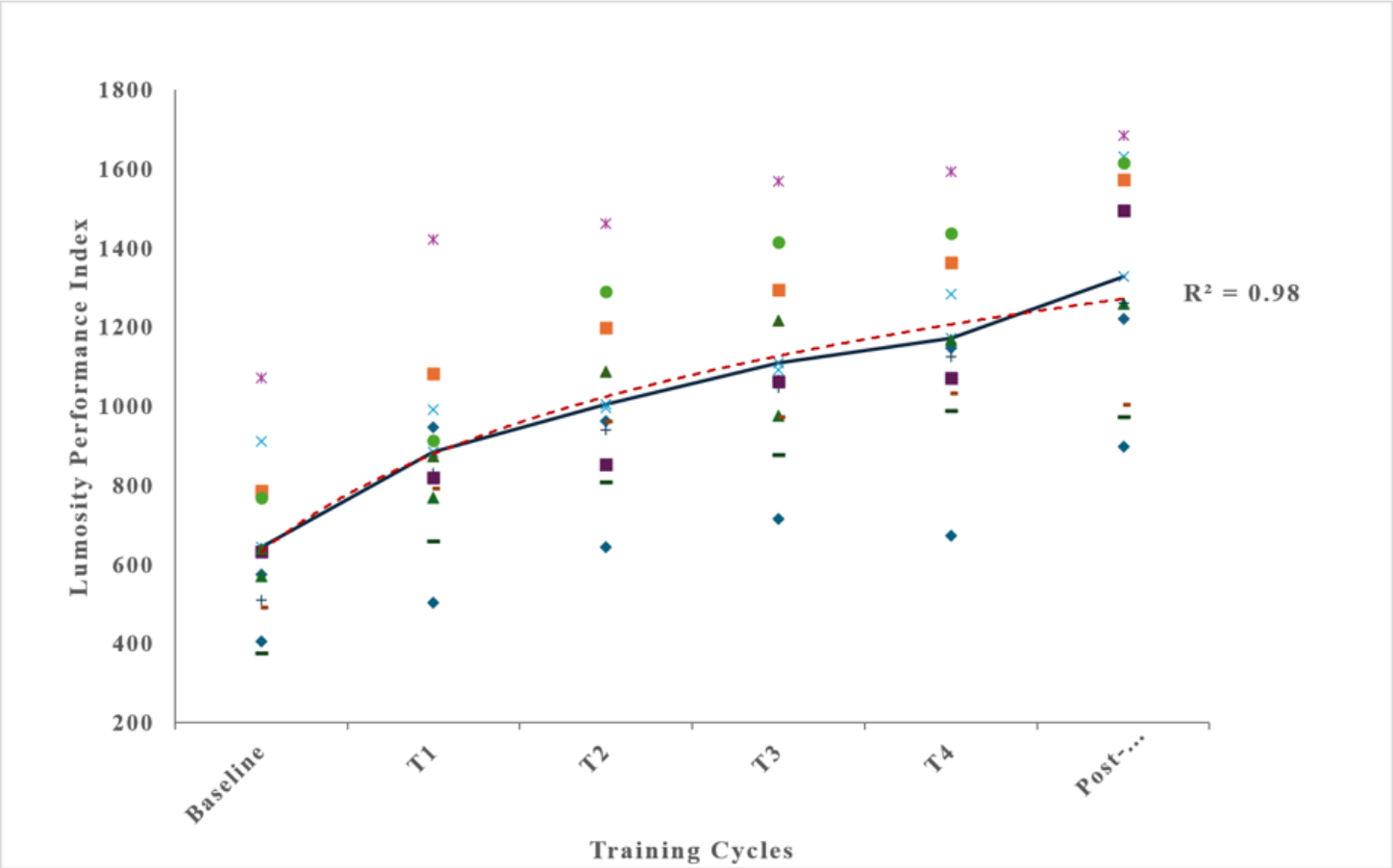


Figure 2

Longitudinal learning trajectory for working memory (WM) training tasks. Each symbol represents an individual participant and is held constant across assessment cycles. The solid line represents the group mean, whereas the dashed line represents the fitted logarithmic trajectory (R^2 = .98).

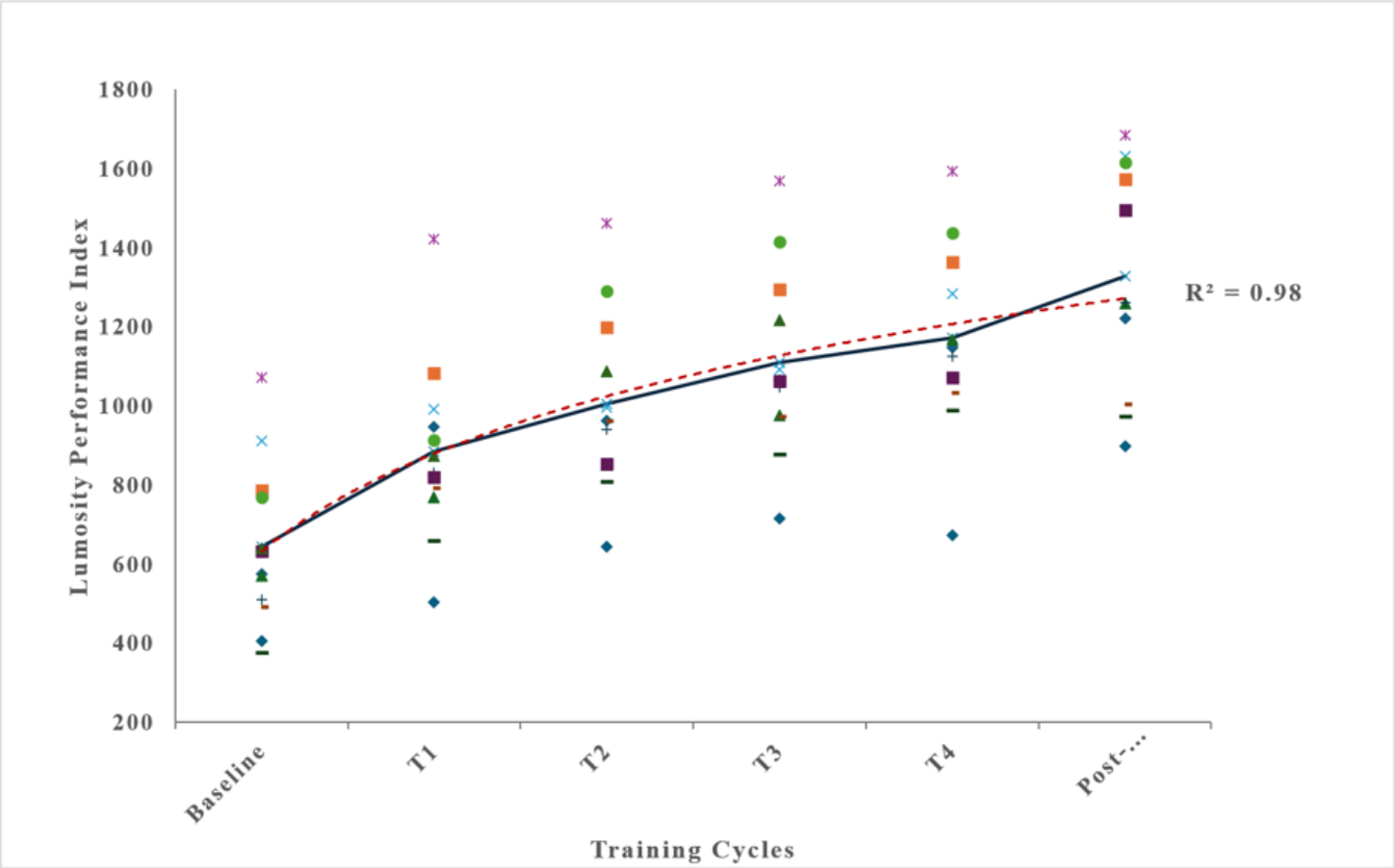


Figure 3

Longitudinal learning trajectory for inhibitory control (IC) training tasks. Each symbol represents an individual participant and is held constant across assessment cycles. The solid line represents the group mean, whereas the dashed line represents the fitted logarithmic trajectory (R^2 = .98).

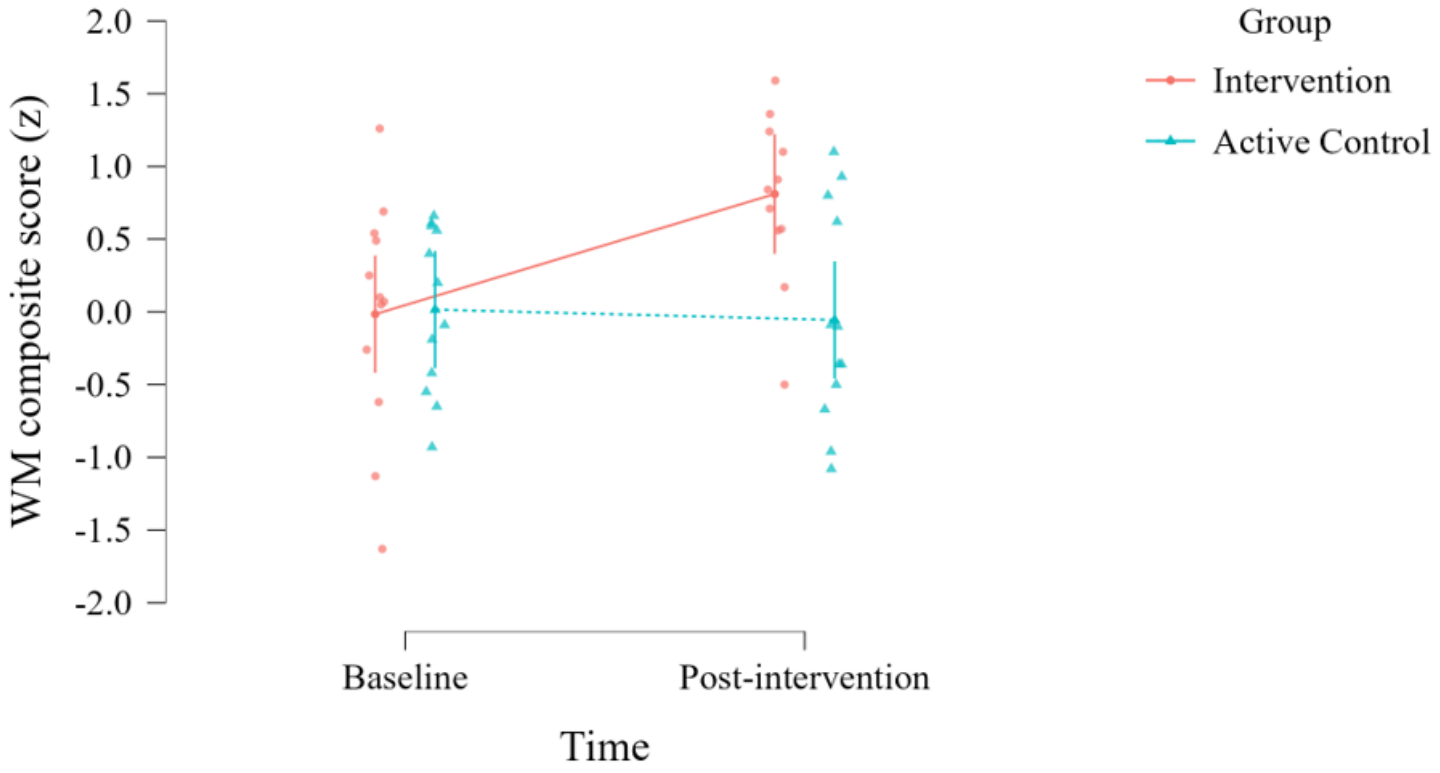


Figure 4

Estimated marginal means of working memory (WM) performance by group at baseline and post-intervention. Points represent individual participants, and error bars indicate 95% confidence intervals.

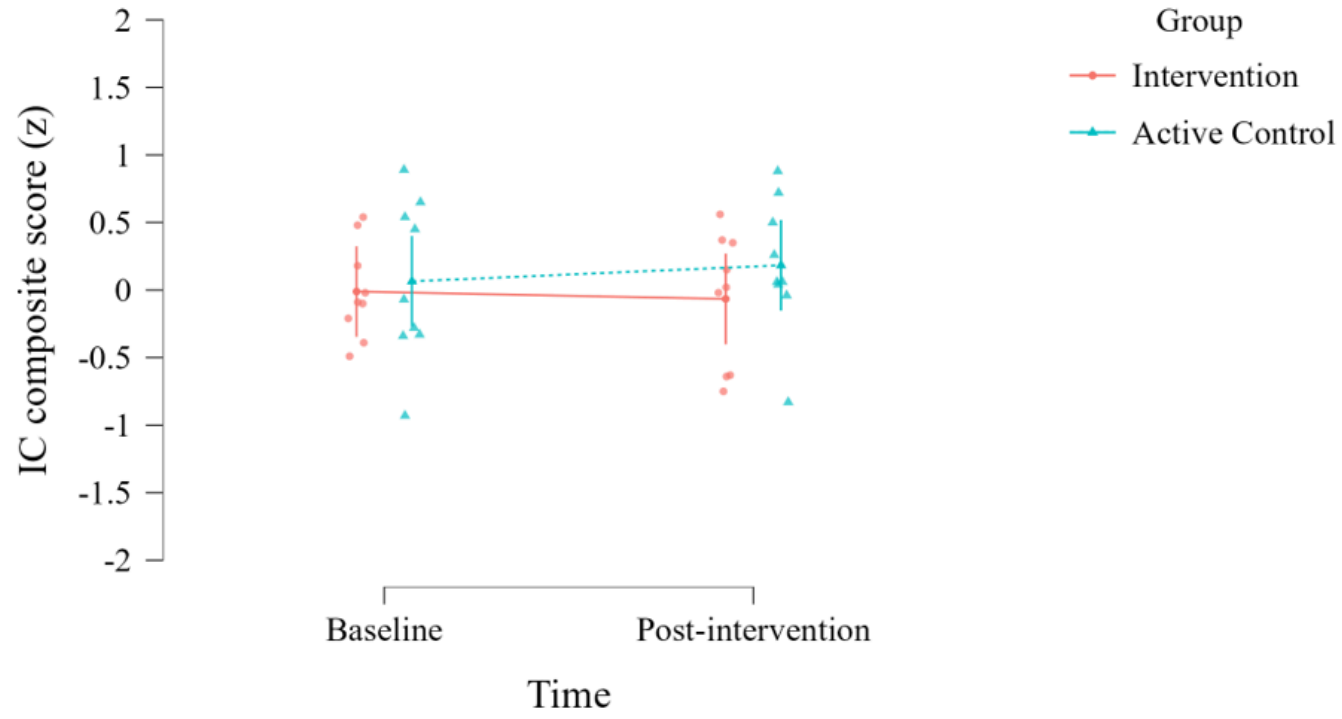


Figure 5

Estimated marginal means of inhibitory control (IC) performance by group at baseline and post-intervention. Points represent individual participants, and error bars indicate 95% confidence intervals.

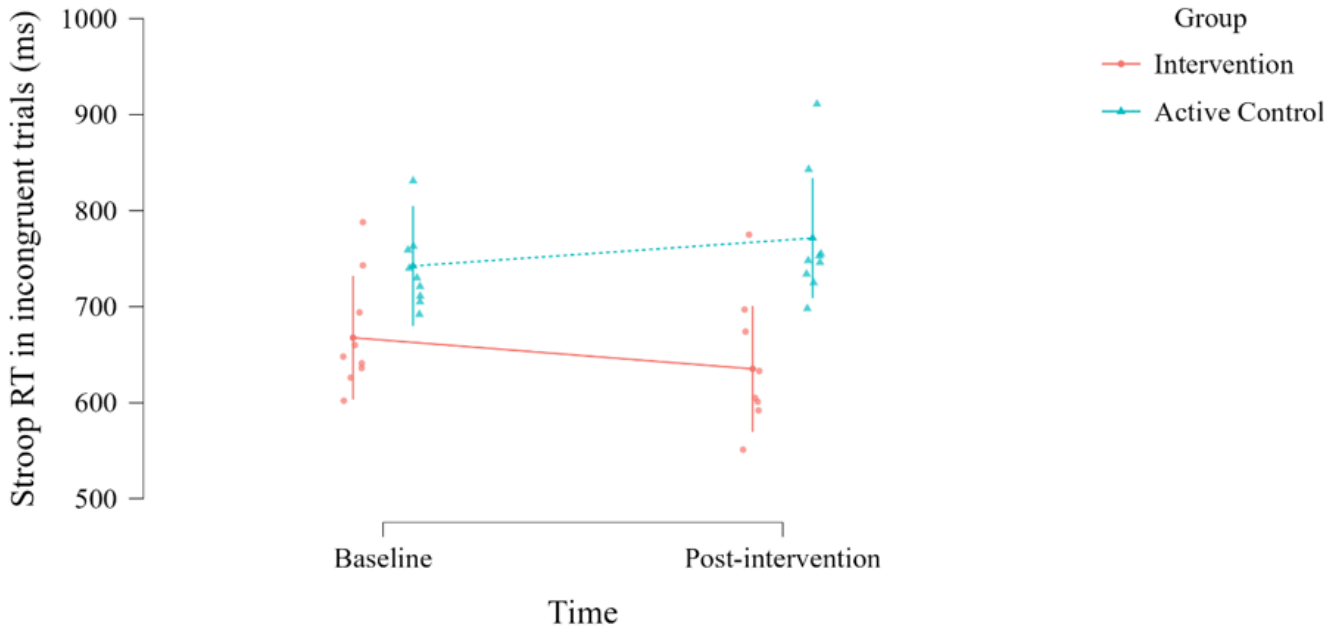


Figure 6

Estimated marginal means of reaction time (RT) during incongruent Stroop trials by group at baseline and post-intervention. Points represent individual participants, and error bars indicate 95% confidence intervals.

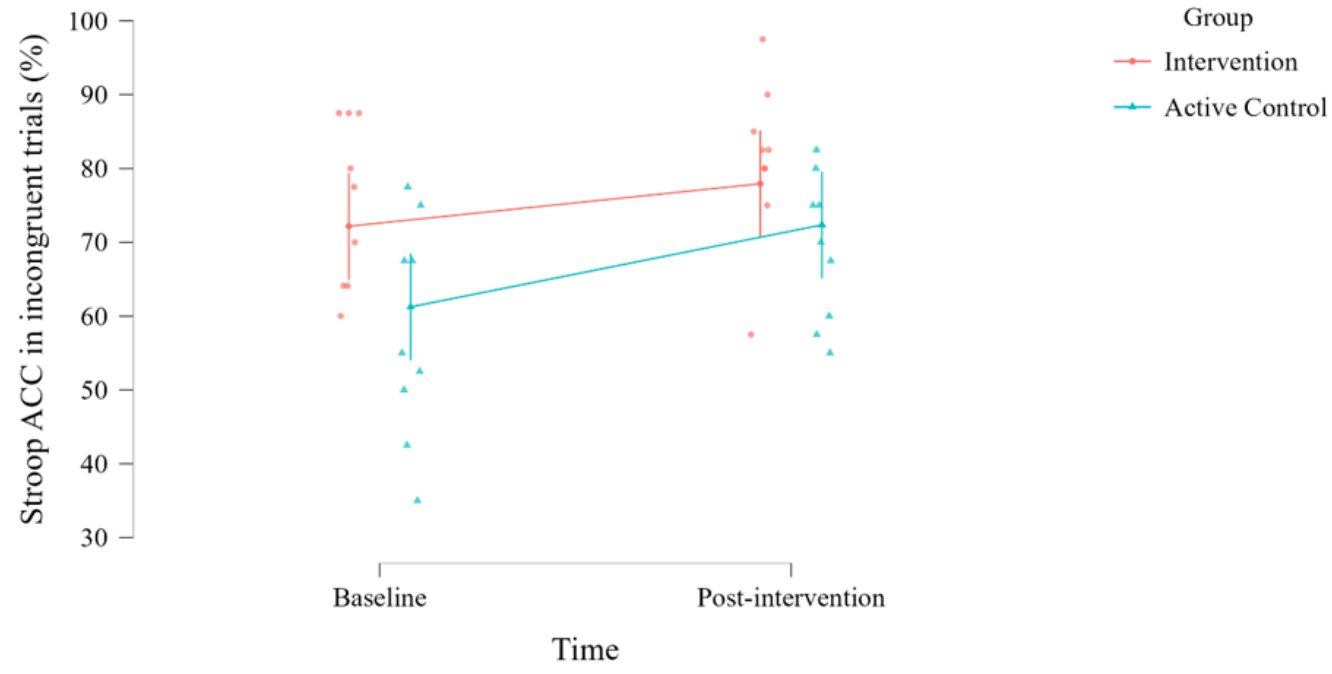


Figure 7

Estimated marginal means of accuracy (ACC) during incongruent Stroop trials by group at baseline and post-intervention. Points represent individual participants, and error bars indicate 95% confidence intervals.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- ESM1.pdf
- ESM2.pdf