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Psychophysiological preparation improves performance without compromising procedural safety in a high-risk motor task

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Article

Keywords: Motor imagery, Pre-performance routine, Procedural safety, Military performance, Heart rate variability, Psychophysiology

Posted Date: November 23rd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11510904/v1

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Additional Declarations: No competing interests reported.

Abstract

High-risk operational tasks require rapid movement without compromising safety-critical motor control. This study examined whether a brief psychophysiological pre-activation routine (PPAR) improves performance and procedural safety during an ecologically valid military obstacle course. Fifty experienced military personnel were allocated to PPAR (n = 25) or a time-matched motivational control (n = 25). Participants completed an 850-m course involving 17 obstacles and 26 prescribed safety procedures on two consecutive days. Before the second trial, PPAR combined breathing regulation, interoceptive and motor imagery, attentional focusing, and self-talk. Completion time and Safety Incident Score (SIS) were assessed in all participants; heart rate (HR) and heart rate variability (HRV) were recorded in 40. Completion time decreased by 11.1% after PPAR (715.7 ± 104.2 to 636.2 ± 71.9 s), versus 2.1% in controls (719.9 ± 99.7 to 704.6 ± 74.6 s; Group × Session interaction: $p < .001$, $\eta^2p = .40$). At POST, SIS was significantly lower in the PPAR group than in controls (0.08 ± 0.28 vs. 0.80 ± 1.08; $U = 465.5$, $p < .001$, $r = .490$). PPAR increased pre-performance HR (93 to 108 beats/min) and significantly modulated HRV spectral indices, with significant Group × Session interactions. A 10-min multimodal preparation routine improved completion time during a demanding real-world task while being associated with fewer safety incidents and distinct pre-performance cardiac responses.

INTRODUCTION

In many performance settings, acting faster is advantageous only as long as motor control over action can be maintained[1]. A long-standing body of research on the speed-accuracy trade-off has shown that increasing response or movement speed commonly results in more error-prone actions, reflecting constraints that extend from decision processes to motor execution[2]. Indeed, time pressure can accelerate motor processes themselves, contributing to the deterioration of action accuracy as response speed increases[1]. Moreover, when speed–accuracy constraints are unexpectedly altered during ongoing whole-body action, corrective motor responses may fail to fully adapt to the new task requirements, highlighting the vulnerability of perception-action coupling under dynamically changing control demands[3]. Yet, much of this experimental evidence derives from highly controlled paradigms in which movement speed and spatial accuracy are manipulated through rapid aiming, pointing, or other goal-directed movements[4–8]. However, real-world performance rarely reduces to an explicit manipulation of target distance, target width, or instructed movement speed. Complex high-stakes environments can require to act faster while simultaneously maintaining precise motor execution, adaptive decision-making, and compliance with safety-critical procedures[9,10]. Recent evidence from high-risk professional settings further suggests that successful decision-making depends not solely on expertise, but also on emotional and cardiac autonomic profiles of the performer[11]. Pre-performance emotions and cognitive appraisals[12,13], attentional states[14], or/and physiological responses[15] have all been associated with subsequent performance across laboratory and sport high-pressure performance contexts. This further extends to tactical populations, where brief psychophysiological preparation strategies have shown

promising effects on operational performance and recovery[16–18], highlighting the potential of pre-performance state regulation beyond conventional sport environments.

Importantly, successful preparation does not simply require reducing activation or anxiety. According to the Individual Zones of Optimal Functioning (IZOF) framework, the functional impact of emotions depends on their idiosyncratic relationship with successful performance, meaning that similar emotional intensities may support optimal performance in one individual while impairing it in another[19,20]. Empirical work has accordingly shown substantial inter-individual variability in the pre-performance states associated with successful execution, with high levels of activation or anxiety being either facilitative or detrimental to performance[20,21]. Complementarily, challenge and threat approaches propose that the way performers mobilize resources in relation to perceived task demands is associated with distinct psychological and cardiovascular responses and, on average, with different performance outcomes[12]. Challenge states are associated with better performance than threat states across performance domains, although the magnitude of this relationship remains modest and context dependent[15]. Together, this body of evidence converges on a functionally important principle: the value of a pre-performance state lies less in achieving a universally low or high level of activation than in supporting the demands of the action to be performed. For tasks requiring intense physical engagement alongside continuous technical control, preparation must therefore seek to facilitate substantial mobilization without disrupting the regulation of safety-critical actions.

Defined as systematic sequences of task-relevant thoughts and actions performed before execution, pre-performance routines are intended to regulate attention, cognition, emotion, and behavior while facilitating motor prediction and internal simulation of the upcoming action[22,23]. Preparatory strategies may incorporate voluntary breathing regulation[23], emotion-regulation processes[24], and mental imagery[25]. Mental imagery enables the internal representation of action without overt execution and has been extensively used to support motor preparation and skilled performance[26]. Of particular relevance, imagery has been shown to modify challenge and threat appraisals and their associated cardiovascular responses, demonstrating that mental preparation can acutely modulate the state preceding performance[27]. Voluntary breathing-based strategies may likewise modify acute psychophysiological regulation[28], while emotion regulation strategies seek to modify the functional meaning and behavioral consequences of affective responses rather than merely suppressing their expression[29,30]. Yet, these approaches have predominantly been examined separately, and pre-performance routine research has largely focused on conventional sport outcomes and relatively discrete or self-paced skills. However, whether a brief multimodal pre-performance routine can improve execution speed while preserving safety-critical procedural performance during prolonged, physically demanding, whole-body actions remains unclear[22].

The French military ‘Piste d'Audace’, a standardized commando obstacle course used in military commando evaluation, provides a unique ecological opportunity to examine this question. This course requires participants to complete an 850-m sequence of 17 aerial obstacles (involving vertical exposures

of up to 80 m) as rapidly as possible while continuously performing standardized safety procedures during climbing, rope progression, unstable crossings, and highly exposed actions (Fig. 1).

Performance time is formally evaluated, yet participants must concurrently execute 26 safety-related technical procedures. Failure to comply with these procedures may not only expose participants to serious injury during obstacle negotiation but also incur substantial performance penalties, compromise successful course completion, and ultimately jeopardize qualification for the Commando Qualification Certificate. Performance speed and safety-related behavioral control can therefore be evaluated within the same real-world performance episode. This task provides a rare model of joint performance demands in which intense physical engagement, emotional challenge, rapid whole-body action, and continuous technical control coexist. The present study investigated whether a brief, task-specific psychophysiological pre-activation routine (PPAR) could improve task execution speed while preserving safety-critical procedural control during complex, high-risk motor actions. Using a randomized, parallel-group design, we compared a 10-min multimodal pre-activation routine combining breathing regulation, interoceptive and motor imagery, attentional focusing, and self-talk with a time-matched motivational control intervention. We hypothesized that the PPAR would produce a greater reduction in course completion time than the control intervention, without a concomitant deterioration in procedural safety, as assessed by the Safety Incident Score. Finally, we hypothesized that the PPAR would induce a greater increase in pre-performance heart rate (HR) and low-frequency power (LF) of heart rate variability (HRV) than the control intervention, consistent with the anticipatory cardiac activation targeted by the routine.

RESULTS

Completion time

The 2 x 2 mixed-design ANOVA revealed a significant main effect of Session (F (1, 48) = 69.82, p < .001, η^2p = .59), no main effect of Group (F (1, 48) = 2.20, p = .145, η^2p = .04), as well as a significant Group x Session interaction (F (1, 48) = 32.00, p < .001, η^2p = .40). Holm-adjusted pairwise comparisons showed no difference between groups at PRE (CTRL: 719.9 ± 99.7s; PPAR: 715.7 ± 104.2s; mean difference = 4.16s, t(48) = 0.14, p = 0.99, d = 0.05). Completion time significantly decreased from PRE to POST in the PPAR group, from 715.7 ± 104.2s to 636.2 ± 71.9s (mean difference = 79.6s, t(48) = 9.91, p < .001, d = 0.90), whereas no significant change was observed in the CTRL group (719.9 ± 99.7s vs. 704.6 ± 74.6s; mean difference = 15.3s, t(48) = 1.908, p = .187, d = 0.17). At POST, the PPAR group completed the course significantly faster than the CTRL group (636.2 ± 71.9s vs. 704.6 ± 74.6s; mean difference = 68.4s, t(48) = 3.30, p < .01, d = 0.77) (Fig. 2).

Safety Incident Score (SIS)

For the Safety Incident Score (SIS), no between-group difference was observed at PRE (CTRL: 1.76 ± 1.92; PPAR: 1.72 ± 1.79; U = 312.5, p = 1.000, r = 0.000). SIS decreased significantly from PRE to POST in both groups, with large within-group effects in CTRL (W = 121, z = 2.77, p < .01, r = 0.787) and PPAR (W = 185.5, z = 3.64, p < .001, r = 0.95). At POST, however, SIS was significantly lower in the PPAR group than in

the CTRL group (0.08 ± 0.28 vs. 0.80 ± 1.08; U = 465.5, $p < .001$, r = − 0.490), corresponding to a 90% lower mean SIS in PPAR (Fig. 3).

Heart Rate (HR)

The 2 × 2 mixed-design ANOVA revealed a significant main effect of Session (F (1, 38) = 56.22, $p < .001$, $\eta^2p = .60$), and Group (F (1, 38) = 6.48, $p < .01$, $\eta^2p = .15$) as well as a significant Group × Session interaction (F (1, 38) = 78.58, $p < .001$, $\eta^2p = .67$). Holm-adjusted pairwise comparisons showed no difference between groups at PRE (CTRL: 92.35 ± 13.05 bpm; PPAR: 93.33 ± 10.18 bpm; mean difference = 0.98 bpm, t(38) = 0.263, $p = 0.99$; $d = 0.09$). HR increased significantly from PRE to POST in the PPAR group, from 93.33 ± 10.18 to 108.0 ± 11.67 bpm (mean difference = 14.64 bpm, t(38) = 11.57, $p < .001$; $d = 1.25$), whereas no significant change was observed in the CTRL group (92.35 ± 13.05 vs. 91.13 ± 10.55 bpm; mean difference = 1.22 bpm, t(38) = 0.966, $p = 0.99$; $d = 0.11$). At POST, HR was significantly higher in the PPAR group than in the CTRL group (108.0 ± 11.67 vs. 91.13 ± 10.55 bpm; mean difference = 16.84 bpm, t(38) = 4.786, $p < .001$; $d = 1.05$) (Fig. 4).

Heart Rate Variability (VFC)

Consistent with established recommendations for the analysis of positively skewed HRV spectral measures, these variables were therefore natural-log transformed prior to inferential analyses[31,32]

Total Power (lnTP)

The 2 × 2 mixed-design ANOVA performed on ln-transformed TP revealed a significant main effect of Session, ($F(1, 38) = 9.05$, $p = .005$, $\eta^2p = .192$), no main effect of Group ($F(1, 38) = 0.42$, $p = .523$, $\eta^2p = .011$), and a significant Group × Session interaction ($F(1, 38) = 24.97$, $p < .001$, $\eta^2p = .397$). Holm-adjusted pairwise comparisons showed no difference between groups at PRE (CTRL: 6.62 ± 0.76 ln.ms²; PPAR: 6.47 ± 0.95 ln.ms²; mean difference = 0.15, t(38) = 0.54, $p = 0.99$; $d = 0.17$). lnTP increased significantly from PRE to POST in the PPAR group, from 6.47 ± 0.95 to 6.98 ± 1.02 ln.ms² (mean difference = 0.51, t(38) = 5.66, $p < .001$; $d = 0.60$), whereas no significant change was observed in the CTRL group (6.62 ± 0.76 vs. 6.49 ± 0.68 ln.ms²; mean difference = -0.13, t(38) = 1.41, $p = .671$; $d = 0.15$). At POST, the between-group difference was not significant (CTRL: 6.49 ± 0.68; PPAR: 6.98 ± 1.02 ln.ms²; mean difference = -0.49, t(38) = 1.79, p = .411; $d = 0.57$) (Fig. 5).

Low Frequency (lnLF)

The 2 × 2 mixed-design ANOVA performed on ln-transformed LF revealed a significant main effect of Session, ($F(1, 38) = 9.33$, $p < .01$, $\eta^2p = .197$), no main effect of Group ($F(1, 38) = 1.19$, $p = .283$, $\eta^2p = .030$), and a significant Group × Session interaction ($F(1, 38) = 24.82$, $p < .001$, $\eta^2p = .395$). Holm-adjusted pairwise comparisons showed no difference between groups at PRE (CTRL: 6.39 ± 0.88 ln.ms²; PPAR: 6.34 ± 0.94 ln.ms²; mean difference = 0.046, $t(38) = 0.158$, $p = 0.99$; $d = 0.05$). lnLF increased significantly from PRE to POST in the PPAR group, from 6.34 ± 0.94 to 6.91 ± 1.02 ln.ms² (mean difference = 0.57, $t(38) = 5.683$, $p < .001$; $d = 0.62$), whereas no significant change was observed in the CTRL group (6.39 ±

0.88 vs. 6.25 ± 0.80 ln.ms²; mean difference = -0.14, $t(38) = 1.363$, $p = .543$; $d = 0.15$). At POST, the between-group difference did not reach statistical significance (CTRL: 6.25 ± 0.80; PPAR: 6.91 ± 1.02 ln.ms²; mean difference = 0.656, $t(38) = 2.26$, $p = .147$; $d = 0.72$) (Fig. 6).

High Frequency (lnHF)

The 2 × 2 mixed-design ANOVA performed on ln-transformed HF revealed no significant main effects of Session, ($F(1, 38) = 0.010$, $p = .922$, $\eta^2p < .001$), or Group ($F(1, 38) = 0.275$, $p = .603$, $\eta^2p = .007$) as well as no significant Group × Session interaction ($F(1, 38) = 0.015$, $p = .904$, $\eta^2p < .001$). In the absence of a significant interaction, no post-hoc comparisons were conducted.

LF/HF ratio

The 2 × 2 mixed-design ANOVA performed on ln-transformed LF/HF ratio revealed a significant main effect of Session ($F(1, 38) = 5.64$, $p = .023$, $\eta^2p = .129$), no main effect of group ($F(1, 38) = 2.31$, $p = .137$, $\eta^2p = .057$), and a significant Group × Session interaction ($F(1, 38) = 15.23$, $p < .001$, $\eta^2p = .286$). Holm-adjusted pairwise comparisons showed no difference between groups at PRE (CTRL: 2.04 ± 1.41; PPAR: 2.20 ± 0.71; mean difference = -0.15, t(38) = 0.427, $p = .860$; $d = 0.14$). ln(LF/HF) increased significantly from PRE to POST in the PPAR group, from 2.20 ± 0.71 to 2.75 ± 0.63 (mean difference = 0.55, t(38) = 4.438, $p < .001$; $d = 0.52$), whereas no significant change was observed in the CTRL group (2.044 ± 1.41 vs. 1.91 ± 1.28; mean difference = 0.13, t(38) = 1.080, $p = .860$; $d = 0.13$). At POST, the between-group difference did not reach statistical significance (CTRL: 1.91 ± 1.28; PPAR: 2.75 ± 0.62; mean difference = 0.84, t(38) = 2.63, $p = .062$; $d = 0.79$) (Fig. 7).

DISCUSSION

The present study investigated whether a brief psychophysiological pre-activation routine could improve performance during a high-risk military obstacle course without compromising procedural safety. Three main findings emerged. First, the PPAR produced a significantly greater reduction in completion time than a time-matched motivational control intervention. Second, participants receiving the PPAR achieved both faster completion times and lower Safety Incident Scores than controls at POST, indicating that improved speed was not accompanied by a deterioration in observed procedural safety. Third, the PPAR elicited a distinct pre-performance cardiac response, characterized by increased heart rate and significant changes in HRV spectral indices. Together, these findings suggest that task-specific psychophysiological preparation may facilitate rapid execution while preserving safety-critical behavioral control under demanding operational conditions.

The primary finding was that the PPAR produced a substantially greater improvement in obstacle-course completion time than the time-matched motivational control intervention. Participants in the PPAR group reduced their mean completion time by 11% relative to PRE, compared with approximately 2% in the control group. The significant Group × Session interaction indicates that this difference cannot be explained solely by influences shared by both groups, including repeated exposure to the course. This

finding is consistent with evidence that motor imagery can enhance subsequent physical performance and that the imagined speed of an action can influence its later execution[33,34]. Importantly, the active motivational control also accounted for nonspecific influences related to instructor attention, encouragement, and interpersonal interaction[35], strengthening the interpretation that the greater improvement in completion time was associated with the task-specific components of the PPAR. Crucially, faster completion was not accompanied by deteriorated procedural safety. Although SIS decreased in both groups, participants receiving the PPAR achieved both significantly faster completion times and lower SIS values than controls at POST. This combination contrasts with the deterioration in accuracy commonly observed when movement speed is prioritized in conventional speed–accuracy paradigms[1,2]. Rather than suggesting that speed and safety are inherently incompatible, these findings indicate that both can coexist within a demanding, ecologically valid motor task. The PPAR combined several complementary forms of preparation, including accelerated motor imagery of locomotor progression, deliberate rehearsal of safety-critical procedures, attentional focusing, anticipation of physical and emotional demands, and voluntary breathing regulation. Although their individual contributions cannot be isolated, these components provide a basis for considering how task-specific preparation may support faster execution while preserving safety-critical behavioral control.

A distinctive feature of the PPAR was that participants did not imagine every part of the course at the same speed. Locomotion and obstacle negotiation were mentally rehearsed at an accelerated pace, whereas safety-critical manipulations were rehearsed at approximately their actual execution speed. This contrast was designed to prepare rapid progression without encouraging participants to rush the actions on which their safety depended. Experimental evidence indicates that imagined movement speed can influence subsequent execution time[34], while more recent work shows that slow and fast motor imagery engage partly distinct patterns of neural activity[36]. Neither finding establishes how temporal imagery operated here, but both support the relevance of imagined movement timing as a potentially meaningful component of the routine. The PPAR also asked participants to identify and rehearse the procedures they personally anticipated as most difficult. This individualized step may have made preparation particularly relevant during transitions where uncertainty, hesitation, or incorrect action sequencing could have substantial consequences. Rather than simply imagining successful completion of the course, participants rehearsed specific transitions between movement and safety procedures. This emphasis on critical transitions is supported by evidence that the effects of motor imagery within an action sequence can vary across its component movements, with particularly difficult transitions showing the greatest delayed gains[37,38]. Together, these findings suggest that differential temporal imagery may have supported the allocation of motor control according to task demands, facilitating rapid progression between obstacles[34] while preserving deliberate execution during safety-critical procedures[39,40]. This account could explain how a shorter completion time coexisted with a low Safety Incident Score. Finally, the performance goal and the repeated self-talk cue, “slow is smooth, smooth is fast,” may have helped participants maintain these priorities during execution. Experimental evidence suggests that self-talk can support attentional control and motor performance under distracting

conditions[41]. Accordingly, the task-specific self-talk incorporated into the PPAR may have helped participants maintain a balance between rapid progression and deliberate execution of safety-critical procedures.

The PPAR prepared participants for the sensations they were likely to encounter during the course. Rather than imagining an effortless performance, they anticipated breathlessness, a rapid heartbeat, muscular burning, and discomfort while mentally rehearsing continued engagement with the task. They also pictured themselves completing demanding sections despite exposure to height and the sensations associated with intense effort. This element of the routine may have reduced the need to interpret those sensations for the first time while negotiating obstacles and performing safety procedures. The challenge-threat framework offers one way to understand this approach. Performance under pressure depends in part on how individuals appraise the demands of a task relative to the resources they believe they can mobilize[12,15]. Other experimental work highlights that imagery can influence challenge and threat appraisals and their accompanying psychological and cardiovascular responses[27]. Within the PPAR, rehearsing successful action in the presence of effort and fear may have helped participants approach these sensations as expected features of the course, rather than as signals that effective action was no longer possible. Moreover, the IZOF framework adds an important qualification: the emotional state that supports performance can differ between individuals, and elevated activation need not be detrimental in itself[19,20]. The routine therefore did not seek a uniformly calm state. It invited participants to acknowledge anticipated sensations while remaining committed to rapid progression and accurate safety procedures. This is also a plausible account of how affective preparation could support performance under simultaneous physical and emotional demands.

The PPAR elicited a distinct pre-performance cardiac response, characterized by a significant increase in heart rate (approximately 15 beats/min) and changes in HRV spectral indices. In particular, LF power increased within the PPAR group, with a significant Group × Session interaction, although the between-group difference at POST did not reach statistical significance. Unlike our previous studies in firefighters, which assessed HRV in both supine and standing positions, operational constraints restricted the present recordings to standing participants[16,17]. Because LF power is influenced by respiratory and baroreflex mechanisms, and its measurement in the standing position may be less reproducible, this methodological constraint warrants consideration when interpreting the cardiac findings[42,43]. Nevertheless, the significant interaction indicates that the temporal pattern of LF responses differed between groups, even in the absence of a significant between-group difference at POST. Several components of the PPAR may have contributed to these cardiac responses. First, the activating breathing pattern introduced toward the end of the routine may have influenced cardiac activity through respiratory–cardiovascular coupling[44]. Second, anticipating intense physical effort and height exposure may have contributed to increased cardiac activation, consistent with evidence of anticipatory heart rate elevations before demanding exercise[45] and high-risk activities such as parachute jumping[46]. Mental imagery of challenging situations can also modify cardiovascular responses through changes in challenge and threat appraisals[27]. Third, motor imagery may have contributed directly to the observed

cardiac response. Imagined locomotor effort has been associated with increases in heart rate and ventilation that vary with the imagined movement speed[47], while first-person motor imagery has been associated with greater LF power than third-person imagery[48]. The concurrent increases in HR and LF power may therefore reflect an acute cardiac response associated with preparation for the impending physical demands, rather than a generalized reduction in physiological activation. This interpretation is consistent with previous findings in firefighters showing that combined motor imagery and voluntary breathing strategies can modify cardiac responses and help maintain performance during demanding efforts[17,18]. The present findings extend this line of research to a prolonged, high-risk military obstacle course involving substantial physical effort, repeated cognitive–motor demands, and exposure to height. However, whether and how the observed cardiac changes contributed directly to improved performance remains to be established.

Strengths, limitations, and future directions for fundamental research

A major strength of the present study is its ecological validity, as the effects of the PPAR were examined during an authentic military qualification assessment requiring rapid whole-body performance alongside strict adherence to safety-critical procedures. Combined with randomized group allocation, blinded outcome assessment, and a time-matched motivational control, this setting provides a rigorous framework for examining the acute effects of task-specific psychophysiological preparation under operationally relevant conditions. Nevertheless, several limitations should be acknowledged when interpreting the findings and considering their underlying mechanisms.

First, because breathing, motor imagery, attentional guidance, and self-talk were combined within a single intervention, their respective contributions to the observed effects cannot be disentangled. Future studies should compare individual components and selected combinations while assessing respiratory patterns, perceived effort, emotional states, and challenge–threat appraisals. Such measurements would help clarify the psychological and physiological processes associated with performance improvements, which cannot be established as mediating mechanisms in the present design. Furthermore, although HR and HRV provide indirect information about cardiac autonomic responses, the neural processes underlying the effects of the PPAR remain unknown. Functional neuroimaging studies examining the brain networks recruited by individual routine components would provide complementary mechanistic insights.

Second, completion time was assessed for the course as a whole, preventing identification of the specific obstacles or transitions responsible for performance gains. Future investigations incorporating obstacle-level timing and separate analyses of safety-incident categories could determine whether improvements primarily reflect faster locomotor progression, more efficient transitions, or changes in safety-critical manipulations.

Finally, the participants were experienced military personnel assessed at a single training site, and outcomes were measured immediately after a single intervention. Whether comparable benefits extend to less experienced populations, other operational tasks, or repeated autonomous use remains unknown. Longitudinal and transfer studies are therefore needed to establish the durability and generalizability of the observed effects.

The present findings suggest that brief, task-specific psychophysiological preparation may complement conventional technical training in demanding operational environments. By integrating mental rehearsal of rapid progression, safety-critical procedures, and anticipated physical and emotional demands, the PPAR offers a practical approach that can be implemented immediately before performance. An important question is whether its effectiveness depends on the performer's level of technical expertise. Our research group is currently investigating this issue by comparing the effects of the PPAR in trainee commandos acquiring the required skills and experienced commandos who have already mastered complex obstacle-negotiation and safety procedures. Beyond military obstacle courses, this approach may be relevant to other activities requiring the simultaneous management of physical effort, environmental exposure, and safety-critical actions, including rescue operations and missions conducted in hostile environments[11,49,50]. However, its effectiveness in these contexts remains to be established. Future research should determine which routine components are most beneficial for specific operational demands, whether individualized adaptations enhance their effectiveness, and whether trained personnel can reproduce the observed benefits when using the routine autonomously.

Conclusion

The present findings suggest that faster performance and procedural safety are not necessarily competing objectives during complex, high-risk motor tasks. A brief, task-specific psychophysiological pre-activation routine produced greater improvements in obstacle-course completion time than a time-matched motivational intervention, while participants also exhibited fewer weighted safety incidents at POST. Although the underlying mechanisms remain to be established, these findings highlight the potential of multimodal pre-performance preparation to support efficient action without compromising safety-critical procedural performance under demanding operational conditions.

METHODS

Participants

An a priori sample size estimation was performed using G*Power. The expected effect size (f = 0.25–0.30) was informed by data from an independent pilot study conducted under comparable operational conditions and by previous psychophysiological studies conducted in military populations[51]. Assuming $\alpha = 0.05$ and a statistical power of 0.95, the analysis indicated that a minimum sample of approximately 34–38 participants was required. A total of 50 military personnel (age: 28.5 ± 6.2 years; height: 180.3 ± 5.8 cm) voluntarily participated in the study. Performance data were collected from all participants.

Cardiac recordings were obtained from a subsample of 40 participants (20 per group), corresponding to the maximum number of wearable cardiac monitoring systems available for simultaneous field deployment. Restricting physiological recordings to this subsample allowed the experimental protocol to be fully integrated into the operational training schedule without disrupting the organization or timing of the Commando Monitor Course. All participants were experienced French Army non-commissioned officers enrolled in the Commando Instructor Course at the Centre National d'Entraînement Commando – 1er Régiment de Choc (CNEC 1er CHOC, France). This elite military qualification is awarded to experienced non-commissioned officers following successful completion of an intensive selection and training program. Certified instructors are subsequently responsible for training military personnel in advanced commando techniques, tactical mobility, obstacle negotiation, the planning and execution of live demolitions using a wide range of explosive charges and breaching techniques, and the application of safety-critical procedures under operational conditions. Consequently, all participants were operationally fit and medically cleared to undertake high-intensity military training and operational deployment. Eligibility criteria are detailed in the Appendix. Participants who did not meet all inclusion criteria were excluded from the study. All participants provided written informed consent prior to participation. The study was conducted in accordance with the Declaration of Helsinki[52] and was approved by the Institutional Ethics Committee of the University of Toulouse (Approval No. 2020-04-21-213).

Study design

This overall study was reported in accordance with the CONSORT 2025 statement for randomized trials[53], and both the experimental and control interventions were described following the Template for Intervention Description and Replication (TIDieR) guidelines[54]. This study employed a randomized, parallel-group, repeated-measures design with blinded outcome assessment and statistical analysis to examine the effects of a psychophysiological pre-activation routine on behavioral, performance, and physiological responses during a high-risk military obstacle course. The blinded outcome assessment and statistical analysis procedure was implemented as follows: certified CNEC instructors responsible for evaluating completion time and safety-related behaviors remained unaware of participants' group allocation throughout the experiment. Furthermore, the investigator responsible for data processing and statistical analyses remained blinded to the correspondence between group labels and experimental interventions until all statistical analyses had been completed.

Participants were randomly assigned to either the control (CTRL, n = 25) or psychophysiological pre-activation routine (PPAR, n = 25) group using computer-generated randomization stratified by military section, the standard organizational unit of the Commando Instructor Course. This procedure ensured a balanced distribution of participants from each section across both groups while preserving the operational organization of the training program. The experiment was conducted during the third week of the Commando Instructor Course, following two weeks of standardized intensive military training characterized by comparable physical and cognitive demands, identical instructional content, and similar sleep restriction across participants. All participants completed two successive trials of the Green 'Piste

d’Audace’ obstacle course at Fort Miradou (Collioure, France), an operational training facility of the Centre National d’Entraînement Commando – 1er Régiment de Choc (CNEC 1er CHOC), as part of the mandatory assessments for the Commando Instructor qualification. During each trial, participants were instructed to complete the course as rapidly as possible while strictly adhering to all prescribed safety procedures. Completion time and safety-related behaviors were continuously assessed by certified CNEC instructors according to official qualification standards. Experimental conditions were standardized across groups, including training schedules, instructors, environmental conditions, obstacle sequence, equipment, hydration procedures, and safety regulations. These two maximal performance trials were conducted on consecutive days. The experimental intervention or the time-matched control intervention was administered immediately before the second performance trial. A detailed description of the experimental timeline and procedures is provided in the following sections. The primary outcome was obstacle-course completion time. Safety performance, quantified using the Safety Incident Score (SIS), was a key secondary outcome used to examine whether faster completion was accompanied by any deterioration in compliance with safety-critical procedures. Heart rate and HRV indices were additional secondary outcomes used to characterize the cardiac responses associated with the pre-performance intervention.

Experimental setting

The experiment was conducted on the Green *‘Piste d'Audace’* located at Fort Miradou (Collioure, France), one of the most famous operational training facilities of the Centre National d'Entraînement Commando – 1er Régiment de Choc (CNEC-1er CHOC). Developed from the French commando training doctrine established after the Second World War and officially implemented at Fort Miradou in the early 1960s, the Green *‘Piste d'Audace’* remains a unique operational training facility designed to develop soldiers' audacity, self-confidence, emotional regulation, autonomous decision-making, and strict adherence to safety procedures under realistic operational constraints. Beyond obstacle negotiation itself, the course constitutes a pedagogical and evaluative tool aimed at preparing military personnel to maintain effective decision-making and behavioral control under demanding physical and psychological conditions. The Green *‘Piste d'Audace’* consists of an 850-m course combining 17 successive aerial and ground obstacles distributed across the Fort Miradou cliffs, with a cumulative elevation gain exceeding 70 m and exposure reaching approximately 100m above sea level at its highest point. Participants successively negotiate suspended cables, zip lines, balance beams, climbing walls, vertical ascents, rope descents, unstable crossings, confined-space passages, and precision jumps performed directly above approximately 100 m of open exposure while continuously executing mandatory self-belaying procedures (Fig. 1). Completion time is only one component of performance. Throughout the course, candidates must correctly perform 26 standardized safety manipulations involving clipping, unclipping, anchor transfers, and rope protection systems according to the official CNEC assessment protocol. Every procedural error result in predefined penalties according to its severity and may compromise both successful course completion and progression toward the Commando Instructor qualification. Unlike conventional obstacle courses, participants were not protected by any secondary belay or backup safety system during obstacle negotiation. Their safety depended exclusively on the correct execution of

prescribed self-belaying procedures under the continuous supervision of certified Commando Instructors. Each instructor monitored between one and three obstacles according to obstacle complexity and safety-system requirements using the official CNEC evaluation framework, ensuring standardized assessment of both technical execution and safety-related behaviors throughout the course. During the present study, all experimental trials were conducted on the same course, under comparable environmental conditions (temperature, humidity, and wind), at the same time of day, and supervised by the same instructors positioned at identical observation points to ensure maximal standardization of performance assessment.

Experimental intervention

Immediately before the second obstacle-course trial, participants assigned to the experimental group completed a standardized 10-min PPAR. The intervention was performed in a standing position, approximately 10 m from the cliff edge marking the starting point of the Green *'Piste d'Audace'*, with participants facing the open exposure. The routine combined controlled breathing, attentional focusing, interoceptive and motor imagery, and self-talk within a standardized temporal sequence designed to progressively shift participants from initial self-regulation toward task-specific psychophysiological activation. During the first minute [0:1 min], participants performed conscious full breathing involving the successive abdominal, thoracic, and upper-thoracic/scapular phases of inspiration and expiration. Inspiratory and expiratory durations were self-selected to maintain respiratory comfort and ease. Participants were instructed to focus their attention on the respiratory process itself and to include brief breath holds following both complete inspiration and complete expiration. During the second minute [1:2 min], while maintaining conscious breathing, participants were instructed to become aware of their current level of stress and perceived activation and to progressively adjust toward a subjectively optimal level of readiness. Breathing was then shifted toward an equal inspiratory–expiratory pattern, with inspiration and expiration performed for equivalent self-selected durations. Concurrently, participants mentally focused on the forthcoming performance goal: completing the obstacle course as fast as possible while committing no safety-related errors. They were instructed to maintain this goal irrespective of task-related fear, discomfort, pain, or fatigue experienced during the forthcoming trial. From 2 to 4 min, participants engaged in anticipatory interoceptive imagery of the physiological and affective sensations expected during maximal obstacle-course performance. They were successively guided to imagine experiencing severe breathlessness, a markedly elevated heartbeat associated with both effort and fear, intense burning sensations in the upper limbs, dry mouth, and a strong sensation of air hunger. Participants were instructed to mentally experience and accept these sensations without allowing them to interfere with their attentional focus, behavioral control, or commitment to the performance goal. From 4 to 7 min, participants performed a guided mental simulation of the entire obstacle course. The locomotor and obstacle-negotiation phases were mentally represented using a deliberately accelerated temporal perspective, whereas all safety-critical procedures (including carabiner handling, rope manipulation, clipping and unclipping, anchor transfers, and self-belaying procedures) were mentally rehearsed at approximately their real and actual execution speed. This differential temporal imagery was intended to preserve the precision of safety-critical actions while maintaining an

overall representation of rapid course completion. From 7 to 8 min, participants transitioned to an activating breathing pattern characterized by a prolonged inspiration, a 2s end-inspiratory breath hold, and a brief expiration. From 8 to 9 min, while maintaining this breathing pattern, participants identified the rope or safety procedures they personally anticipated as the most difficult or concerning and mentally rehearsed their successful execution with fluidity, control, and speed. This imagery was accompanied by the standardized internal self-talk cue, “slow is smooth, smooth is fast,” repeated internally four to five times. During the final minute (9–10 min), participants were instructed to progressively increase the amplitude of the activating breathing pattern while performing motor imagery of the first three actions they would execute immediately after the start signal. Simultaneously, they anticipated the early emergence of intense exercise-related sensations in the forearms and mentally associated these sensations with a state of strength, readiness, and task-focused concentration. The routine concluded immediately before participants moved to the starting position and initiated the second obstacle-course trial.

Participants in the CTRL group completed a time-matched 10-min control intervention under the same environmental and interpersonal conditions as the experimental group. They were positioned at the same location, approximately 10 m from the cliff edge marking the starting point of the Green *‘Piste d’Audace’*, standing and facing the open exposure. The instructor occupied the same position relative to the participants as during the experimental intervention. In both groups, participants were free to keep their eyes open or closed according to individual preference and comfort. During the 10-min control intervention, the instructor delivered a standardized positive and motivational speech focusing on the participants’ experiences during the preceding weeks of the Commando Instructor Course, the challenges they had already successfully overcome, their previous accomplishments during training, and the instructor’s confidence in their ability to successfully complete the forthcoming obstacle-course trial. Importantly, the motivational speech contained no task-specific technical instructions or guidance regarding obstacle negotiation, pacing, or safety procedures. No controlled-breathing instructions, attentional or interoceptive exercises, motor or performance imagery, task-specific mental rehearsal, or standardized self-talk cues were provided to the CTRL group. The control intervention was therefore designed to match the experimental condition for intervention duration, physical setting, body posture, exposure to the forthcoming task environment, instructor presence and positioning, and the amount of interpersonal attention and verbal interaction received immediately before performance. The use of an active motivational control condition rather than passive waiting was intended to minimize nonspecific effects related to instructor attention, social interaction, encouragement, and general motivational support, thereby allowing between-group differences to be more specifically attributed to the psychophysiological components of the experimental pre-activation routine.

Physiological measurements

Heart rate (HR) and heart rate variability (HRV) were assessed (S810i, Polar, Aulnay-sous-Bois, France) immediately before (PRE) and after (POST) the intervention, i.e., before and after the PPAR in the experimental group and before and after the motivational speech in the control group. Participants

remained in a standardized standing position throughout each recording in both groups. Each recording lasted 7 min, following the recommendations of Schmitt et al. (2013). The acquisition and HRV processing procedures were identical to those previously described in detail in our earlier studies [16,17]. Briefly, beat-to-beat cardiac intervals were recorded under standardized conditions, and HRV indices were subsequently derived from the resulting R–R interval time series. Frequency-domain indices included total spectral power (TP; calculated as LF + HF), low-frequency power (LF), high-frequency power (HF), and the LF/HF ratio. The same acquisition and processing procedures were applied to all participants and at both measurement time points.

Performance Outcomes

Performance was assessed using two complementary outcomes: course completion time and safety incident score. The course completion time was defined as the time required to complete the entire high-risk obstacle course. Timing was recorded using a BlazePod system (BlazePod, Play Coyotta Ltd., Israel), with participants manually activating one touch-sensitive pod immediately when starting the course and a second pod upon crossing the finish point. Safety performance was quantified using a Safety Incident Score (SIS) based on the occurrence and severity of incidents observed during course completion. Incidents were weighted according to their potential safety consequences: an action that could result in disconnection from the safety system was assigned 2 penalty points, a safety-rule violation 1 penalty point, and the use of a non-compliant obstacle-crossing technique 0.5 penalty points. The SIS corresponded to the sum of penalty points accumulated over the entire course, with higher scores indicating poorer safety performance. Safety incidents were assessed in real time by Level 2 commando instructors positioned at each obstacle. To minimize inter-rater variability across participants, the same instructor was assigned to each respective obstacle throughout the entire experiment.

Statistical Analyses

All statistical analyses were performed using JASP (version 0.96; JASP Team, University of Amsterdam, The Netherlands). Statistical significance was set at $\alpha = .05$ (two-tailed). Effect sizes were reported alongside inferential statistics to complement *p* values and facilitate interpretation of the magnitude of the observed effects. Distributional assumptions were assessed using the Shapiro–Wilk test, and homogeneity of variance between groups was examined using Levene's test.

For completion time, the normality assumption was satisfied across groups and conditions (all Shapiro–Wilk $p \geq .157$), and homogeneity of variance was supported at both PRE and POST (Levene's $p = .965$ and $p = .482$, respectively). Completion time was therefore analyzed using a 2 × 2 mixed-design analysis of variance (ANOVA), with Session (PRE, POST) as the within-subject factor and Group (CTRL, PPAR) as the between-subject factor. The Session × Group interaction was considered the primary test of whether changes from PRE to POST differed between groups. Main effects of Group and Session were also examined. Effect sizes for ANOVA effects were expressed as partial eta squared (η^2p). When a

significant interaction was identified, Holm Post-Hoc were conducted to characterize the interaction[56], with Cohen's *d* reported as the corresponding standardized effect size[57].

Safety Incident Score (SIS) data exhibited substantial departures from normality (all Shapiro–Wilk $p < .01$), consistent with their discrete and bounded distribution, and were therefore analyzed using non-parametric procedures. Between-group comparisons (CTRL vs. PPAR) were performed separately at PRE and POST using Mann–Whitney U tests. Within-group changes from PRE to POST were assessed separately in each group using Wilcoxon signed-rank tests. Rank-biserial correlations (*r*) were reported as effect-size estimates for these comparisons, with conventional benchmarks of .10 (small), .30 (medium), and .50 (large)[58,59].

Heart rate variability analyses included HR, LF, HF, TP and LF/HF ratio. Inspection of the raw spectral indices revealed departures from normality for LF, HF, TP, and LF/HF in at least one group or condition (all Shapiro–Wilk $p \leq .004$). Consistent with established recommendations for the analysis of positively skewed HRV spectral measures, these variables were therefore natural-log transformed prior to inferential analyses[31,32]. Following transformation, the normality assumption was satisfied for all spectral indices across groups and conditions (all Shapiro–Wilk $p \geq .26$). HR satisfied the normality assumption in its original scale and was therefore analysed without transformation. Homogeneity of variance was additionally assessed using Levene's test. HR and each log-transformed HRV index (lnLF, lnHF, lnTP, and lnLF/HF) were analyzed separately using 2 × 2 mixed-design ANOVAs, with Session (PRE, POST) as the within-subject factor and Group (CTRL, PPAR) as the between-subject factor. For each outcome, the Session × Group interaction was used to determine whether the PRE-to-POST response differed between groups, while the main effects of Group and Session were also reported. Effect sizes were expressed as partial eta squared (η^2p). Where a significant interaction was observed, pairwise comparisons were conducted using Holm post-hoc tests[56], with Cohen's *d* reported as the corresponding standardized effect size[57].

Fidelity of the intervention

Intervention fidelity was ensured throughout the experiment. Both the PPAR and control intervention were delivered according to standardized procedures, with identical duration (10 min), setting, and participant positioning across individuals. For the PPAR, all components (breathing, attentional focus, mental imagery, and self-talk) were delivered in the same predefined sequence and for the prescribed duration. The control intervention was similarly standardized in content and duration and did not include any specific voluntary breathing, mental imagery, self-talk, or task-execution instructions. In particular, control participants were explicitly checked to ensure that they had not engaged in mental imagery or visualization of the course during the motivational speech. No deviations from the prescribed intervention procedures were observed.

Declarations

Disclaimer

The CNEC-1er CHOC of the French Army approved this publication for universal distribution. The Organization's Institutional Review Board approved the study as an exempt protocol (2020-04-21-213) in April 2020. The information, content, and conclusions do not necessarily represent the official position or policy of the CNEC-1er CHOC and the French Army.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This research is sponsored by funding (BQR 2021) from the National University Institute Champollion, and by the French National Research Agency (ANR) through the ASTRID 2026 programme, funded by the French Defence Innovation Agency (AID), under the "FLOW-OPS" project.

Author Contribution

C.C., D.A., and L.F. conceived of this study and wrote the protocol. L.F. obtained funding and L.F. with D.A. obtained the IRB. L.F. acted as liaison to Organizations and orchestrated all approvals for military field observations. JP.B., and L.F. developed the content and script for the PPAR. JB.P., C.C., and L.F. recruited participants and collected the data under the supervision of L.F.. L.G. performed the statistical analyses under the supervision of D.A. and L.F.. L.G. and L.F. wrote the first draft of this paper. All authors read, revised, and approved the final manuscript.

Acknowledgement

The authors sincerely thank Pierre V., Gilles F. and Thygo V. for their invaluable assistance in coordinating with military authorities and their proactive support in facilitating the implementation of this study at the CNEC-1er CHOC. We also gratefully acknowledge all commando instructors who voluntarily supervised the Green Obstacle Course trials, as well as all military personnel who volunteered to participate in this study during their Commando Instructor Training Course.

Data Availability

The datasets generated and analyzed during the current study are not publicly available due to restrictions associated with research involving military personnel and operational training environments. Anonymized data supporting the findings of this study may be obtained from the corresponding author upon reasonable request, subject to applicable institutional and military data-sharing requirements.

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Figures

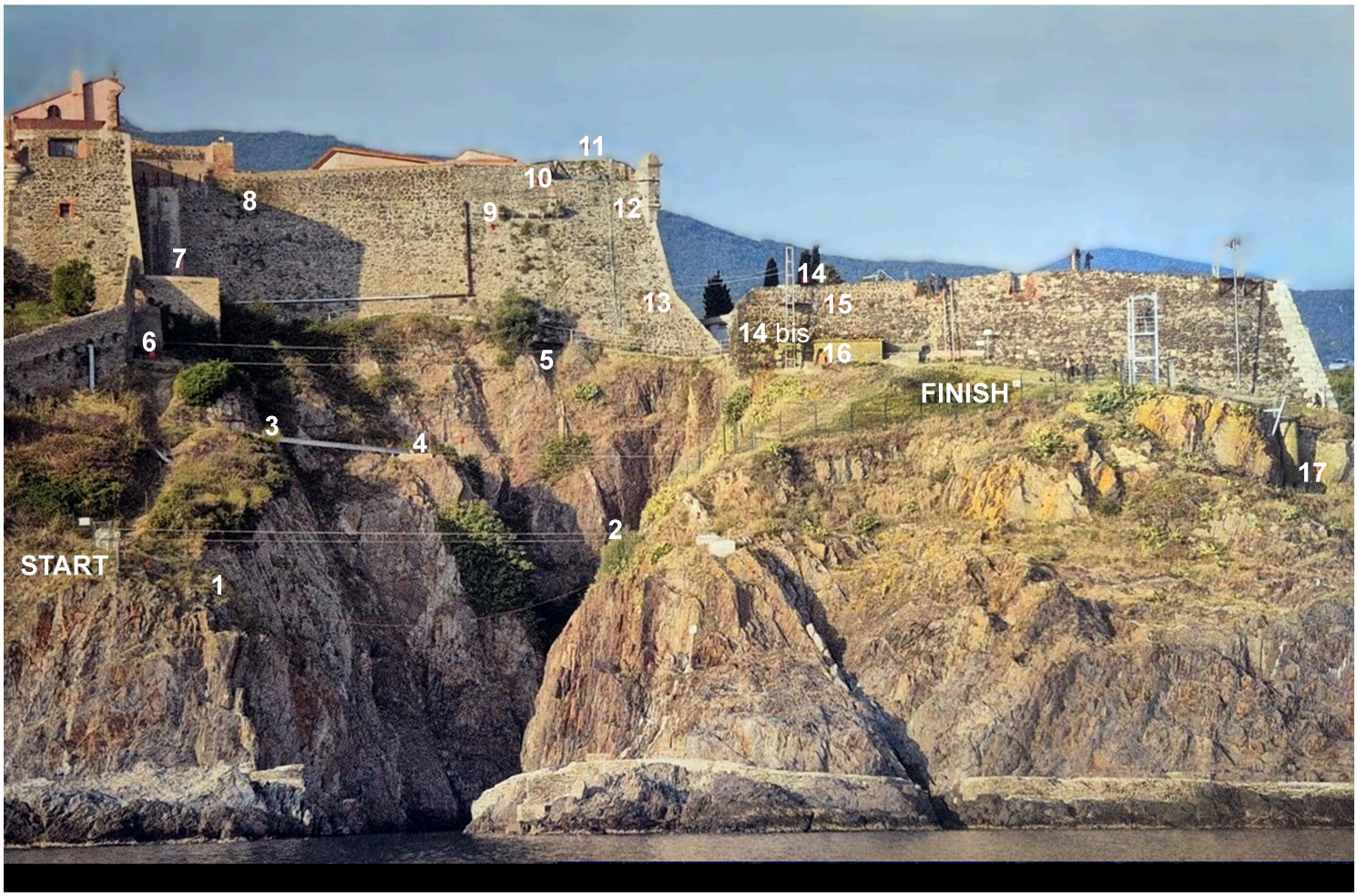

Figure 1

Overview of the Green 'Piste d'Audace' located at Fort Miradou (Collioure, France), within the Centre National d'Entraînement Commando – 1er Régiment de Choc (CNEC-1er CHOC). The 850-m obstacle course comprises, in sequence: a single horizontal zip line (1), a double horizontal zip line (2), an oscillating balance rail (3), a double vertical zip line (4), a jungle bridge (5), a vertical wall climb (6), a gutter ascent (7), a horizontal traverse of the fortress wall using climbing staples (8), and a series of projecting wall supports (corbeaux) negotiated by bounding strides (9) to reach the top of the rampart. The course then continues with an ascending inclined rail (10) leading to the 'Saut de Puce' ("Leap of Faith") (11), a precision jump requiring participants to leap from the edge of the fortress rampart onto a second rampart located approximately 1.20 m forward and 1.50 m below. The landing area measures only 0.80 × 0.80m, with its leading edge immediately bordering approximately 90 m of open exposure. Consequently, participants must precisely calibrate jump amplitude: overshooting the platform increases exposure to the cliff edge, whereas an overly conservative jump results in a backward fall of several meters onto the lower rampart, effectively eliminating any possibility of successfully completing the course within the required time limits. After regaining balance, participants descend a smooth rope (12), negotiate an angled zip line (13), climb an electrical pole (14), traverse another series of climbing staples (15) to descend onto the roof of a concrete structure, and perform a forward leap across open exposure to re-grasp the electrical pole (14 bis). The course then proceeds through a dark confined-space section exiting via a horizontal culvert (16), before

concluding with the ascent of a vertical cylindrical chimney (17) followed by a sprint to the finish line. Photograph reproduced with permission from CNEC-1er CHOC.

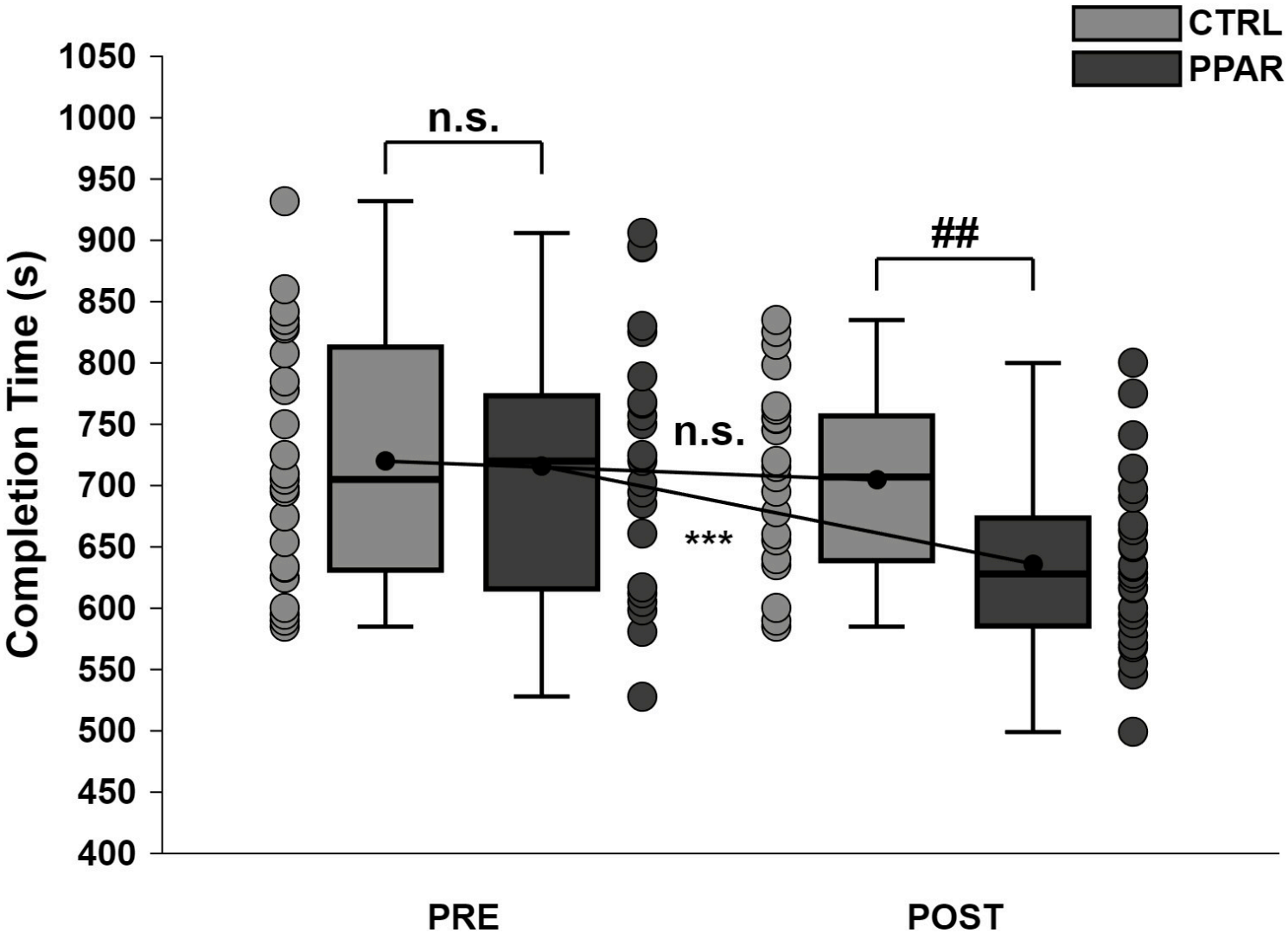

Figure 2

*Completion time before (PRE) and after (POST) the intervention in the control (CTRL, in light gray) and psychophysiological pre-activation routine (PPAR, in dark grey) groups. Boxplots represent the median and interquartile range, with whiskers indicating the range; individual dots represent participants. Black circles connected by lines indicate group means across Session. Holm-adjusted pairwise comparisons were used to characterize the Group × Session interaction. *** p < .001 for within-group PRE–POST comparisons; ## p < .01 for between-group comparisons; n.s., non-significant.*

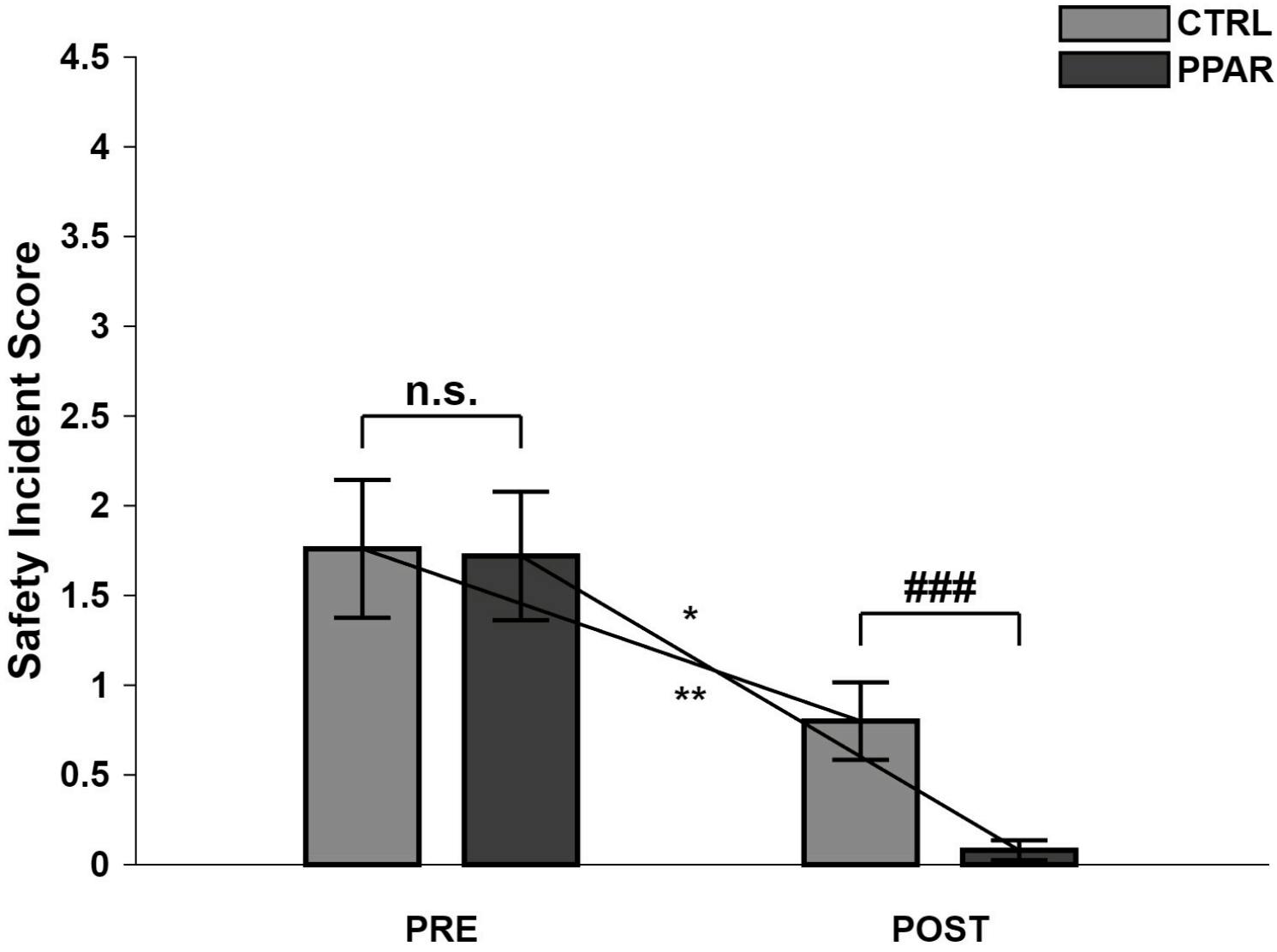

Figure 3

*Safety Incident Score (SIS) before and after the intervention in the control (CTRL, in light grey) and psychophysiological pre-activation routine (PPAR, in dark grey) groups. Bars represent mean SIS values and error bars indicate the standard deviation of the mean. Lines connect group means across Session. Between-group comparisons at PRE and POST were performed using Mann–Whitney U tests. Groups did not differ at PRE (n.s., p = 1.0), whereas SIS was significantly lower in the PPAR group than in the CTRL group at POST (###p < .001). * p < .05 and ** p < .01 indicate within-group PRE–POST differences; n.s. = non-significant.*

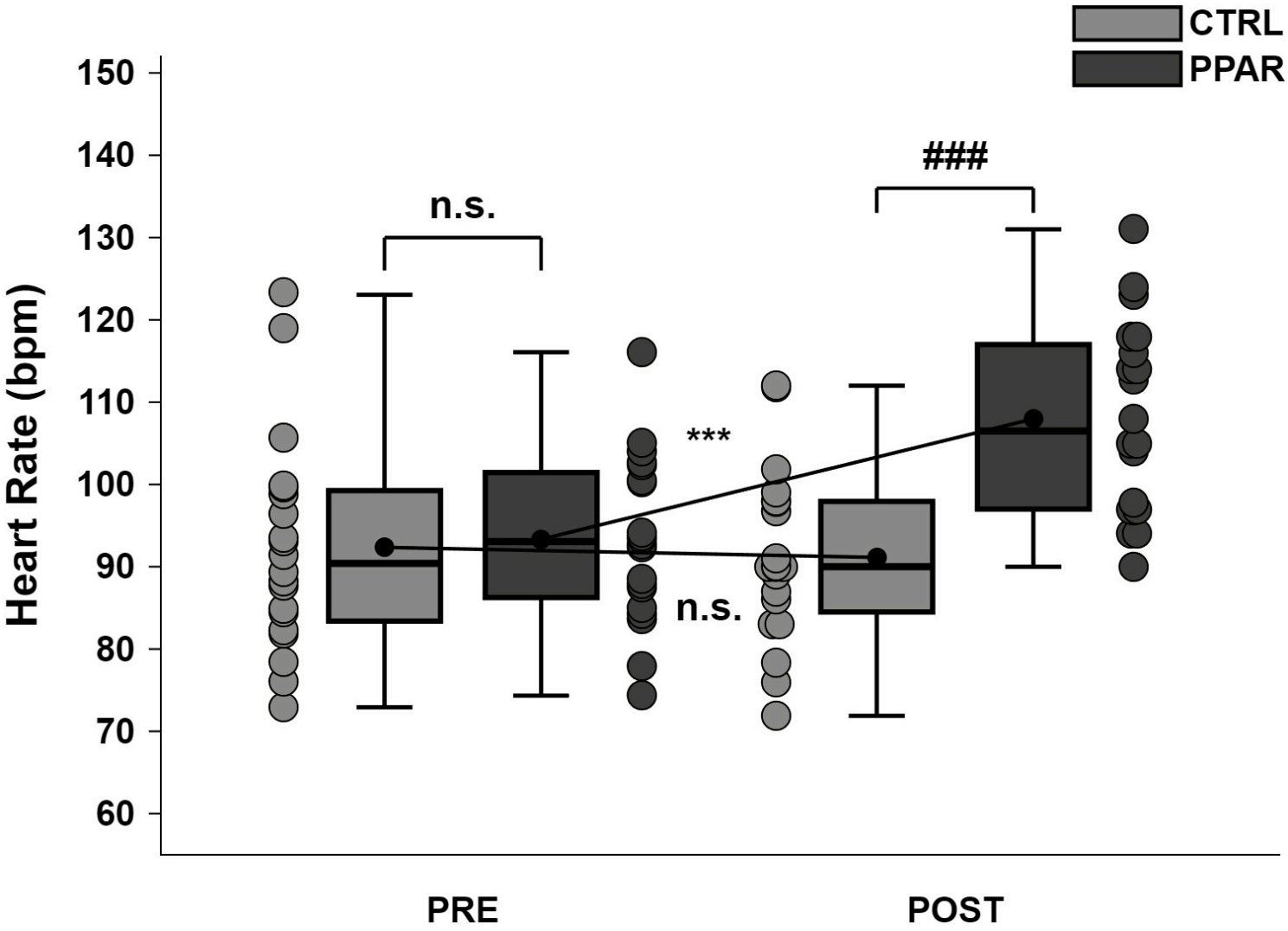

Figure 4

*Heart rate (HR) before (PRE) and after (POST) the intervention in the control (CTRL, light grey) and psychophysiological pre-activation routine (PPAR, dark grey) groups. Boxplots represent the median and interquartile range, with whiskers indicating the range; individual dots represent participants. Black circles connected by lines indicate group means across Session. Holm-adjusted pairwise comparisons were used to characterize the Group × Session interaction. **p < .001 for within-group PRE–POST comparisons; ###p < .001 for between-group comparisons; n.s., non-significant.*

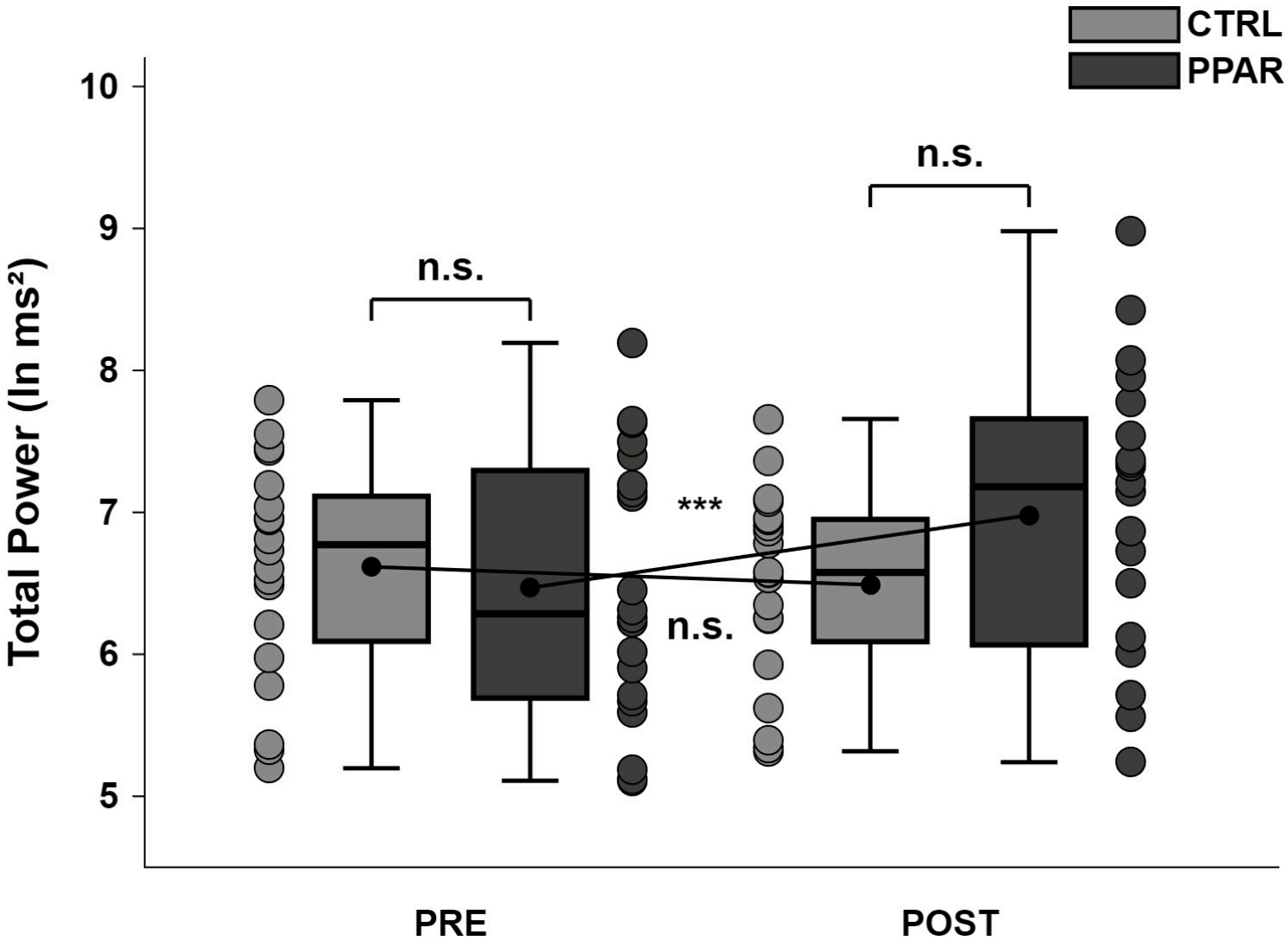

Figure 5

*Total power (TP) before (PRE) and after (POST) the intervention in the control (CTRL, in light grey) and psychophysiological pre-activation routine (PPAR, in dark grey) groups. TP values were natural-log transformed (lnTP) prior to statistical analysis. Boxplots represent the median and interquartile range, with whiskers indicating the range; individual dots represent participants. Black circles connected by lines indicate group means across Session. Holm-adjusted pairwise comparisons were used to characterize the Group × Session interaction. **p < .001 for within-group PRE–POST comparisons; n.s., non-significant.*

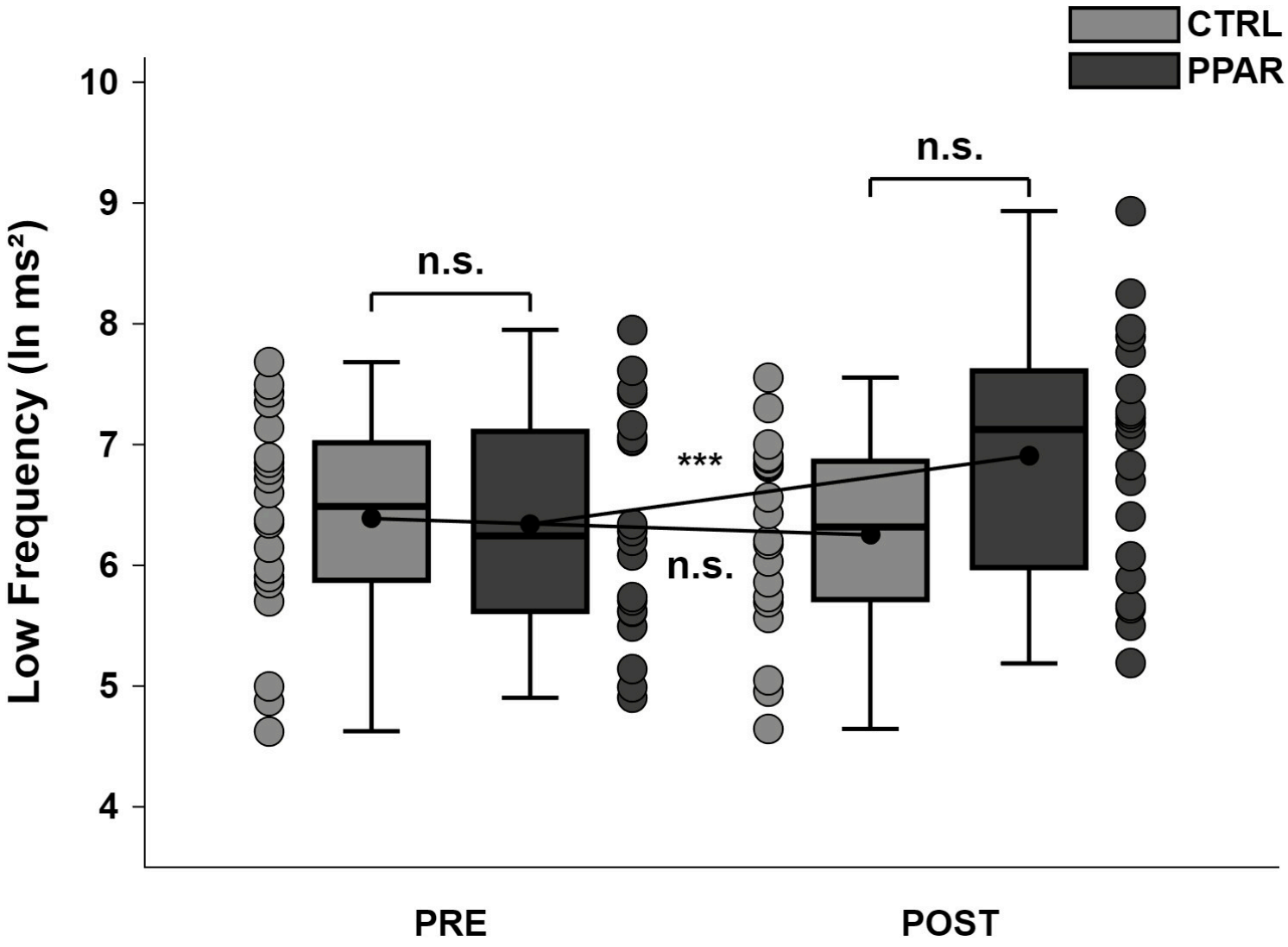

Figure 6

*Low-frequency power (LF) before (PRE) and after (POST) the intervention in the control (CTRL) and psychophysiological pre-activation routine (PPAR) groups. LF values were natural-log transformed (lnLF) prior to statistical analysis. Boxplots represent the median and interquartile range, with whiskers indicating the range; individual dots represent participants. Black circles connected by lines indicate group means across Session. Holm-adjusted pairwise comparisons were used to characterize the Group × Session interaction. ***p < .001 for within-group PRE–POST comparisons; n.s., non-significant.*

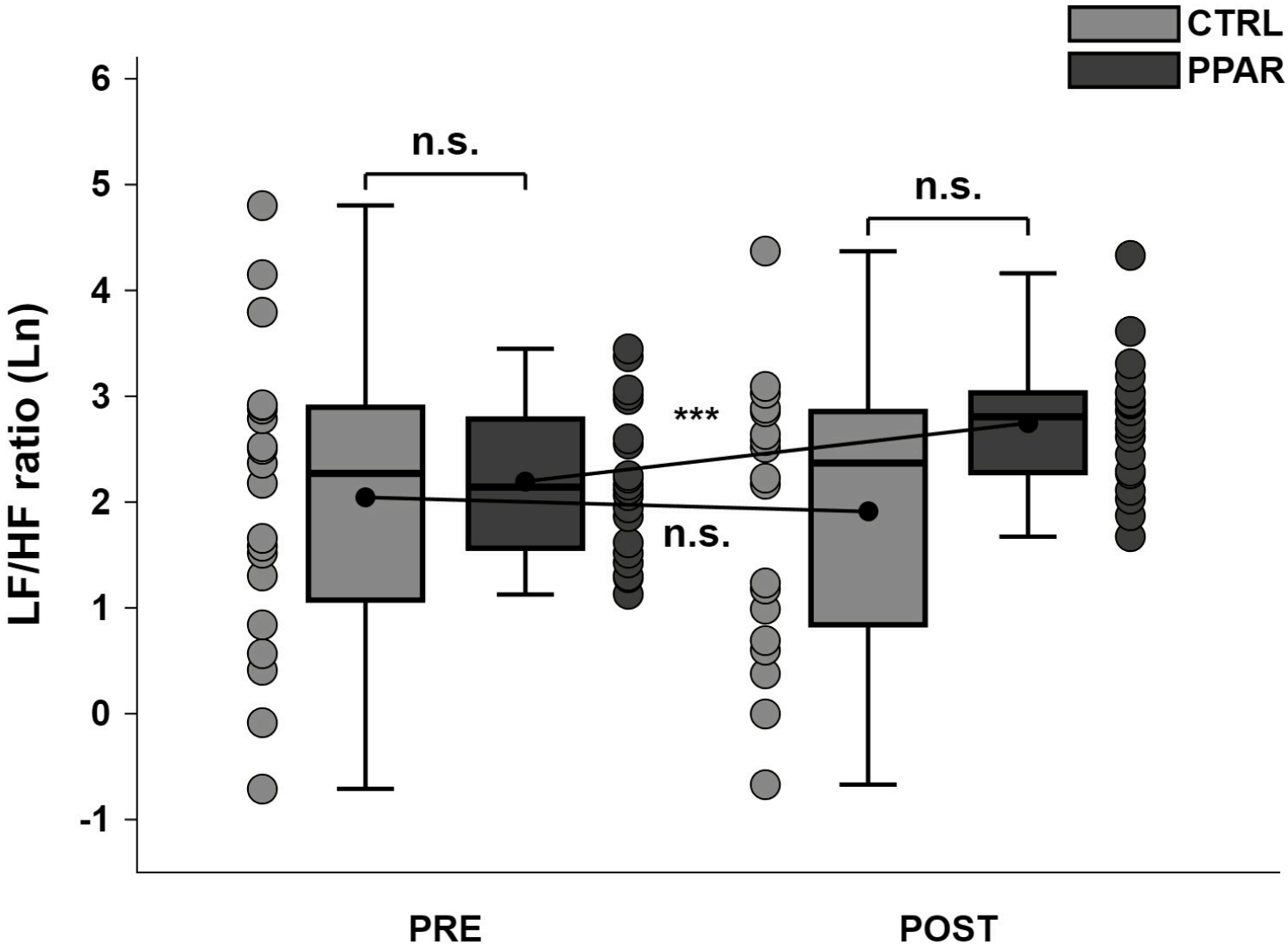

Figure 7

*LF/HF ratio before (PRE) and after (POST) the intervention in the control (CTRL, in light grey) and psychophysiological pre-activation routine (PPAR, in dark grey) groups. LF/HF values were natural-log transformed [ln(LF/HF)] prior to statistical analysis. Boxplots represent the median and interquartile range, with whiskers indicating the range; individual dots represent participants. Black circles connected by lines indicate group means across Session. Holm-adjusted pairwise comparisons were used to characterize the Group × Session interaction. ***p < .001 for within-group PRE–POST comparisons; n.s., non-significant.*