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Circadian modulation of core temperature and thermoregulatory strain during live-fire compartment exposure in firefighters

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ABSTRACT

Firefighters are repeatedly exposed to extreme radiant and convective heat during live-fire training, yet the potential influence of circadian timing on their thermoregulatory tolerance remains unexplored. This study tested whether time-of-day modulates physiological strain during standardized container fire exposures. Twenty-one professional male firefighters completed two identical 40-min live-fire sessions on the same day: late-morning (09:00 h, heat-gain phase) and late-evening (21:30 h, heat-loss phase). Core temperature (ingestible sensor), heart rate, skin temperature, under-PPE temperature and humidity, body mass, total body water, and ratings of perceived exertion were recorded. Environmental conditions were strictly matched between sessions. Core temperature rose faster and higher in the morning (ΔTcore $+1.10 \pm 0.25$ °C; slope 0.028 °C·min^{-1}) than in the evening ($+0.49 \pm 0.21$ °C; 0.012 °C·min^{-1}), despite similar peak values. Post-exposure cooling was slower in the morning (-0.37 vs -0.63 °C·h^{-1}), with a delayed hypothermic rebound. Morning sessions also elicited higher heart rates, greater perceived exertion, larger body-mass and water losses, and higher sub-garment humidity. These findings demonstrate that circadian phase significantly influences heat storage and recovery, with late-morning exposures imposing greater thermophysiological strain under identical workloads. Incorporating chronobiological principles into firefighter training schedules may reduce heat-related risk and optimize recovery strategies in extreme environments.

1. Introduction

Compartment Fire Behaviour Training (CFBT) provides a controlled yet severe thermal environment used to teach smoke reading, door control, pulsed cooling, and progression under self-contained breathing apparatus (SCBA). Unlike climate-chamber protocols—typically limited to tropical heat (28–35 °C) without radiant load or multilayer PPE—CFBT containers reproduce the radiative and convective conditions encountered during real structural firefighting. Within these containers, steep vertical thermal gradients are recorded: near-ceiling gas temperatures may reach 300–600 °C, occasionally 700–800 °C, while mid-layer values range between 150 and 300 °C and near-floor air temperatures from 50 to 100 °C, depending on fuel, ventilation, and container geometry (Eglin, 2007; Eglin et al., 2004; Perroni et al., 2014; Watt et al., 2016; Smith and Petruzzello, 1998). These steep thermal gradients and high radiant fluxes induce substantial heat strain even in static kneeling positions. For safety reasons, some training centres monitor core temperature to limit cumulative heat exposure (Eglin, 2007).

Physiological strain during live-fire training is considerable. Prior studies have reported core temperatures exceeding 40 °C, skin temperatures sufficient to cause burns, body-mass losses above 3 %, and near-maximal heart rates. Microclimate temperatures beneath turnout gear can average ~48 °C (peaks ~62 °C), with relative humidity exceeding 80–100 % (Eglin, 2007; Eglin et al., 2004; Perroni et al., 2014; Watt et al., 2016; Smith and Petruzzello, 1998). Air temperatures of ~55 °C have been recorded beneath hoods, with radiant fluxes of ≈5–10 kW m^{-2}. Such responses depend on heat load, workload, PPE characteristics, hydration, and fitness (Eglin, 2007; Eglin et al., 2004; Perroni et al., 2014; Watt et al., 2016; Smith and Petruzzello, 1998).

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Beyond these determinants, time of day may systematically modulate thermoregulatory strain, yet this dimension has been largely overlooked in firefighter research. Resting core temperature (Tcore) exhibits a circadian rhythm, reaching its minimum near 04:00–06:00 h and peaking around 17:00–18:00 h before falling again toward early morning (Waterhouse et al., 2004, 2007; Aldemir et al., 2000; Otani et al., 2020). Humans operate in a “heat-gain” or thermogenic mode during the rising phase and a “heat-loss” or thermolytic mode during the descending phase, with transitions near the rhythm's peaks and troughs (Waterhouse et al., 2004, 2007; Aldemir et al., 2000; Otani et al., 2020; Edwards et al., 2025; Reilly and Brooks, 1986; Torii et al., 1995; Souissi et al., 2002). This concept—illustrated in Fig. 1 (adapted from Edwards et al. (2025))—implies that circadian phase could influence heat storage and dissipation under thermal stress.

Exercise studies confirm time-of-day differences in sweating and skin blood flow for identical heat loads, typically showing larger effector responses in the afternoon or evening, provided hydration and convection are adequate (Waterhouse et al., 2004; Reilly and Brooks, 1986; Torii et al., 1995; Souissi et al., 2002). A higher baseline T_core in the afternoon reduces the core-to-skin gradient, potentially accelerating the attainment of critical thresholds during radiant exposure in PPE, while enhanced thermoeffector responses may mitigate heat storage. The net effect on ΔT_core remains uncertain, especially within encapsulating PPE. Importantly, no study has tested these mechanisms in live-fire conditions combining radiant heating, restricted evaporation, and structural PPE (Del Bene et al., 1990).

Differences between laboratory and field results may be explained by radiative exposure. Afternoon heat strain is strongly influenced by solar radiation during outdoor exercise (Otani et al., 2017, 2019), whereas laboratory studies conducted under purely convective conditions sometimes find no time-of-day effect on core temperature or sweating (Ravanelli and Jay, 2021). These discrepancies highlight the need for ecologically valid field-based protocols to examine circadian influences under firefighting-relevant conditions.

Structural firefighting PPE exacerbates heat strain by restricting evaporation and convection, increasing humidity and heat storage, and elevating cardiovascular strain for a given workload (Goldman, 1988; McLellan and Havenith, 2016a). Excessive sweating without appropriate fluid replacement can cause dehydration, impairing thermoregulation (González-Alonso et al., 1997) and physical performance (Cheuvront and Haymes, 2001; Nielsen et al., 1981). Radiant load, ventilation conditions, fuel characteristics, and PPE moisture saturation vary dynamically, making ΔT_core kinetics and sweating responses potentially sensitive to circadian phase.

To date, no research has determined whether heat-gain versus heat-loss circadian phases influence thermoregulatory and cardiovascular responses during live-fire training. The present study compares exposures at 09:00 (mid heat-gain phase) and 21:30 (mid heat-loss phase) during a standardized CFBT protocol. We hypothesised that:

(1) late-morning exposure would result in a steeper ΔT_core slope and/or higher peak T_core than late-evening exposure;
(2) heart rate, Physiological Strain Index (PSI) (Moran et al., 1998), and subjective indicators of heat strain would be greater in the morning;
(3) whole-body sweat rate and under-PPE humidity would be higher in the morning, indicating reduced evaporative efficiency and greater heat storage.

2. Methods

2.1. Participants

Twenty-one male professional firefighters (age 35.9 ± 8.5 y; body mass 81.3 ± 6.2 kg; height 1.84 ± 0.07 m; body fat 13.6 ± 3.8 %) from the Departmental Fire and Rescue Service of Saône-et-Loire (SDIS 71, France) participated. Body composition was assessed by bioelectrical impedance (Tanita MC-780 MA P, Tanita Corp., Tokyo, Japan).

Inclusion criteria were professional firefighters (male, ≥18 y), medically cleared for operational duty, and scheduled for container live-fire training. Exclusion criteria included gastrointestinal disorders, cardiac arrhythmia, implanted devices, dehydration, fever, or contraindication to ingestible sensors.

The study conformed to the Declaration of Helsinki and French regulations, approved by the Comité de Protection des Personnes Est I (AFSSAPS No. 2010-A00485-34). Participants provided written informed consent. A physician supervised all sessions. No compensation was given. Data were pseudonymized and stored per institutional data-protection policy.

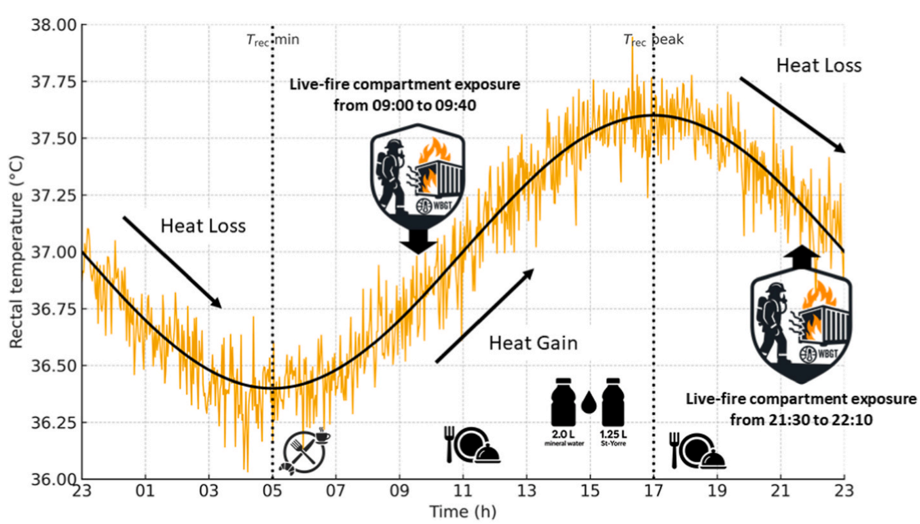

Fig. 1. The schematic showing the circadian rhythm of rectal temperature with the curve's “peak,” “minimum,” “heat loss,” and “heat gain” phases (Adapted from Edwards et al., 2009) depicts the main steps of the protocol: meals at 06:30, 11:30, and 18:30 h; standardized daily fluid intake (2.0 L mineral water and 1.25 L St-Yorre); live-fire container exposure in the morning 09:00–09:40 during the Heat Gain phase, and in the late-evening 21:30–22:10 h during the Heat Loss phase. Gastrointestinal temperatures were measured continuously throughout the day (Δt = 30 s). Skin temperature, under-PPE temperature and humidity and heart rate were recorded continuously from 2 h before entering the container to 45 min after exit. RPE was assessed 10 min after exiting the container in both morning and late-evening sessions. Body mass and percentage of body water (bioimpedance) were taken Pre: 5 min before suiting up and Post: 45 min after exit.

2.2. Experimental design

Each participant completed two identical 40-min live-fire exposures on the same day: late-morning (AM, 09:00–09:40 h) and late-evening (PM, 21:30–22:10 h).

These times were intentionally selected to represent two distinct circadian phases: the post-nadir heat-gain phase (AM) and the post-acrophase heat-loss phase (PM). Participants arrived 3 h fasted and abstained from caffeine, alcohol, and exercise for 24 h before testing. Fig. 1 illustrates the positioning of the two exposures within the circadian rhythm of core temperature.

To minimise confounding influences, several measures were implemented. First, the two exposures were separated by 12 h, providing a recovery window far exceeding that required for the return of core temperature and cardiovascular variables to baseline following static live-fire tasks. Second, two identical 40-ft steel containers were used—one dedicated to AM and one to PM—to eliminate residual thermal load inside the structure. Third, standardized meals were provided at 11:30 and 18:30, and hydration was controlled (2.0 L mineral water + 1.25 L St-Yorre per day). Participants were instructed to maintain identical nutritional intake between AM and PM sessions.

Each cohort (n = 7: one instructor, six trainees) completed the scenario once in each session. The same instructor reproduced, as consistently as possible, identical ignition, fuel load, ventilation patterns, and instructional sequences in the AM and PM exposures. This approach ensured that radiant heat load, fire behaviour, and instructional pacing remained comparable between conditions. All participants used standard structural firefighting PPE and SCBA.

This cross-over, within-day design was chosen to minimise inter-individual variability and maximise sensitivity to circadian effects, while avoiding the uncontrolled environmental drift that would arise from testing on separate days.

2.3. Live-fire facility and environmental monitoring

Training was conducted in a 40-ft (≈12.2 m) compartment fire behaviour training container composed of an entry lock and burn room lined with steel and calcium-silicate boards. Controlled fuels (wood pallets and oriented-strand-board panels) provided repeatable heat release. Container ventilation, ignition sequence, fuel load, and instructional pacing were reproduced as consistently as possible by the same certified instructor for both AM and PM exposures.

Air temperature was recorded using vertical thermocouple trees (Type N, mineral-insulated, Inconel-600 sheath, Ø 3 mm, Labfacility Ltd., West Sussex, UK) connected to a dataTaker DT85 logger (Thermo Fisher Scientific Australia Pty Ltd). Probes were positioned at 0.10, 0.50, 1.00, 1.50 and 2.30 m heights (sampling 0.5 Hz). Duplicate trees near the door and combustion zone captured vertical and longitudinal gradients. Vertical thermocouple trees are the standard method for characterising thermal stratification in CFBT environments. This approach allowed quantification of the typical stratified structure of live-fire containers (high-temperature ceiling layer, intermediate mixing layer, and cooler near-floor region).

2.4. Recovery procedure

To avoid residual heating effects, two identical containers were used—one exclusively for the morning session and one for the evening session. Ambient outdoor temperature and relative humidity were recorded before each exposure using a calibrated thermo-hygrometer (Testo 635–2, Testo SE & Co., Germany). Although small differences in outdoor conditions were unavoidable between AM and PM (typical of June in central France), these remained minor compared with the radiative and convective heat loads generated inside the burn chamber. As such, environmental variations outside the container were considered insufficient to account for differences in physiological responses across circadian phases.

Immediately after exiting the container, participants completed a standardized two-phase recovery protocol.

Phase 1 – Outdoor recovery (≈15 min): firefighters sat on benches located ~10 m from the container door, removed SCBA, helmet and gloves, and participated in a short instructor debriefing. Outdoor temperatures in June ranged from 17.4 ± 1.2 °C (AM) to 15.8 ± 0.9 °C (PM), representing a small but consistent difference between sessions.

Phase 2 – Indoor recovery: participants then walked to the same indoor monitoring room (~100 m), where ambient temperature was maintained at 20.5–21.5 °C and relative humidity at 48–52 %. No fans or cooling devices were used. Physiological monitoring (Tcore, HR, hydration markers) continued throughout both phases.

This standardized two-phase recovery ensured equivalent procedural conditions between AM and PM sessions despite minor differences in outdoor temperature.

2.5. Physiological and perceptual measurements

Core temperature (Tcore) was measured using an ingestible e-Celsius® capsule (BodyCap, Caen, France; 17.7 × 8.9 mm; accuracy ±0.2 °C; sampling 0.033 Hz). These capsules are validated for high-temperature environments and ambulatory heat-stress research, with accuracy assessed against rectal thermometry in previous studies. The timing of capsule ingestion followed established methodological recommendations for telemetric gastrointestinal thermometry. In accordance with Byrne & Lim (24), ingestible sensors were administered 2–3 h prior to data collection to ensure reliable gastric transit and to avoid artefacts caused by gastric thermal inertia. Participants therefore ingested the capsule between 05:30 and 06:00, under fasted conditions, ensuring pyloric passage before the AM exposure and aligning with recommended procedures for gastrointestinal telemetric monitoring [(Byrne and Lim, 2007); BodyCap technical guidelines]. Data were transmitted in real time to an external receiver positioned outside the container.

Skin temperature was monitored at the chest (mid-sternum) and nape (right paravertebral, C7/T1) using iButton® Thermochron DS1922T-F5# loggers (Analog Devices Inc., Wilmington, MA, USA; 0–125 °C; ±0.5 °C; 0.033 Hz). Sensors were attached with Tegaderm™ Transparent Film Dressing 1622 W (3 M Health Care, Minnesota, USA) to ensure stable thermal contact under PPE.

Under-PPE microclimate humidity and temperature were recorded at the chest using iButton® Hygrochron DS 1923 (−20–85 °C; 0.0625 °C resolution; 0–100 % RH; 0.6 % RH resolution; 0.033 Hz). The placement site was selected to reflect the region of highest evaporative resistance and sweat accumulation.

Heart rate was measured continuously 45 min before, during, and 45 min after exposure with a Polar H10 chest strap and Polar Pacer watch (Polar Electro Oy, Kempele, Finland). Beat-to-beat RR data were exported for analysis. HR values were later used to compute the Physiological Strain Index (PSI) following Moran et al. (1998). The combination of core temperature and heart rate allowed computation of the Physiological Strain Index (PSI), a widely used integrative indicator of heat strain in occupational settings (Moran et al., 1998).

Perceptual responses. Ratings of perceived exertion (RPE) were obtained 5–10 min after exiting the container using the 6–20 Borg scale. Participants remained seated outdoors during this period, immediately after removing SCBA and helmet, for a standardized 15-min passive recovery before being escorted to the monitoring room (≈100 m away; 20.5–21.5 °C).

Hydration status was assessed by body mass (±0.1 kg) and total body water (bioimpedance; Tanita MC-780MA-N S, Tanita Corp., Tokyo, Japan) pre- and post-exposure (−5 min/+45 min). No fluid intake or voiding occurred between measures. PPE was dried between sessions.

2.6. Data synchronisation and analysis

All devices were synchronized to a single NTP-calibrated clock. Sampling rates were: thermocouples 0.5 Hz; Tcore/skin/humidity 0.033 Hz; HR beat-to-beat.

Data were processed in R (v4. x) using *lme4*, *lmerTest*, *afex*, and *emmeans*. Within-subject linear mixed-effects models assessed fixed effects of time-of-day (AM vs PM), time, and their interaction, with random intercepts for subjects. Kenward–Roger degrees of freedom and Holm-adjusted pairwise contrasts were applied. Model diagnostics verified assumptions; when violated, rank-based or robust alternatives were used. Effect sizes (Cohen's dz, ηp^2) followed Batterham & Hopkins (Batterham and Hopkins, 2006) thresholds.

2.7. Repeated-measures ANOVA for core-temperature kinetics

For the comparison of core-temperature trajectories, a repeated-measures ANOVA (RM-ANOVA) was performed on six standardized exposure time points: 0, 8, 16, 24, 32, and 40 min. These values correspond to 8-min averaged bins, computed to reduce physiological noise from high-frequency sampling and to obtain evenly spaced repeated measures suitable for RM-ANOVA.

The statistical model included two within-subject factors: Time (6 levels) and Time-of-Day (AM vs PM), plus their interaction (Time × Time-of-Day).

2.8. Assumption testing

Normality of residuals was assessed using Shapiro–Wilk tests. Sphericity was examined using Mauchly's test, and Greenhouse–Geisser corrections were applied when required. Independence of observations was ensured by the crossover AM–PM design.

2.9. Robustness check

All RM-ANOVA results were cross-validated using linear mixed-effects models with random intercepts for subjects, which yielded identical conclusions. This dual approach confirms the robustness of the time-course analyses.

2.10. Physiological Strain Index (PSI)

Cardiovascular and thermal strain were quantified using the Physiological Strain Index proposed by Moran et al. (1998). PSI was computed for each participant during AM and PM exposures using $Tcore_0$, Tcore,t, HR_0 and HR,t extracted at container exit. This index provides an integrative measure of combined thermal and cardiovascular stress and is widely used in firefighter heat-stress research. The PSI combines relative changes in core temperature and heart rate according to:

$$PSI = 5\left(\frac{Tcore,t - Tcore,0}{Tcore,\max - Tcore,0}\right) + 5\left(\frac{HRt - HR0}{HRmax - HR0}\right)$$

$$\text{Or PSI} = 5\left((\text{Tcore},\text{t} - \text{Tcore},0) / (\text{Tcore},\max - \text{Tcore},0)\right) + 5\left((\text{HR},\text{t} - \text{HR0}) / (\text{HRmax} - \text{HR0})\right)$$

where:

- Tcore,t refers to the core temperature measured at the end of the live-fire exposure;
- Tcore,0 refers to the core temperature measured immediately before entering the container;
- Tcore, max refers to the maximum core temperature reached during the exposure;
- HRt refers to the heart rate measured at the end of the live-fire exposure;
- HR0 refers to the heart rate measured immediately before entering the container;
- HRmax refers to the maximum heart rate recorded during the live-fire session.

3. Results

3.1. Environmental conditions

Container conditions were highly reproducible between sessions. Thermal stratification showed a steep vertical gradient, with hot gases accumulating near the ceiling and cooler layers near the floor. Mean air temperature increased progressively over the 40 min exposure, following a near-linear profile modulated by ventilation cycles. The 3-sessions average differences between morning (AM) and late-evening (PM) exposures were negligible: +0.00, +1.00, +0.03, +0.58 and + 10.16 °C at 0.10, 0.50, 1.00, 1.50 and 2.30 m, respectively (all $p > 0.69$; $\eta p^2 \leq 0.004$). Thus, both time-of-day sessions occurred under statistically identical heat loads (Fig. 2; Table 1).

Ambient outdoor conditions during June were also recorded at the container exits, where firefighters remained seated for approximately 15 min before walking to the recovery room. Morning air temperature at the container door averaged 17.4 ± 1.2 °C, whereas late-evening temperature averaged 15.8 ± 0.9 °C. Although this difference was small (≈1.6 °C), it may have contributed to slightly faster initial cooling in PM sessions. Importantly, these outdoor values remained far below the thermal load inside the container and did not modify the equivalence of environmental stressors between AM and PM exposures.

3.2. Resting and baseline core temperature

A clear circadian effect was observed before exposure. Resting Tcore was higher in the evening (PM > AM; $F(1,20) = 55.0$, $p < 0.001$; Mean ± SD: AM 36.54 ± 0.37 °C, PM 37.15 ± 0.32 °C; circadian elevation ≈ +0.61 °C.) with no difference between experimental and reference days (Table 1).

3.3. Core temperature kinetics during exposure

Absolute Tcore increased significantly over time ($F(5,100) = 4366.8$, $p < 10^{-110}$) in both sessions. The Time-of-Day × Time interaction was strong ($F(5,100) = 963.8$, $p < 10^{-83}$). After 40 min, ΔTcore was +1.10 ± 0.25 °C in AM and +0.49 ± 0.21 °C in PM ($p < 10^{-16}$; $dz = -10.2$). Area-under-curve analysis confirmed greater cumulative heat storage in AM (22.97 ± 3.10 vs 13.11 ± 2.85 °C·min; $p < 10^{-15}$). Peak absolute Tcore converged at ~37.64 °C in both conditions ($p = 0.996$), suggesting a physiological ceiling (Fig. 3a, Table 1). Although baseline Tcore was higher in PM, the morning session showed a steeper rise (ΔTcore slope 0.028 ± 0.003 $°C\cdot min^{-1}$ vs 0.012 ± 0.002 $°C\cdot min^{-1}$; $p < 10^{-16}$; Fig. 3b–Table 1).

3.4. Post-exposure recovery

Following exit, Tcore continued to rise transiently (after-rise +0.51 ± 0.09 °C at +40 min in AM vs +0.11 ± 0.05 °C at +32 min in PM; $p = 0.0016$). Cooling was slower in the morning (−0.37 ± 0.06 vs −0.63 ± 0.08 $°C\cdot h^{-1}$; $p < 0.001$). Return to baseline occurred after 3 h 06 ± 18 min in AM and 2 h 26 ± 14 min in PM. A hypothermic rebound followed recovery (−0.22 ± 0.06 vs −0.18 ± 0.05 °C), indicating post-heat decompensation (Fig. 4, Table 1).

3.5. Post-exposure hypothermic rebound (decompensation)

A transient hypothermic rebound (Tcore–D-Off) was observed after recovery, during which core temperature dropped below the circadian reference baseline. This decompensation was significantly greater and

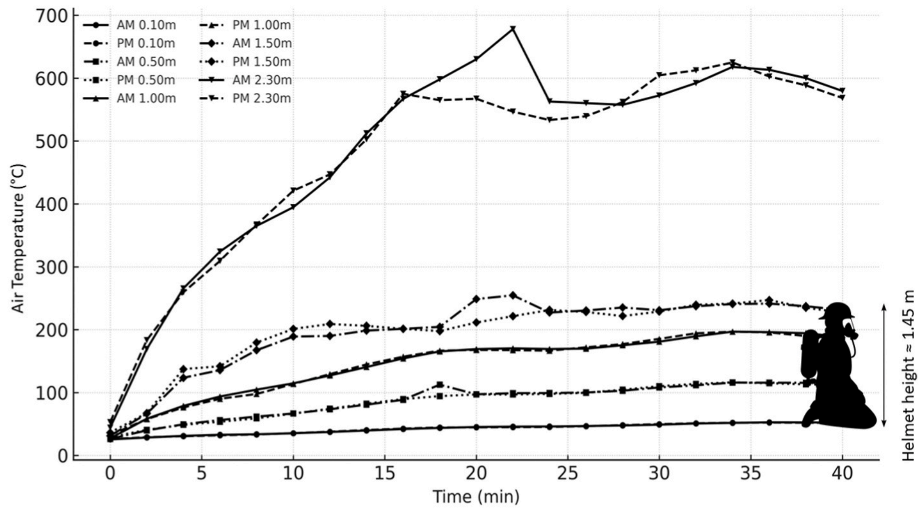

Fig. 2. Mean air temperature inside the live-fire training container during morning (AM, black solid/dashed lines) and late-evening (PM, grey dotted/dash–dot lines) exposures for the 40 min of exposure time. Temperatures to which kneeling firefighters seated back on their heels (mandatory position) are exposed were recorded at seven heights above the floor: 0.10 m (boots), 0.50 m (thighs), 0.85 m and 1.00 m (torso/chest), 1.30 m (face), 1.45 m (top of helmet), and 2.30 m (ceiling). Burn profiles across the three morning and three late-evening sessions were identical, and the curves overlap. The data show a progressive rise in temperature over time and a strong vertical thermal gradient, with consistently higher values near the ceiling (2.30 m).

longer in the morning (−0.22 ± 0.06 °C, 13:13–20:12 h) than in the evening (−0.18 ± 0.05 °C, 23:48–06:52 h; $F(1, 20) = 7.32$, $p = 0.013$, $\eta p^2 = 0.27$), indicating a stronger over compensatory thermolytic response and delayed return to thermal equilibrium after AM exposure (Fig. 5, Table 1).

3.6. Cardiovascular and perceptual responses

Cardiovascular strain was greater in the morning. HR_mean = 170 ± 9 vs 164 ± 8 bpm ($p = 0.009$), HRmax = 181 ± 10 vs 176 ± 9 bpm ($p = 0.017$), corresponding to 89.7 ± 4.5 % and 95.4 ± 5.0 % of predicted HRmax in AM vs 86.4 ± 4.9 % and 92.5 ± 5.2 % in PM. Perceived exertion (RPE) was higher in AM (16.9 ± 0.8 vs 15.9 ± 0.9; $p = 0.007$), (Table 1). Given the combined differences in heart rate and core temperature, the Physiological Strain Index (PSI) was computed to quantify integrated heat strain (Moran et al. (1998)).

3.7. Hydration and body composition

Body-mass loss averaged −0.60 ± 0.22 kg (−2.17 ± 0.33 %) in AM vs −0.40 ± 0.18 kg (−1.62 ± 0.26 %) in PM ($p = 0.023$). TBW% declined −0.9 ± 0.3 vs −0.4 ± 0.2 percentage-points ($p < 0.001$). Both time and time-of-day × time effects were significant, confirming larger fluid depletion and reduced hydration efficiency in the morning (Table 1).

3.8. Skin and microclimate temperatures

Chest skin temperature was higher in AM (37.51 ± 0.54 vs 37.01 ± 0.45 °C; $p < 0.001$); maximum values reached 38.70 ± 0.72 vs 37.84 ± 0.51 °C. Neck temperature showed no time-of-day difference ($p = 0.45$). Under-PPE temperature remained similar (42.0 ± 4.0 vs 41.9 ± 3.4 °C; $p = 0.88$), while relative humidity was higher in AM (83.9 ± 6.3 vs 80.1 ± 6.8 %; $p < 0.001$; Table 1).

3.9. Physiological Strain Index (PSI)

The Physiological Strain Index (PSI), computed from core temperature and heart-rate kinetics, reached very high values in both conditions. PSI_AM was 9.88 ± 0.12 and PSI_PM was 9.84 ± 0.15 ($p = 0.041$, $dz = 0.32$, $\eta p^2 = 0.05$). Although the morning session showed slightly higher strain, the absolute difference was very small due to ceiling effects: 18 of 21 participants reached PSI ≥9.8 in AM, and 17 of 21 reached PSI ≥9.8 in PM, with several individuals attaining the maximum score of 10 in both exposures.

This pattern indicates that under the static, high-radiant-load live-fire conditions used here, the PSI rapidly approached its upper limit regardless of circadian phase. As a consequence, the PSI was less sensitive than ΔTcore, ΔTcore slope, AUC, cardiovascular responses and hydration markers for detecting time-of-day differences in thermoregulatory strain. The near-saturation of the index reflects the extreme physiological load imposed by the CFBT scenario, rather than an absence of circadian modulation.

4. Discussion

Thermal conditions during live-fire exercises were rigorously standardized across late-morning (AM) and late-evening (PM) sessions. Identical fuel loads, ventilation sequences, and container configurations produced nearly superimposable vertical thermal gradients and under-PPE microclimate profiles (Fig. 1, Table 1). This high degree of environmental reproducibility confirms that the marked physiological differences observed between AM and PM exposures predominantly reflect internal, biological modulation—principally circadian phase—rather than variations in external heat stress.

Despite equivalent environmental heat loads, thermophysiological strain was substantially greater during late-morning exposure. Core temperature increased by +1.61 °C in AM compared to +0.61 °C in PM, with a ΔT_core slope more than doubled (0.028 vs. 0.012 °C·min^{-1}). This occurred despite lower baseline T_core in AM (36.5 °C vs. 37.1 °C). Cardiovascular responses mirrored this pattern, with higher mean (170 bpm) and peak (181 bpm) heart rates in AM than in PM (mean:164 bpm and peak:176 bpm), alongside greater perceived exertion (RPE 16.5 vs. 15.7). Hydration markers also differed: body-mass loss was −1.75 kg in AM versus −1.32 kg in PM, and TBW declined more in AM (−0.78 % vs. −0.44 %). Under-PPE microclimate humidity was slightly but consistently higher in AM (~84 % vs. ~80 %), indicative of reduced evaporative efficiency. Together, these findings reveal a robust circadian influence on heat tolerance during compartment-fire behaviour training.

This pattern is coherent with established chronobiological mechanisms. Thermolytic capacity is known to be reduced during the morning "heat-gain" phase, with lower sudomotor and vasodilatory

Table 1
Summary of physiological, thermal, and perceptual responses to live-fire training at two times of day.

Variable	Main effect TOD (AM vs PM)	Main effect Time	Interaction (TOD × Time)	Notes/Effect size/Comment
Resting Tcore (day-off vs experimental)	PM > AM ($p < 0.001$)	ns	ns	Circadian elevation +0.60 ± 0.45 °C PM–AM.
Baseline Tcore (experimental)	AM 36.54 ± 0.37/PM 37.15 ± 0.32 ($p < 0.001$)	–	–	Starting difference ≈ +0.61 °C.
ΔTcore slope (°C·min^{-1})	AM 0.028 ± 0.003 > PM 0.012 ± 0.002 ($p < 10^{-16}$)	$p < 0.001$	$p < 10^{-82}$	Faster heat storage AM ($\eta p^2 = 0.975$).
ΔTcore 40 min (°C)	AM +1.10 ± 0.25 > PM +0.49 ± 0.21 ($p < 10^{-16}$)	$p < 10^{-115}$	$p < 10^{-82}$	Nearly × 2 higher in AM.
AUC ΔTcore (°C·min)	AM 22.97 ± 3.10 > PM 13.11 ± 2.85 ($p < 10^{-15}$)	–	–	Large cumulative heat gain ($d_z = -3.58$).
Peak Tcore (°C, 0–40 min)	ns (AM 37.64 ± 0.32/PM 37.64 ± 0.32; $p = 0.996$)**	$p < 0.001$	ns	Convergent plateau ≈ 37.64 °C.
Post-exit after-rise (°C)	AM +0.51 ± 0.09 > PM +0.11 ± 0.05 ($p = 0.0016$)	$p \leq 0.006$	$p \leq 0.006$	Delayed peak: AM +40 min/PM +32 min.
Cooling slope (°C·h^{-1})	AM −0.37 ± 0.06 < PM −0.63 ± 0.08 ($p < 0.001$)	$p < 0.001$	ns	Slower thermal recovery AM.
Time to Day-Off alignment (hh:mm)	AM 3 h 06 ± 0 h 18 > PM 2 h 26 ± 0 h 14	–	–	To Cosinor intersection ≈ AM 3 h 54/PM 2 h 42.
Hypothermic rebound amplitude (°C)	AM −0.22 ± 0.06/PM −0.18 ± 0.05	–	–	Post-recovery dip below circadian baseline.
Thermal decompensation onset (min)	AM 26 ± 5 < PM 34 ± 6 ($p = 0.003$)	–	–	Earlier transition AM (compensation→decomp.).
HR_mean (bpm)	AM 170 ± 9 > PM 164 ± 8 ($p = 0.009$)	$p < 0.001$	ns	Greater cardiovascular load AM.
HR_mean (% pred. HR_max)	AM 89.7 ± 4.5 % > PM 86.4 ± 4.9 % ($p < 0.01$)	–	–	–
HR_max (bpm)	AM 181 ± 10 > PM 176 ± 9 ($p = 0.017$)	–	–	–
HR_max (% pred. HR_max)	AM 95.4 ± 5.0 % > PM 92.5 ± 5.2 % ($p = 0.021$)	–	–	–
RPE (AU)	AM 16.9 ± 0.8 > PM 15.9 ± 0.9 ($p = 0.007$)	–	–	Higher perceptual strain AM.
Body-mass loss (kg)	AM 0.60 ± 0.22 > PM 0.40 ± 0.18 ($p = 0.023$)	$p < 0.001$	$p = 0.023$	Pre–post AM 78.4 → 77.8/PM 80.1 → 79.7.
Body-mass loss (%)	AM −2.17 ± 0.33 > PM −1.62 ± 0.26 ($p < 10^{-7}$)	–	–	–
TBW loss (%-points)	AM −0.9 ± 0.3 > PM −0.4 ± 0.2 ($p < 0.001$)	$p < 0.001$	$p < 0.001$	Lower hydration AM.
Chest skin temperature (°C)	AM 37.51 ± 0.54 > PM 37.01 ± 0.45 ($p < 0.001$)	$p < 0.001$	ns	T_max AM 38.70 ± 0.72/PM 37.84 ± 0.51.
Neck skin temperature (°C)	ns ($p = 0.45$)	$p < 0.001$	ns	T_max AM 60.6 ± 5.0/PM 61.9 ± 6.0.
Under-PPE temperature (°C)	ns ($p = 0.88$)**	$p < 0.001$	ns	Mean 42.0 ± 4.0 (AM) vs 41.9 ± 3.4 (PM); T_max 54.0 ± 6.7 vs 54.3 ± 5.2.
Under-PPE relative humidity (%)	AM 83.9 ± 6.3 > PM 80.1 ± 6.8 ($p < 0.001$)	$p < 0.001$	ns	RH_max 96.1 ± 4.8 > 92.9 ± 5.6 ($p < 0.001$)**.
Air temp 0.10 m (°C)	AM ≈ PM ($F = 0.00$, $p = 0.995$)	Strong rise over time ($F = 807.3$, $p < 0.001$)	ns	AM–PM mean Δ ≈ 0.00 °C (0–40 min). Identical burn profiles; Mean ± SD: AM: 42.46 °C ± 8.51 °C vs PM: 42.46 °C ± 8.46 °C
Air temp 0.50 m (°C)	AM ≈ PM ($F = 0.12$, $p = 0.73$)	Strong time effect ($F = 304.58$, $p < 0.001$)	ns	AM–PM Δ ≈ +1.00 °C; Mean ± SD: AM: 87.47 °C ± 27.63 °C vs PM: 86.47 °C ± 48.17 °C
Air temp 1.00 m (°C)	AM ≈ PM ($F = 0.00$, $p = 0.995$)	Strong time effect ($F = 236.57$, $p < 0.001$)	ns	AM–PM Δ ≈ +0.03 °C; Mean ± SD: AM: 146.04 °C ± 49 °C vs PM: 146 °C ± 49.17 °C
Air temp 1.50 m (°C)	AM ≈ PM ($F = 0.16$, $p = 0.695$)	Strong time effect ($F = 129.56$, $p < 0.001$)	ns	AM–PM Δ ≈ +0.58 °C; Mean ± SD: AM: 196 °C ± 60 °C vs PM: 195 °C ± 56 °C
Air temp 2.30 m (°C)	AM ≈ PM ($F = 0.13$, $p = 0.724$)	Strong time effect ($F = 85.69$, $p < 0.001$)	ns	AM–PM Δ ≈ +10.16 °C; Mean ± SD: AM: 487 °C ± 168 °C vs PM: 477 °C ± 157 °C

Values are presented as mean ± SD unless otherwise indicated. AM = 09:00 h exposure (late-morning, heat-gain phase); PM = 21:30 h exposure (late-evening, heat-loss phase); TOD = time of day. Tcore = core temperature; TBW = total body water; RPE = rating of perceived exertion; RH = relative humidity.
Main effects and interactions were analysed using repeated-measures ANOVA or linear mixed-effects models with Holm correction. Significant differences ($p < 0.05$) are reported for main effect of time of day (AM vs PM), main effect of time (Pre vs Post, or within-exposure change), and their interaction (TOD × Time).
Thermal decompensation refers to the transition from compensated heat storage to net heat gain exceeding dissipation, while Tcore–D-Off denotes the post-exposure hypothermic rebound below the circadian reference curve.

responsiveness (Waterhouse et al., 2004, 2007; Aldemir et al., 2000; Otani et al., 2020; Edwards et al., 2025; Reilly and Brooks, 1986; Torii et al., 1995; Racinais, 2010). Afternoon and evening exposures typically elicit more effective heat dissipation, provided that evaporation and convection are available. Classical work (Reilly and Brooks, 1986; Otani et al., 2017) and more recent studies (Aldemir et al., 2000; Otani et al., 2017, 2019) consistently report greater morning heat storage for identical workloads, whereas under moderate, dry conditions some studies find minimal circadian modulation (Ravanelli and Jay, 2021). The extreme radiant load, saturated humidity, and convective restriction inherent to PPE and CFBT likely amplify these intrinsic circadian differences, creating conditions in which biological timing becomes physiologically consequential.

A delayed rise in core temperature following exit—peaking 30–40 min post-exposure—was observed in both AM and PM sessions. This "redistribution" phase reflects continued heat transfer from peripheral

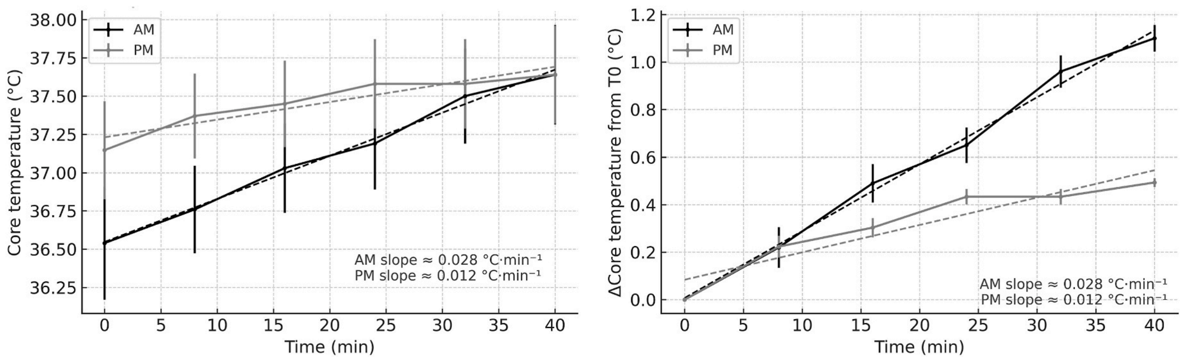

Fig. 3. Core temperature (Tcore) and change from baseline (ΔTcore) during live-fire compartment exposure. Left panel: Absolute Tcore trajectories (mean ± SD) for 21 firefighters during 40 min of exposure performed in the morning (AM, black) or late-evening (PM, grey). Right panel: ΔTcore (change from individual baseline at 0 min) over the same period. Core temperature increased significantly over time in both sessions ($p < 0.001$), but the rise was steeper and larger in the AM condition, leading to a significant Condition × Time interaction ($p < 10^{-82}$). PM exposures started from a slightly higher baseline yet accumulated less internal heat, while AM exposures produced a greater ΔTcore despite cooler initial values. Error bands represent standard deviation across subjects. Mean (SD) change in core temperature values (ΔTcore) during the 40-min container exposure, where values were averaged in 8-min bins from baseline (T0). AM (black circles/solid line) and PM (grey squares/dashed line). Straight lines are least-squares fits to group means (AM slope ≈ 0.028 °C·min^{-1}, PM slope ≈ 0.011 °C·min^{-1}). Repeated-measures ANOVA showed main effects of Condition ($F(1,20) = 411.07$, $p < 10^{-13}$, $\eta p^2 = 0.954$) and Time ($F(4,80) = 1470.19$, $p < 10^{-73}$, $\eta p^2 = 0.987$), and a significant Condition × Time interaction ($F(4,80) = 768.00$, $p < 10^{-62}$, $\eta p^2 = 0.975$), indicating a steeper rise in the morning.

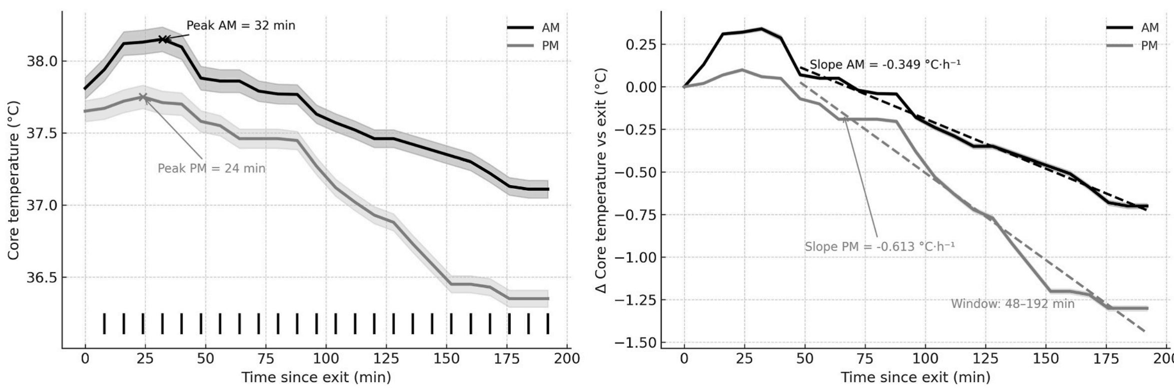

Fig. 4. Post-exposure Tcore recovery following live-fire training (n = 21). Left panel: Absolute Tcore from container exit (T = 00:40; Time 0). Curves show mean ± SD for AM (black) and PM (grey); short vertical ticks on the x-axis mark time points with AM ≠ PM after Holm correction ($p < 0.05$). Group-mean peaks occurred at +40 min (AM) and +32 min (PM). Right panel: Change in Tcore relative to exit (ΔTcore = T_t − T_exit), mean ± SD. Dashed segments are linear fits over a common recovery window (48–192 min), yielding cooling slopes of −0.367 °C·h^{-1} (AM) and −0.626 °C·h^{-1} (PM), indicating slower morning cooling. Sampling interval: 8 min. A mixed-effects model with polynomial time terms (Time-of-day × [time, time^2]) confirmed higher Tcore in AM across recovery and a significant interaction ($p \leq 0.006$).

tissues toward the core while PPE insulation and limited air flow restrict convective and evaporative cooling (McEntire et al., 2013). This phenomenon underscores that instantaneous post-exit T_core values underestimate total heat burden and highlights the need for extended monitoring following high-intensity thermal exposures.

Several hours later, both sessions exhibited a hypothermic rebound, more pronounced after morning exposure (approximately −0.25 to −0.30 °C below baseline). Such post-hyperthermia decompensation has been described following exercise and passive heating (Cramer and Jay, 2015; Flouris and Schlader, 2015) and is associated with sustained vasodilation, continued sweating, and autonomic down-regulation. These mechanisms have been linked to transient reductions in alertness and psychomotor performance (McLellan and Havenith, 2016b; Valdez, 2019), and although the present study did not assess cognitive function directly, the temporal alignment with documented fatigue-related incidents among emergency responders is notable (Patterson et al., 2012).

Quantitatively, the observed physiological strain remained within reported limits for controlled flashover-training environments. Peak core temperatures (~38.1 °C) did not approach the extreme hyperthermias (>40 °C) documented in uncontrolled firefighting scenarios. Under-PPE temperatures (54–65 °C) and humidity (>90 %) were consistent with prior research (Eglin, 2007; Eglin et al., 2004; Perroni et al., 2014; Watt et al., 2016; Smith and Petruzzello, 1998). Heart-rate responses (~170 bpm, ~90 % HR_max) also matched values previously observed in firefighter-instructor populations (Watt et al., 2016). These convergences reinforce both the safety and ecological validity of the protocol and the reliability of the circadian effects identified.

Although outdoor temperature differed slightly between morning and evening (~1.5 °C cooler in PM), this effect was minor compared with the extreme internal thermal load and did not influence the equivalence of AM–PM live-fire conditions. The brief outdoor phase (≈15 min) served mainly to remove PPE and initiate supervised decompression, but core-temperature data confirmed that thermal strain patterns were driven by circadian phase rather than by external microclimatic differences.

Finally, the Physiological Strain Index (PSI) approached its upper limit (~10) in both sessions, reflecting the extreme thermal and cardiovascular load of CFBT. Under such conditions, PSI becomes less discriminative than ΔT_core, core-temperature slope, or hydration markers. High PSI values should therefore be interpreted as a consequence of near-maximal strain rather than as an absence of circadian

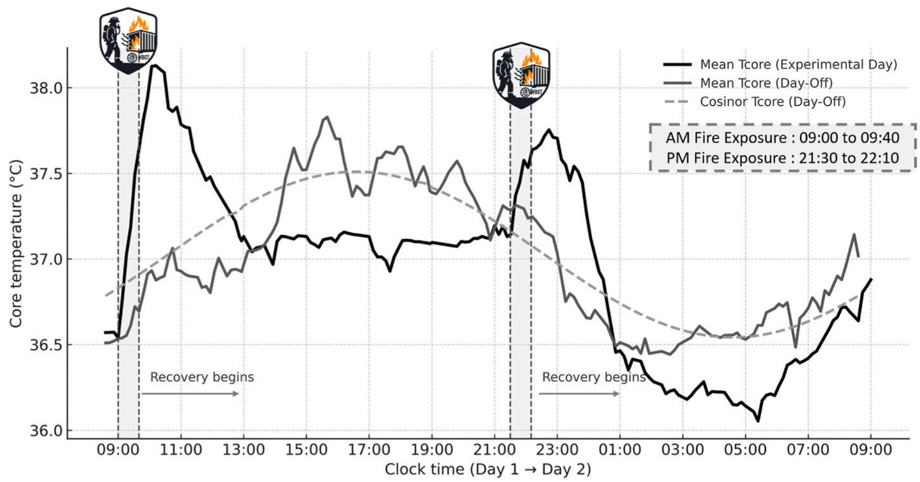

Fig. 5. Core body temperature (Tcore) during baseline, live-fire training, and post-exposure recovery (n = 21). Mean ± SD core temperature across Day-Off (grey), Experimental Day (black), and Cosinor-fit Day-Off (dashed line). Shaded areas indicate live-fire exposure periods in the training container (AM = 09:00–09:30; PM = 21:30–22:10). Vertical dashed lines mark exposure limits and the onset of post-exposure recovery ("Recovery begins"). Core temperature rose transiently after each exposure before progressively declining toward baseline overnight. The recovery of core body temperature was slower in the morning than in the late-evening. To return to levels comparable to Tcore Day-Off, approximately 3 h 06 were required, or 3 h 54 when considering the intersection with the Day-Off cosinor curve. In the late-evening session, recovery was shorter, requiring 2 h 26 to 2 h 42 for the temperature curve to intersect the Day-Off cosinor and the Day-Off Tcore minimum, respectively.

modulation, which is clearly evidenced by multiple physiological systems in this study.

Overall, the present findings demonstrate that circadian phase strongly modulates thermophysiological responses during structurally identical live-fire exposures. These results extend laboratory chronobiology into a high-radiance, high-humidity, PPE-restricted setting, highlighting the need to incorporate biological timing when interpreting physiological strain in firefighting contexts. Further research should examine how circadian phase interacts with sleep status, hydration strategies, repeated exposures, and operational workloads to influence safety and performance in real-world settings.

5. Conclusion

This study demonstrates that, under strictly standardized live-fire training conditions, circadian phase markedly influences thermophysiological strain. Late-morning exposures elicited faster and greater increases in core temperature, higher cardiovascular load, and greater fluid losses than equivalent late-evening exposures. These findings indicate that the late-morning period represents a window of reduced heat tolerance, even when external thermal load is held constant.

Although thermal responses remained within expected limits for controlled flashover training, the persistence of a post-exposure afterrise and the occurrence of a delayed hypothermic rebound highlight the complexity of thermal recovery in this environment. The extreme nature of the heat stress also limited the sensitivity of certain indicators—such as the PSI—which tended toward ceiling values.

This study has limitations, including the exclusive inclusion of male participants, the assessment of acute rather than repeated exposures, and the absence of direct measures of vigilance or cognitive performance. Minor variations in combustion or ventilation cannot be fully excluded despite careful environmental control.

Overall, these findings underline the importance of integrating circadian considerations when interpreting thermal strain during live-fire training. Future studies should examine how circadian phase influences performance, safety, and longer-term physiological adaptation in operational firefighting contexts.

CRediT authorship contribution statement

Benoit Mauvieux: Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Adrian Markov:** Writing – review & editing. **Stéphane Besnard:** Writing – review & editing. **Yvan Touitou:** Writing – review & editing. **Ben J. Edwards:** Writing – review & editing, Data curation.

Ethical approval

All procedures were conducted in accordance with the Declaration of Helsinki and approved by the Comité de Protection des Personnes Est I, France (AFSSAPS No. 2010-A00485-34).

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yvan Touitou reports financial support was provided by Fonds National de la Prévention (CNRACL). Yvan Touitou reports financial support was provided by Adolphe de Rothschild Foundation Hospital. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The dataset supporting this article is available on Mendeley Data at https://data.mendeley.com/drafts/7ghxcsd9sz (private link for reviewers; public access upon publication).

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