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Title

A comparison of heat acclimation by post-exercise hot water immersion and exercise in the heat

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ABSTRACT

Objectives: To compare heat acclimation adaptations after three and six days of either post-exercise hot water immersion (HWI) or exercise-heat-acclimation (EHA) in recreationally active individuals.

Design: Randomised, mixed model, repeated measures.

Methods: Post-exercise HWI involved a daily 40-min treadmill-run at 65% $\dot{V}O_{2peak}$ in temperate conditions (19°C, 45% RH) followed by HWI ($\leq$ 40 min, 40°C water; n=9). Daily EHA involved a $\leq$60-min treadmill-run in the heat (65% $\dot{V}O_{2peak}$; 33°C, 40% RH; n=9), chosen to elicit a similar endogenous thermal stimulus to HWI. A thermoneutral exercise intervention (TNE, 19°C, 45% RH; n=9), work-matched to EHA, was also included to determine thermoregulatory adaptations to daily exercise in temperate conditions. An exercise heat-stress-test was performed before and after three and six intervention days and involved a 40-min treadmill-run and time-to-exhaustion (TTE) at 65% $\dot{V}O_{2peak}$ in the heat (33°C, 40% RH).

Results: ANCOVA, using baseline values as the covariate, revealed no interaction effects but significant group effects demonstrated that compared to EHA, HWI elicited larger reductions in resting rectal temperature (T_{re}; p=0.021), T_{re} at sweating onset (p=0.011), and end-exercise T_{re} during exercise-heat-stress (−0.47°C; p=0.042). Despite a similar endogenous thermal stimulus to HWI, EHA elicited a modest reduction in end-exercise T_{re} (−0.26°C), which was not different from TNE (−0.25°C, p=1.000). There were no main effects or interaction effects for end-exercise T_{sk}, heart rate, physiological strain index, RPE, thermal sensation, plasma volume, or TTE (all p≥0.154).

Conclusion: Compared with conventional short-term exercise heat acclimation, short-term post-exercise hot water immersion elicited larger thermal adaptations.

Keywords: acclimatization, endurance training, running, thermotolerance, performance, hot bath.

INTRODUCTION

In preparation for competing or working in the heat, athletes, military personnel and occupational workers who reside in temperate conditions are advised to complete a period of heat acclimation.[1, 2] Heat acclimation adaptations, that improve endurance capacity and reduce susceptibility to exertional heat illness,[3] include an earlier onset of cutaneous vasodilatation and sweating, an increase in sweating rate, and a reduction in resting and exercising body temperature.[4, 5] Recommendations to maximise adaptations are to complete ≥ 15 daily exercise heat acclimation exposures (long-term heat acclimation), which initiate profuse sweating and maintain an elevated body temperature for ≥ 60 min.[3, 6] However, protocols can be costly, impractical, ineffective as trained individuals are considered partially heat acclimatised,[7, 8] and the physical demands of daily exercise-heat-stress can disrupt training and lead to fatigue.[6, 9] As a consequence, athlete engagement with long-term exercise heat acclimation is poor.[1] To reduce the time commitment, sport scientists have designed short-term heat acclimation interventions (≤ 7-days), supported by the premise that ~80% of adaptations occur in 7-days.[10] However, research investigations report inconsistent reductions in core body temperature at rest and during exercise-heat-stress following short-term exercise heat acclimation.[11]

Post-exercise passive heating, such as sauna bathing[12] and hot water immersion (HWI),[13-15] provide alternative, more accessible and time efficient heat acclimation strategies compared to conventional exercise-based approaches. These exposures to hot air/water can be incorporated into normal training, e.g., HWI as part of a post-exercise washing routine, and may also support muscle recovery.[16] Six days of post-exercise HWI presents a short-term heat acclimation strategy, which provides reductions in thermal strain that compare favourably with long-term interventions.[11] HWI exposes individuals to a large dual thermal stimulus (i.e. elevated core and skin temperatures), which is purported to induce a more complete state of heat acclimation.[17] Furthermore, exposure to high skin temperatures has been shown to accelerate heat acclimation adaptation in females.[18]

The primary aim of the current study was to compare thermal adaptations from three and six days of post-exercise HWI with exercise heat acclimation (EHA) in recreationally active males. In addition, by including a work-matched thermoneutral exercise intervention (TNE), we investigated the individual contributions of daily submaximal exercise and heat stress to adaptation following EHA. We hypothesised that post-exercise HWI would accelerate the speed of adaptation compared to EHA, and that the benefits of EHA beyond that of TNE would be modest.

METHODS

Participants: Twenty-seven recreationally active and non-heat-acclimatised males provided written informed consent to participate. The study received local and Ministry of Defence Research Ethics Committee approval and was conducted following the Declaration of Helsinki (2013; although was not pre-registered) and received Defence Science and Technology Laboratory permission to publish. Participants were matched for fitness characteristics in groups of three and randomly assigned to either HWI, EHA, or TNE (randomiser.org; see Table 1 for participant characteristics). HWI involved a 40-min treadmill-run in temperate conditions (19°C) followed by hot water immersion (≤ 40-min, 40°C water). To elicit a similar endogenous thermal stimulus to HWI (i.e. area under the curve, AUC, time and magnitude T_{re} was >38.5°C, $°C \cdot min^{-1}$; Supplement A), EHA involved a ≤ 60-min treadmill-run in the heat (33°C, 40% RH). Pilot data demonstrated a similar AUC from post-exercise HWI[12] *vs*. a 60-min treadmill run in the heat (65%$\dot{V}O_{2peak}$; 33°C, 40% RH). We deemed it unnecessary to include a thermoneutral water immersion intervention as we have previously demonstrated that it provides no heat acclimation benefits.[15] We did however include a thermoneutral exercise intervention (TNE) to account for the effect of daily submaximal exercise on thermoregulatory adaptations. To enable work-matching with EHA, TNE participants completed the same external work ≥ 1-day after EHA participants.

Table 1. Participant characteristics of post-exercise hot water immersion (HWI), exercise heat acclimation (EHA) and thermoneutral exercise (TNE).

	HWI	**EHA**	**TNE**
Age (years)	22 ± 3	20 ± 2	21 ± 2
Height (cm)	177 ± 5	181 ± 5	178 ± 6
Body mass (kg)	73 ± 7	74 ± 7	70 ± 7
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	53 ± 6	54 ± 3	53 ± 4

Data are displayed as mean ± SD. N = 9, each group.

Fig. 1 near here

Fitness assessment: Participants completed a fitness assessment within a week before their first experimental trial. $\dot{V}O_{2peak}$ was assessed using a continuous maximal incremental exercise test performed on a motorised treadmill (HP Cosmos Mercury 4.0, Nussdorf-Traunstein, Germany) in a temperate laboratory (19°C) to volitional exhaustion. $\dot{V}O_{2peak}$ was determined as the highest oxygen uptake attained over a 30-s period. A running speed that elicited 65% $\dot{V}O_{2peak}$ in temperate conditions was determined by the interpolation of the running speed–$\dot{V}O_2$ relationship. Participants were then familiarised with the treadmill running speed and experimental trial procedures. As temperate training influences heat acclimation adaptations,[7] participants' physical activity time (> 3 METS) for the duration of the study was assessed (Fitbit Flex, San Francisco, USA).

Experimental trials: Participants completed three experimental trials: before and after three, and six days of their assigned intervention (Fig. 1). Twenty-four hours before experimental trials, participants refrained from exercise, alcohol, diuretics, and caffeine. Before the first experimental trial, participants completed a diet diary and replicated this food and fluid intake before subsequent experimental trials. To ensure a similar circadian pattern, participants were instructed to sleep between 2200-h and 0700-h before experimental trials; sleep duration and quality were confirmed (Actigraph wGT3X-BT, Actigraph, Pensacola, USA).

On the day of the experimental trials (Fig. 1), participants arrived at the laboratory at 0730-h and were provided with a standardised breakfast (2091 kilojoules, 71 g carbohydrate, 18 g fat, 17 g protein) and a bolus of water ($7\ mL\cdot kg^{-1}$ of body mass). Following 20-min seated rest in temperate conditions (19°C, 45% RH), participants completed the Profile of Mood States questionnaire[19] to determine total mood disturbance and energy index (vigour–fatigue), to detect perceived training-induced fatigue. A venous blood sample was taken without stasis and total haemoglobin mass, blood volume, and plasma volume were assessed using the optimised carbon monoxide rebreathing technique.[20] Briefly, aliquots of whole blood were used for the immediate determination of haemoglobin concentration ($g\cdot dL^{-1}$), in duplicate (Hemocue, Sheffield, UK) and haematocrit (%), in triplicate (capillary tube method). Total haemoglobin mass was estimated from the percentage change in carboxyhaemoglobin concentration (ABL80 CO-OX Flex hemoximeter Radiometer; Copenhagen, Denmark) measured in duplicate from earlobe capillary blood samples collected before and after rebreathing a mixed bolus of (0.8 mL·kg^{-1} body mass) carbon monoxide (99.9%) and oxygen (3 L, 99.5%). Total haemoglobin mass, haemoglobin concentration and haematocrit (%) was used to calculate blood volume (mL; [haemoglobin mass / haemoglobin concentration] × 100) and red cell mass (mL; blood volume × [haematocrit / 100]) for the calculation of plasma volume (mL; = blood volume − red cell mass).[20] A urine sample was analysed using a handheld refractometer (Atago Uricon-Ne refractometer, NSG Precision cells, New York, USA); exercise began when urine specific gravity was < 1.03.[21] A rectal thermistor (Henleys Medical Supplies Ltd., Herts, UK), fitted 10 cm beyond the anal sphincter, and a data logger (YSI model 4000A; YSI, Dayton, Ohio, USA) provided a measure of rectal core temperature (T_{re}). A pre-exercise nude body mass was recorded using a digital platform scale (Model 703; Seca, Hamburg, Germany). Skin thermistors (Grant EUS-U, Cambridge, UK) were attached on the right side of the body (on the chest at a midpoint between the acromion process and the nipple, the lateral mid-bicep, the anterior mid-thigh and lateral calf) and recorded using a data logger (Grant SQ2020, Cambridge, UK); mean skin temperature (T_{sk}) was calculated using the following four-site weighted equation: $T_{\mathrm{sk}} = 0.3(T_{\mathrm{chest}} + T_{\mathrm{arm}}) + 0.2(T_{\mathrm{thigh}} + T_{\mathrm{calf}})$.[22] Following instrumentation, participants rested for a further 30-min in temperate conditions (19°C, 45% RH) to establish baseline measures.

At 0945-h, dressed in shorts, socks, and trainers, participants entered the environmental chamber (Delta Environmental Systems, Chester, UK; 33°C, 40% RH; 0.2 m·s^{-1} wind velocity) to complete a 40-min treadmill run at 65% $\dot{V}O_{2\mathrm{peak}}$. No fluids were consumed and T_{re}, skin temperatures, and heart rate (Polar FT1, Polar Electro, Kempele, Finland) were monitored continuously. Local forearm sweat rate was measured by dew point hygrometry. Anhydrous compressed nitrogen was passed through a 5-cm^2 capsule affixed to the lower arm ventral surface (halfway between the antecubital fossa and carpus) and connected to a hygrometry system (DS2000; Alpha Moisture Systems, UK). Local forearm sweating rate was calculated using the difference in water content between effluent and influent air and the flow rate (1 L·min^{-1}) and normalised for the skin surface area under the capsule (expressed in milligrams per square centimetre per minute). T_{re} at sweating onset was determined by plotting the relationship between local forearm sweat rate and T_{re} (recorded at 20-s intervals) before using segmented linear regression to identify the breakpoint in the two line segments.[23] Rating of perceived exertion (RPE),[24] thermal sensation,[25] oxygen uptake ($\dot{V}O_2$) and respiratory exchange ratio (RER), assessed by the Douglas bag method, were recorded every 10-min. On completion of the exercise, participants rested for 20-min in temperate conditions (19°C, 45% RH), during which they completed a modified Stroop test,[26], and provided a nude body mass to estimate whole-body sweat rate.

Participants then re-entered the environmental chamber and completed a TTE on a motorised treadmill at 65% $\dot{V}O_{2\mathrm{peak}}$. Participants were instructed to "run for as long as possible". TTE was terminated when participants stopped running owing to volitional exhaustion, thermal discomfort, or when T_{re} exceeded 39.5°C. No fluids were consumed, no feedback was provided, and T_{re} and heart rate were monitored continuously. Following the cessation of exercise, capillary blood lactate concentrations were assessed (Lactate Pro 2™, Arkray, Australia) as a marker of short-term overreaching. Participants were provided with a bolus of water and were free to leave the laboratory when $T_{\mathrm{re}} \leq$ 38.5°C.

Daily intervention: Each participant completed two, three consecutive day blocks of their assigned intervention (Fig. 1), during which they consumed their normal diet and fluid intake. Each day, participants arrived at the laboratory (0600-h and 1300-h), fitted a rectal thermistor to monitor T_{re}, and completed a 15-min seated rest in temperate conditions. Participants commenced their assigned intervention dressed in shorts, socks, and trainers. A bolus of water (5 $\mathrm{mL \cdot kg^{-1}}$ of nude body mass) was consumed during the first 20-min of exercise.

HWI involved a 40-min treadmill run in temperate conditions (65% $\dot{V}O_{2\mathrm{peak}}$; 19°C, 45% RH; 0.2 $\mathrm{m \cdot s^{-1}}$ wind velocity) followed by a semi-recumbent ≤ 40-min hot water immersion (40°C) to the neck, as described.[15] EHA and TNE involved a ≤ 60-min treadmill run at the predetermined speed that reflected 65% $\dot{V}O_{2\mathrm{peak}}$ (in temperate conditions) in hot (33°C, 40% RH; 0.2 $\mathrm{m \cdot s^{-1}}$ wind velocity) or temperate conditions (19°C, 45% RH; 0.2 m·s^{-1} wind velocity). Intervention sessions were terminated if maximal immersion or exercise duration was reached, at the participant's volition, or if T_{re} exceeded 39.5°C.

Statistical Analysis: A sample size estimation (G*Power 3.1.9)[27] was performed using data from post-exercise HWI (−0.36°C),[15] exercise heat acclimation (−0.22°C)[28] and thermoneutral exercise (0.00°C), with a pooled SD of 0.2°C. A one-way analysis of variance (ANOVA; alpha = 0.05, power = 0.8, correlation = 0.7) estimated that eight participants per group was required to detect a difference in the change in end-exercise T_{re} between groups. However, following statistical advice during the review process, a two-way mixed-methods analysis of covariance (ANCOVA) was considered the more appropriate and statistically powerful approach for comparing the effectiveness of interventions. To ensure adequate power and allowing for dropout, nine participants per group were recruited. All data were checked for normality and sphericity, presented as mean and standard deviation (SD), and statistical significance was accepted at $p<0.050$. Uncertainty in the true (population) values of effects is presented as 95% confidence intervals (CI). A two-way mixed model ANCOVA with baseline (PRE) as the covariate was used to compare hallmark heat acclimation adaptations (e.g., end-exercise T_{re}) across time (post three days *vs.* post six days) and between groups (HWI *vs.* EHA *vs.* TNE). The endogenous thermal stimulus and physical activity during each of the daily interventions was compared using a two-way mixed model analysis of variance (ANOVA). Bonferroni-adjusted pairwise comparisons were used where appropriate to determine where differences occurred. The magnitude of effect was reported using Cohen's *d*, where 0.2, 0.5, and 0.8 represent small, medium, and large effects, respectively.[29] Pearson's correlations determined the strength of the relationship between hallmark adaptations and changes in TTE. To assess endogenous thermal stimulus, the AUC was performed on the daily intervention T_{re} (time and magnitude T_{re} was >38.5°C) in each group using the trapezoid method.[30] A statistically meaningful change in end-exercise T_{re} was defined as −0.34°C based on the large beneficial effect observed in a recent meta-analysis.[11] Data were analysed using SPSS version 27 (IBM Corporation, NY, USA), or GraphPad Prism Version 9 (GraphPad Software Inc. La Jolla, USA).

RESULTS

Daily intervention: All participants completed six days of their assigned intervention. Differences in the daily endogenous thermal stimulus were observed between groups (main effect of group, *f*=29.756, p<0.001; Supplement A), for example, mean daily AUC for T_{re} > 38.5°C was similar in HWI and EHA (HWI, 17 ± 3°C·min^{-1}; EHA, 17 ± 7°C·min^{-1}; p=1.000) but lower in TNE (2 ± 3°C·min^{-1}; p<0.001; Supplement A). The daily endogenous thermal stimulus was maintained throughout the six-day intervention (main effect of time, *f*=0.035, p=0.853; interaction effect, *f*=1.019, p=0.376), owing to an increase (main effect of time, *f*=7.897, p=0.010) in mean daily HWI (days 1–3, 31 ± 6 min; days 6–8, 35 ± 5 min) and EHA duration (days 1–3, 49 ± 9 min; days 6–8, 54 ± 8 min) . Following a significant main effect of group (*f*=4.315, p=0.025), *post hoc* pairwise comparisons revealed that total external work was lower in HWI (37 ± 6 km) compared to EHA (48 ± 9 km, p=0.026), but no differences were detected between TNE (45 ± 9 km) and EHA (p=1.000), or between TNE and HWI (p=0.169). No differences were observed for daily physical activity time (> 3 METS) throughout the study protocol, evidenced by no main effects of time or group, and no interaction effect (all p≥0.423; Supplement A).

Hallmark heat acclimation adaptations: No differences were detected between groups for sleep duration (6 ± 1 h), sleep efficiency (86 ± 9%) or urine specific gravity (1.019 ± 0.007) before experimental trials, evidenced by no main effects of time or group, and no interaction effects (all p≥0.336). A two-way mixed model ANCOVA, with baseline as the covariate, detected a main effect of group for resting T_{re} (*f*=6.438, p=0.006, Fig. 2A and C), end-exercise T_{re} (*f*=5.299, p=0.013, Fig. 2B and D), T_{re} at sweating onset (*f*=7.633, p=0.003), and whole-body sweat rate (*f*=7.633, p=0.001, Supplement B); there were no main effects of time or interaction effects (all p≥0.144). *Post hoc* pairwise comparisons revealed that HWI elicited a larger reduction in resting T_{re} (baseline-adjusted: −0.38 ± 0.23°C, CI: −0.26 to −0.49°C, *d*=1.6) compared to EHA (−0.14 ± 0.23°C, CI: −0.03 to −0.26°C, p=0.021, *d*=0.6) and TNE (−0.12 ± 0.23°C, CI: −0.01 to −0.24°C, p=0.011, *d*=0.5; Fig. 2A). Similarly, the reduction in end-exercise T_{re} was larger following HWI (−0.47 ± 0.23°C, CI: −0.36 to −0.58°C, *d*=2.1) compared to EHA (−0.26 ± 0.24°C, CI: −0.15 to −0.38°C, p=0.042, *d*=1.1) and TNE

(−0.25 ± 0.23°C, CI: −0.14 to −0.37°C; p=0.025, d=1.1; Fig. 2B). Furthermore, HWI elicited a statistically meaningful decrease in end-exercise T_{re} (i.e. ≥0.34°C reduction)[11] after only three days. No differences were observed between EHA and TNE for resting T_{re} (p=1.000) or end-exercise T_{re} (p=1.000). T_{re} at sweating onset was reduced in accordance with resting T_{re}, with reductions being larger following HWI compared with EHA (p=0.011) and TNE (p=0.005; Supplement B); no differences were observed between EHA and TNE (p=1.000). Whole-body sweat rate was greater following HWI (p=0.001) and EHA (p=0.009) compared to TNE, but no difference was detected between HWI and EHA (p=0.950; Supplement B). The change in T_{re} during the 40-min treadmill-run in the heat was lower at POST6 compared to at POST3, evidenced by a main effect of time (f=4.444, p=0.046, Supplement B); however, no differences were detected between groups (main effect of group, f=1.046, p=0.368; interaction effect, f=1.046, p=0.368). No main effects of time or group, and no interaction effects were detected for end-exercise T_{sk}, heart rate, physiological strain index, RPE, thermal sensation, plasma volume, blood volume, total haemoglobin mass, mean $\dot{V}O_2$ or mean RER (all p≥0.154; Supplement B).

Fig. 2 near here

Seven participants were removed from the TTE analysis owing to: reaching the T_{re} ethical cut-off (HWI, n=2); going to the toilet (EHA, n=1); lower limb discomfort (TNE, n=1); exercise-induced bronchoconstriction (TNE, n=1); nausea (TNE, n=1); and an obvious lack of effort without markers of overreaching at rest (TNE, n=1). No main effects of time or group, and no interaction effects (all p≥0.416) were observed in the remaining 20 participants who completed the TTE protocol (7 HWI; 8 EHA; 5 TNE; Supplement C). Correlational analysis revealed that the change in TTE was associated with the magnitude of adaptation in end-exercise T_{re} ($r = -0.47$, p=0.019), end-exercise physiological strain index ($r = -0.54$, p=0.008), and whole-body sweat rate ($r = 0.49$, p=0.013). There were no main effects of time or group, and no interaction effects detected for markers of short-term overreaching (all p≥0.172), including: mood disturbance, energy index, Stroop reaction time, Stroop accuracy, end-TTE heart rate, end-TTE blood lactate, and sleep efficiency. Although interestingly, the three EHA participants who experienced no improvement or a decline in endurance capacity (Supplement C) showed some signs of overreaching, evidenced by an increase in total mood disturbance (+29), and decreases in energy index (−15), sleep efficiency (−13%), and Stroop accuracy (−3%).

DISCUSSION

The current study sought to compare adaptations after three and six days of post-exercise HWI and EHA in recreationally active males. In addition, the individual contributions of daily submaximal exercise and heat stress to the adaptations following EHA were investigated. The novel finding is that short-term post-exercise HWI elicits larger thermal adaptations compared with short-term EHA. For example, resting T_{re} was lower following HWI (−0.38°C) compared to EHA (−0.14°C), which translated to a lower end-exercise T_{re} (−0.47°C) during exercise-heat-stress. Despite a similar daily endogenous thermal stimulus during HWI and EHA (Supplement A), the benefits of exercising in the heat beyond exercising in temperate conditions appear modest (end-exercise T_{re} reduction: EHA, −0.26°C; TNE, −0.25°C).

Post-exercise HWI initiated a large reduction in resting T_{re} (−0.38°C), which accounted for most of the reduction in end-exercise T_{re} during exercise-heat-stress (~81%). The induction of a large reduction in resting T_{re} following HWI is likely due to exposure to a large dual thermal stimulus (average end-immersion T_{re} was 39.3°C and T_{sk} was 40°C), which is purported to induce a more complete state of heat acclimation.[17] We contend that this dual thermal stimulus is necessary for meaningful heat acclimation adaptations to arise; a recent post-exercise HWI study eliciting an end-intervention T_{re} of only 38.4°C observed no further benefit compared to exercise in the heat alone.[31] Furthermore, the HWI protocol in the current study likely elicited a greater peripheral stimulus as skin temperature was continuously elevated for the whole immersion duration. In the present study, EHA had no effect on resting T_{re} beyond that of exercise in temperate conditions, despite eliciting a similar endogenous thermal stimulus to HWI. The larger reductions in resting T_{re}, end-exercise T_{re} and T_{re} at sweating onset after HWI compared to EHA are likely due to a higher skin temperature during the daily intervention (40°C *vs.* ~35°C). This finding is supported by previous work that demonstrated an accelerated rate of phenotypic adaptation when a high skin temperature was employed in conjunction with conventional exercise heat acclimation.[18] Research has linked the repeated elevation in skin temperature and activation of warm-sensitive neurons to the induction of hypothalamic neural network changes that reduce resting core temperature.[32] Accordingly, the induction of meaningful heat acclimation benefits is dependent upon the magnitude of both the endogenous thermal stimulus and skin temperature.[17] In addition, HWI may elicit haematological adaptations (e.g., plasma volume expansion) distinct from conventional exercise heat acclimation;[33] however, no differences were observed in plasma volume following the interventions.

The inclusion of a work-matched thermoneutral exercise intervention allows for insights into the individual influence of daily submaximal exercise and heat stress on adaptations in recreationally active participants. For example, after adjusting for baseline, ~96% of the reduction in end-exercise T_{re} following six days of EHA, was observed from daily thermoneutral exercise alone (−0.26°C *vs.* −0.25°C). Aligning with previous research,[11] EHA had a larger effect on increasing whole-body sweat rate compared to daily exercise in temperate conditions, but this did not translate to an improvement in endurance capacity in the heat. It is however worth noting that three EHA participants experienced either a decline or no change in TTE, coinciding with evidence of short-term overreaching (e.g. total mood disturbance and sleep efficiency).[34] The combined stressors of daily exercise-heat-stress could have exhibited these abnormal training responses within our recreationally active population.[34] As such, interventions should be undertaken with caution, while ensuring adequate time for recovery to minimise fatigue and ensure adaptations are fully realised.[6]

The reduction in end-exercise T_{re} following six days of post-exercise HWI in the present study (−0.47°C) exceeds that previously reported (−0.36°C).[15] This is likely explained by the lower aerobic fitness of the participants in the present study (53 $\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$ *vs.* 61 $\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$);[14] endurance-trained individuals are considered partially heat acclimatised and to have a reduced adaptation potential.[7, 8] Furthermore, the current study involved an additional exercise-heat exposure (experimental trial) and rest-day after three days (Fig. 1). It is possible that previous research, adopting a limited recovery period between the final heat acclimation bout and the exercise-heat-stress test, may underplay heat acclimation benefits, as the full effects may manifest after adequate recovery.[35]

While the data clearly demonstrate heat acclimation adaptations, findings on the effectiveness of the interventions for improving TTE should be considered with caution owing to the small sample size. As such, future work with a larger sample size is required to confirm (or reject) whether post-exercise HWI provides favourable improvements in endurance capacity in the heat compared to EHA. We also recognise that while the approach used in the current study allowed us to examine the importance of the dual thermal stimulus for heat acclimation adaptation, mean body temperature (calculated from core and skin temperature) was likely higher during HWI compared to EHA. Hence, further research is required to determine whether post-exercise HWI compares favourably to EHA when mean body temperature is matched.

Conclusion

Short-term post-exercise HWI intervention elicited larger thermal adaptations compared with conventional short-term exercise heat acclimation. In addition, the thermal benefits of conventional short-term exercise heat acclimation beyond exercising in temperate conditions appear modest.

Practical Implications

- Conventional short-term fixed intensity exercise heat acclimation initiates inconsistent and relatively modest thermal adaptations.
- Short-term post-exercise hot bath intervention initiates larger thermal adaptations compared with conventional short-term exercise heat acclimation.
- Taking a hot bath submerged to the neck, for up to 40 min, following habitual training in temperate conditions, presents a practical and economical heat acclimation intervention — eliminating the requirement for an increased training load, access to an environmental chamber or relocation to a hot climate.
- To facilitate adaptations from the post-exercise hot bath intervention, exposure to a large dual thermal stimulus (i.e. maintained elevation in both core temperature > 38.5°C and skin temperature ~40°C) is required.

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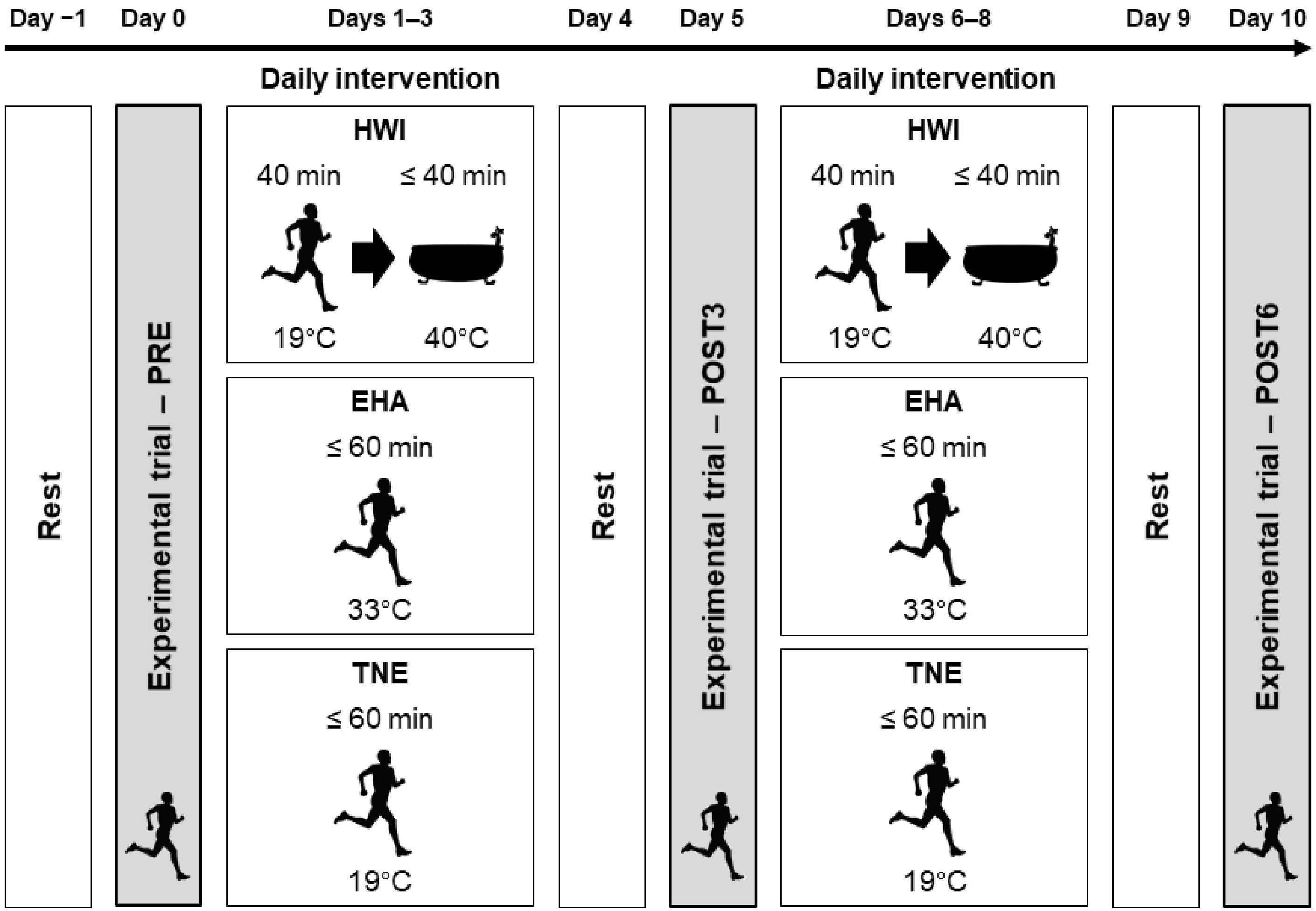
FIGURE LEGENDS

Fig. 1. Schematic of study design. HWI; post-exercise hot water immersion, EHA; exercise heat acclimation and TNE; work-matched thermoneutral exercise.

Fig. 2. Influence of three (POST3) and six days (POST6) of thermoneutral exercise (TNE), exercise heat acclimation (EHA), or post-exercise hot water immersion (HWI) on resting rectal core temperature (T_{re}) (A) and end-exercise T_{re} following a 40-min treadmill run at 65% $\dot{V}O_{2peak}$ in the heat (33˚C, 40% RH) (B). Bars represent the baseline-adjusted mean change from baseline; circles represent individual participant responses.



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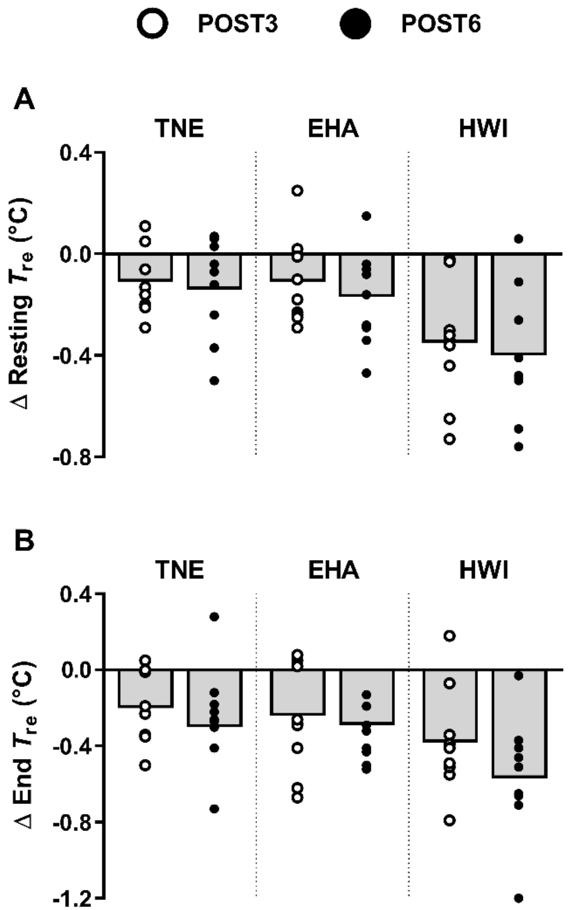

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446 **Fig. 2.** Influence of three (POST3) and six days (POST6) of thermoneutral exercise (TNE), exercise heat acclimation (EHA), or post-exercise hot water 447 immersion (HWI) on resting rectal core temperature (T_{re}) (A) and end-exercise T_{re} following a 40-min treadmill run at 65% $\dot{V}O_{2peak}$ in the heat (33˚C, 40% 448 RH) (B). Bars represent the baseline-adjusted mean change from baseline; circles represent individual participant responses.

Supplementary material

Supplement A The daily thermal stimulus for adaptation and physical activity during days 1–3 and days 6–8 of thermoneutral exercise (TNE), exercise heat acclimation (EHA) and post-exercise hot water immersion (HWI).

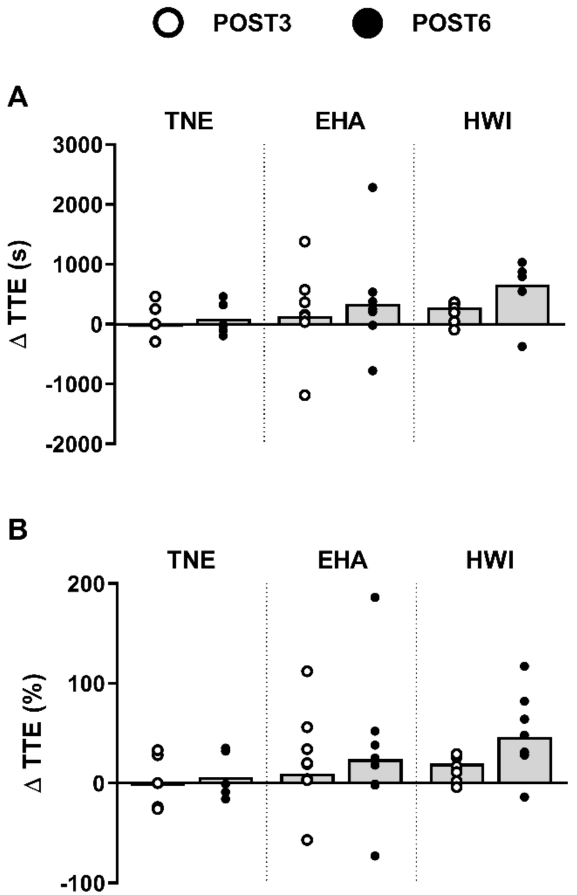
	1–3			**4–6**		
	TNE	**EHA**	**HWI**	**TNE**	**EHA**	**HWI**
Duration $T_{\mathrm{re}} \geq 38.5$°C (min) $^{\#\#}$	9 ± 15	36 ± 12 §§	35 ± 5 §§	7 ± 11	37 ± 10 §§	39 ± 7 §§
AUC ($°\mathrm{C}\cdot\mathrm{min}^{-1}$) $^{\#\#}$	2 ± 5	18 ± 9 §§	16 ± 4 §§	2 ± 4	16 ± 7 §§	18 ± 3 §§
End intervention T_{re} (°C) $^{\#\#}$	38.2 ± 0.5	39.2 ± 0.3 §§	39.2 ± 0.2 §§	38.2 ± 0.5	39.2 ± 0.2 §§	39.3 ± 0.1 §§
Physical activity > 3 METS (min)	121 ± 80	138 ± 81	138 ± 55	120 ± 46	125 ± 43	135 ± 66

T_{re}; rectal core temperature, AUC; area under the curve for $T_{re} > 38.5$°C. Data are displayed as mean ± SD of days 1–3 and days 6–8. $^{\#\#}p<0.01$ denotes main effect of group; $^{\S\S}p<0.01$ denotes group different from TNE overall.

Supplement B Influence of three (POST3) and six days (POST6) of thermoneutral exercise (TNE), exercise heat acclimation (EHA) or post-exercise hot water immersion (HWI) on heat acclimation adaptations at rest and during a 40-min treadmill run at 65% $\dot{V}O_{2peak}$ in the heat (33°C, 40% RH).

	TNE			**EHA**			**HWI**		
	PRE	POST3	POST6	PRE	POST3	POST6	PRE	POST3	POST6
Resting T_{re} (°C) $^{\#\#}$	37.05 ± 0.25	36.97 ± 0.19	36.94 ± 0.22	37.08 ± 0.29	36.96 ± 0.19	36.90 ± 0.22	37.10 ± 0.24	36.72 ± 0.19†,§	36.68 ± 0.22†,§
End-exercise T_{re} (°C) $^{\#}$	38.68 ± 0.49	38.62 ± 0.26	38.52 ± 0.21	38.98 ± 0.31	38.58 ± 0.26	38.53 ± 0.21	38.80 ± 0.27	38.44 ± 0.26†,§	38.25 ± 0.20†,§
T_{re} at sweating onset (°C) $^{\#\#}$	36.99 ± 0.25	36.92 ± 0.18	36.89 ± 0.20	37.03 ± 0.32	36.93 ± 0.18	36.83 ± 0.20	37.08 ± 0.27	36.70 ± 0.18†,§§	36.58 ± 0.20†,§§
Δ T_{re} during exercise (°C) *	1.63 ± 0.49	1.66 ± 0.26	1.58 ± 0.28	1.91 ± 0.19	1.62 ± 0.26	1.64 ± 0.29	1.69 ± 0.31	1.72 ± 0.25	1.57 ± 0.28
Whole-body sweat rate ($L \cdot h^{-1}$) $^{\#\#}$	0.84 ± 0.12	0.85 ± 0.08	0.83 ± 0.06	0.91 ± 0.16	0.94 ± 0.08§§	0.93 ± 0.06§§	0.92 ± 0.20	0.95 ± 0.08§§	0.97 ± 0.06§§
End-exercise T_{sk} (°C)	35.63 ± 0.62	35.15 ± 0.49	35.06 ± 0.45	35.78 ± 0.79	35.22 ± 0.50	34.97 ± 0.46	35.19 ± 0.62	34.91 ± 0.51	34.86 ± 0.47
End-exercise heart rate ($beats \cdot min^{-1}$)	182 ± 16	177 ± 6	173 ± 6	189 ± 11	175 ± 6	170 ± 6	183 ± 11	173 ± 6	167 ± 6
End-exercise physiological strain	7.6 ± 1.2	7.4 ± 0.6	7.1 ± 0.5	8.5 ± 0.9	7.2 ± 0.6	7.0 ± 0.5	8.0 ± 0.4	7.1 ± 0.5	6.6 ± 0.5
Plasma volume (ml)	3031 ± 365	3139 ± 269	3197 ± 228	3203 ± 248	3287 ± 270	3314 ± 228	3108 ± 659	3169 ± 268	3249 ± 227
Blood volume (ml)	5647 ± 604	5711 ± 343	5771 ± 328	5625 ± 755	5864 ± 347	5930 ± 331	5688 ± 853	5819 ± 344	5925 ± 329
Total haemoglobin mass (g)	861 ± 90	847 ± 49	851 ± 46	847 ± 103	878 ± 50	869 ± 46	851 ± 125	899 ± 49	843 ± 46
Mean $\dot{V}O_2$ ($L \cdot min^{-1}$)	2.72 ± 0.26	2.65 ± 0.13	2.65 ± 0.15	3.01 ± 0.35	2.98 ± 0.13	2.96 ± 0.15	2.90 ± 0.50	2.86 ± 0.13	2.86 ± 0.14
Mean RER	0.92 ± 0.03	0.91 ± 0.04	0.91 ± 0.03	0.92 ± 0.08	0.93 ± 0.05	0.92 ± 0.03	0.93 ± 0.04	0.92 ± 0.05	0.93 ± 0.03
End-exercise RPE (6–20 scale)	16 ± 2	15 ± 1	15 ± 0	15 ± 3	14 ± 1	14 ± 0	15 ± 2	14 ± 1	14 ± 0
End-exercise thermal sensation (1–13 scale)	11 ± 1	11 ± 0	11 ± 0	11 ± 1	10 ± 0	10 ± 0	10 ± 1	10 ± 0	10 ± 0
Time to exhaustion (s)	1300 ± 349	1327 ± 497	1395 ± 664	1156 ± 423	1342 ± 515	1512 ± 687	1821 ± 936	2031 ± 532	2466 ± 710

*Tre, rectal core temperature; Tsk, mean skin temperature; RER, respiratory exchange ratio; RPE, rating of perceived exertion. Data are mean ± SD at PRE and baseline-adjusted mean ± SD at POST3 and POST6. *p<0.05 denotes main effect of time; $^{\#}$p<0.05, $^{\#\#}$p<0.01; denotes main effect of group; †p<0.05 denotes HWI different from EHA overall; §p<0.05, §§p<0.01 denotes group different from TNE overall.*



Supplement C Influence of three (POST3) and six days (POST6) of thermoneutral exercise (TNE, *n* = 5), exercise heat acclimation (EHA, *n* = 8) or post-exercise hot water immersion (HWI, *n* = 7) on treadmill (65% $\dot{V}O_{2peak}$) time to exhaustion (TTE) in the heat (33°C, 40% RH). Bars represent the baseline-adjusted mean change (A) and percentage change (B) from baseline; circles represent individual participant responses.