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RESEARCH ARTICLE

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Individual baseline differences outweigh personal traits in short-term heat acclimation adaptations

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ABSTRACT

Previous studies found individual variations during long-term heat acclimation, for short-term heat acclimation (STHA), this remains unclear. This study aimed to examine the impact of individual characteristics on thermophysiological adaptations during STHA. Forty-six service members participated in an STHA protocol in 35.1 ± 0.4 °C and 50 ± 4% RH. Gastrointestinal temperature (T_{gi}), mean skin temperature (T_{sk}), heart rate (HR), whole-body sweat loss, and subjective scores were recorded and analysed using mixed-effect modelling. Both end-of and change-during fixed work-rate T_{gi}, T_{sk}, and HR showed a decline from day 1 to 5 ($p \leq 0.011$). Subjective scores improved ($p \leq 0.005$). Fat percentage, body surface area-to-mass ratio, body mass, sex, and age showed relationships ($p \leq 0.05$) with one or more outcome measures. STHA results in physiological and subjective benefits, although most of the variance remains unexplained by the recorded characteristics. No individual- or group-level time interactions were found during STHA, indicating the military population adapted uniformly to heat.

Practitioner Summary: This study investigated whether individual characteristics (e.g. age, sex, and body composition) affect the adaptations observed during short-term heat acclimation (STHA). Forty-six service members participated in a 5-day acclimation protocol. Although STHA adaptations were observed, no relationship was found between the individual characteristics and physiological adaptations in this military population.

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KEYWORDS
Heat acclimation; 5-day protocol; individual characteristics; military

1. Introduction

Exposure to high environmental temperatures significantly impairs physical and cognitive performance while increasing the risk of heat-related illnesses, such as heatstroke (Périard, Racinais, and Sawka 2015; Sawka et al. 2011; Parsons 2007). Heat acclimation, defined as physiological adaptation to repeated heat exposure over time, can mitigate potential adverse physical and cognitive effects (Périard, Racinais, and Sawka 2015; Ashworth, Cotter, and Kilding 2020; Tyler et al. 2024). While heat acclimation involves a variety of adaptations, reductions in core temperature and heart rate are two classic markers (Périard, Racinais, and Sawka 2015; Sawka et al. 2011; Ashworth, Cotter, and Kilding 2020; Tyler et al. 2024; Brown et al. 2024; Garrett et al. 2009). Other adaptations include increased sweating rates and lower skin temperature (Périard, Racinais, and Sawka 2015; Sawka et al. 2011; Ashworth, Cotter, and Kilding 2020; Tyler et al. 2024; Brown et al. 2024; Garrett et al. 2009). These adaptations facilitate heat loss, thereby enhancing the body's ability to maintain a thermal balance under heat exposure.

Acclimation involves two synergistic thermo-effector pathways: the sudomotor (i.e. sweating response) and the cardiovascular pathway (Sawka et al. 2011; Horowitz 2014). Enhanced sudomotor activity facilitates heat dissipation through evaporation from the skin and releases heat into the environment (Sawka et al. 2011; Horowitz 2014; Périard, Eijsvogels, and Daanen 2021). Adaptations in the cardiovascular pathway include improved efficiency of heat loss and increased cutaneous vasodilation; transferring excess heat from the body's core to the periphery (Sawka et al. 2011; Horowitz 2014; Périard, Eijsvogels, and Daanen 2021). The rates at which the two thermo-effector pathways

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adapt to heat exposure can differ (Périard, Racinais, and Sawka 2015). The cardiovascular system (e.g. lower heart rate and higher plasma volume) tends to adapt first, and adaptations seem to plateau (i.e. further adaptation is minimal or absent) around the sixth day of heat acclimation (Périard, Racinais, and Sawka 2015). Changes in the sudomotor response typically occur later, becoming evident from the fifth day of heat acclimation onwards (Périard, Racinais, and Sawka 2015).

Heat acclimation is generally recommended for at least eight consecutive days to ensure that the aforementioned adaptations can fully develop across all phenotypes (Périard, Racinais, and Sawka 2015). However, the time required for both thermo-effector pathways to fully adapt may not always align with logistical constraints in professions that typically utilise such protocols (e.g. armed forces, athletes, and workers). Previous research indicates that short-term heat acclimation (STHA) (≤5 days) can still lead to significant physiological adaptations (Garrett et al. 2009; Moss et al. 2020; Garrett et al. 2012; Saillant, Charkoudian, and Salgado 2022), making it an attractive alternative for situations where heat acclimation is beneficial but time is limited.

The relative contributions of the two thermo-effector pathways are thought to depend on individual characteristics (specifically, body dimensions and composition). Alkemade et al. (2021) reported that during long-term heat acclimation (LTHA), individuals with a higher body mass primarily adapt via the sudomotor response whereas individuals with a lower body mass adapt via the cardiovascular response. The effect of body fat percentage and body surface area-to-mass (BSA-to-mass) ratio at a single timepoint on core temperature is understood. Research by Cramer and Jay (2015) and Crowe, Meehan, and Jones (2025) showed that fat percentage positively relates to core temperature during exercise and that BSA-to-mass-ratio is positively associated to thermal tolerance, respectively. To our knowledge, it is currently not known whether the dependence on individual characteristics of the preferred thermo-effector pathway by which individuals adapt to heat can also be observed during STHA, and if the benefits of STHA are the same for all individuals. Especially considering the differences in the time course of heat acclimation adaptations, the dependence on individual characteristics could mean that some of the individuals adapt to heat during STHA while others do not (yet). When STHA is used as a prevention strategy to reduce risk of heat-stress induced adverse cognitive and physiological effects, it is essential to know not only the population-average reduction in heat stress risks, but also to be aware of the variation in adaptation between individuals. Individuals who adapt slower or less may be at higher risk than their peers while operating under the assumption they are equally protected by the STHA.

Therefore, it is essential to determine whether there is any relationship between individual characteristics and heat acclimation during the limited timespan of STHA. This understanding is important given the relationship between heat acclimation, heat-related illnesses, and ultimately, employability in professions, such as armed forces, athletes, and workers. As such, the present study aimed to investigate the impact of individual characteristics on the (thermo)physiological adaptations observed during STHA in military personnel.

2. Methods

2.1. Participants

Forty-six service members (7 females, 39 males) on active duty were recruited from different operational commands within the Dutch Ministry of Defense (Table 1; Navy: $n = 22$, Airforce: $n = 9$, Army: $n = 12$, Military Police: $n = 3$). The underrepresentation of females is a reflection of the underrepresentation of females in the Dutch military, yet their inclusion enables exploration of potential sex-based differences in adaptations. This is particularly relevant given that women represent an increasingly prominent segment of military populations. The procedures were approved by the Dutch Ministry of Defense and conformed to the standards of the Declaration of Helsinki (2013). Written informed consent was obtained from all participants before the study. Participants who had experienced heat-related illnesses in the last five years or with medical contraindications to exercise in the heat were excluded from participation.

2.2. Design

This study was conducted during late autumn in the Netherlands (November), minimising prior acclimatisation effects. Participants reported to the laboratory on five consecutive days at approximately the same time

Table 1. Participant characteristics ($n = 46$).

Characteristic	Mean ± *SD*	Range
Age (years)	32 ± 10	19–61
Height (cm)	180 ± 7	164–193
Body mass (kg)	79.2 ± 11.0	59.8–102.5
BSA (m^2)	2.0 ± 0.2	1.6–2.3
BSA-to-mass ratio (cm^2 ·kg^{-1})	253.0 ± 16.7	225.5–287.2
Body fat (%)	19.0 ± 6.5	6.7–30.6

of day (±30 min) and were required to wear sports shoes and clothing throughout the entire protocol. Each visit consisted of 90 min cycling (Excalibur Sport, Lode B.V., Groningen, the Netherlands) in a portable environmental chamber (Tectoniks Ltd, Kinton, Nesscliffe, Shropshire, UK) set to a hot-humid condition (35.1 ± 0.4 °C with a range of 34.2–36.3 °C, 50 ± 4% RH with a range of 41–56%, and minimal air flow). Participants initially cycled at a fixed work rate [1.5 W·kg^{-1} (n = 21) or 1.75 W·kg^{-1} (n = 25), Figure 1] for 30 min, followed by 60 min of exercise, during which work rate was adjusted to maintain a core temperature slightly above 38.0 °C (i.e. controlled hyperthermia). The two different work rates can be explained by optimisation of the protocol over time. The study was conducted in two groups that underwent the protocol one after another. It appeared that for the first group, cycling at 1.5 W·kg^{-1} (n = 21), the work rate was rather suboptimal to increase the core temperature to ≥38.0 °C within 30 min. The second group (n = 25) therefore cycled at 1.75 W·kg^{-1}. Controlled hyperthermia ≥38.0 °C was chosen because this temperature is used in practical scenarios involving STHA for the Dutch military field setting; specifically, it aligns with physiological response data obtained from heat acclimatisation in military field settings (unpublished data, Dutch Ministry of Defense). Secondly, higher intensity cycling was anticipated to be unfeasible for all service members considering varying individual capacities due to varying operational demands. No separate pre- and post-heat stress tests were done. Instead the physiological data over the five acclimation sessions was used to quantify the effects of heat acclimation over time. The baseline (non-acclimated) physiological

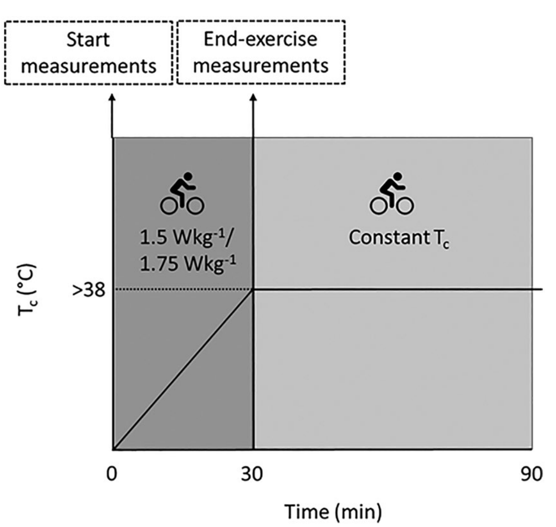

Figure 1. Cycling protocol during each of the five consecutive heat acclimation days. Data was gathered during the fixed work rate section of the protocol.

response to the STHA protocol is measured on the first day of the five-day protocol and is then tracked over time.

2.3. Measurements

Participants were asked to ingest a telemetric pill (BodyCap, e-Celsius Performance, Hérouville Saint-Clair, France) 1–2 h before the experimental procedures, after they had ensured hydration by drinking 500 mL of water. Thereafter, they were not allowed to drink until after the first 30 min of exercise, which consisted of fixed work rate cycling (Figure 1). This allowed for measurements of gastrointestinal temperature (T_{gi}) every minute, which can be used as an indicator of the core temperature (Casa et al. 2007). On the first day of heat acclimation, participants' height (stadiometer, Seca, Hamburg, Germany), body mass (MPE 250K100PM, Kern & Sohn GmbH, Balingen, Germany), and body fat percentage [caliper according to the 4-skinfold methods (Durnin and Womersley 1974)] were measured. To calculate whole-body sweat loss (WBSL), body mass was measured before and immediately after 30 min of exercise (i.e. the fixed work rate cycling). For the WBSL measurement, the participants left the bike and towel dried their bodies. Body mass was measured while participants only wore their undergarments. Heart rate (HR; Polar OH1, Kempele, Finland) was measured beat-by-beat on the upper arm, skin temperature (T_{sk}) was measured every minute on the neck, scapula, hand, and shin (i-Buttons, Maxim Integrated Products Inc., San Jose, CA, USA), and the weighted mean T_{sk} was calculated according to ISO 9886 (Equation 1) (ISO-9886 2004). Subjective scores were assessed after 30 min using three scales: rating of perceived exertion (RPE) on a 10-point scale [ranging from 0 (rest) to 10 (maximal exertion)] (Borg 1962), thermal sensation (TS) on a nine-point scale [ranging from −4 (very cold) to +4 (very hot)] (ISO 10551 2019), and thermal comfort (TC) on a five-point scale [ranging from 1 (comfortable) to 5 (extremely uncomfortable)] (ISO 10551 2019).

2.4. Calculations

T_{sk} and BSA were calculated using Equation (1) (ISO-9886 2004) and Equation (2) (Borg 1962), respectively. Three participants were missing one of the four temperatures listed in Equation (1), because one of the i-Buttons was not properly recording during the protocol. For these three sets of data, the skin temperature was estimated using Equation (1) using only the available sensors and dividing by the sum of all weights from the available sensor locations (Equation 3). The weights for each location were obtained from Equation (1). In addition, T_{sk} data were missing for three participants because of technical problems.

$$T_{sk}\left(°C\right) = 0.28T_{neck} + 0.28T_{scapula} + 0.16T_{hand} + 0.28T_{shin} \quad (1)$$

$$BSA\left(m^2\right) = 0.007184 * height^{0.725} * bodymass^{0.425} \quad (2)$$

$$T_{sk}\left(°C\right) = \frac{\sum_{loc,available} w_{loc} \cdot T_{loc}}{\sum_{loc,available} w_{loc}} \quad (3)$$

2.5. Data analysis

Start- and end-of-exercise outcomes were calculated for each of the aforementioned physiological parameters (T_{gi}, T_{sk}, HR, and WBSL), where start-of-exercise values indicate the average of the first 5 min and end-of-exercise values indicate the average of the last 5 min of the fixed work rate part of the protocol (i.e. the first 30 min, see Figure 1). The difference between start and end-of-exercise for each measure was also included as an outcome. WBSL was collected only from pre- to post-fixed work rate cycling and was corrected for body weight.

To assess the effect of STHA and its relationship with individual characteristics, a linear mixed-effects model was fitted (using maximum likelihood) to the physiological and subjective outcomes grouped by participant number. The model was initialised in its simplest form, a constant with a random intercept per participant. This random intercept reflects each participant baseline response to the STHA protocol. After that, the predictor variables (day number, work rate, sex, and individual characteristics from Table 1) were added one at a time in a forward stepwise manner. At each step, the Akaike information criterion (AIC) was calculated (Akaike 1974). The model with the largest decrease in AIC was selected as the new best model, provided that the decrease was larger than 2. The process is then repeated until the addition of an additional predictor does not decrease the AIC by two or more. Model selection was performed using AIC because it incorporates a complexity penalty to discourage overfitting and mitigate the inflation of Type I error rates. In the same forward stepwise manner, random slopes were modelled for day number, which included interaction terms between day number and other variables. No other interaction terms are modelled, as there is no convincing argument for this in the literature (Alkemade et al. 2021).

The initial random-intercept model only captures the individual's average response to the STHA protocol across the five days. Model performance is expected to improve with the inclusion of additional predictors. If the STHA protocol is effective, responses should systematically vary with day number, making it a significant predictor; the random intercept would then represent the individual's baseline response. Likewise, if personal characteristics consistently influence responses, they should emerge as significant predictors, reducing the relative weight of the random intercept and providing quantifiable measures instead. Interaction effects with the day number variable were explicitly modelled, as these would be indicative of the individual characteristics affecting the effectiveness or adaptation rate of the acclimation process (increasing or decreasing the rate and/or magnitude of the adaptations). Finally, all continuous predictors were standardised (z-scored) to ensure comparability and to avoid numerical issues.

Measured values are reported as mean ± *SD*, while modelled values are reported as median and 95% confidence intervals (CI). Where applicable, values are accompanied by effect size (Cohen's *d*). Statistical significance was set at $p \leq 0.05$.

3. Results

The results section is based on the 30-min fixed work rate cycling part of the data to allow for fair comparisons. After these 30 min, the 60-min constant T_c part started (Figure 1), where each participant's work rate was adjusted to maintain their T_c ≥38.0 °C. They were also allowed to drink water during the last 60 min, meaning no valid T_{gi} data could be collected.

3.1. Physiological

Body mass was not significantly different between the first and fifth day of heat acclimation (79.2 ± 11.0 and 79.1 ± 10.9 kg, $p = 0.315$). Figure 2 lists the start- and end-of-exercise T_{gi}, T_{sk}, HR, and WBSL responses for all days of the five heat acclimation sessions. For the majority of individuals, all acclimation indicators decreased, except WBSL, as expected. Specifically, we found a decrease from day one to day five in $T_{gi,start}$ ($n = 26/46$), $T_{gi,end}$ ($n = 36/46$), $T_{sk,start}$ ($n = 26/43$), $T_{sk,end}$ ($n = 28/43$), HR_{start} ($n = 24/46$), HR_{end} ($n = 39/46$), and WBSL ($n = 16/46$). Additionally, all three of $T_{gi,end}$, $T_{sk,end}$, and HR_{end} decreased for more than half of participants ($n = 22/43$).

The fitting of mixed-effects models (Section 3.3) found a statistically significant reduction over the days for $T_{gi,end}$, ΔT_{gi}, $T_{sk,end}$, ΔT_{sk}, HR_{end}, and ΔHR (see Table 2 for details). $T_{gi,end}$ decreased from 38.3 ± 0.4 to

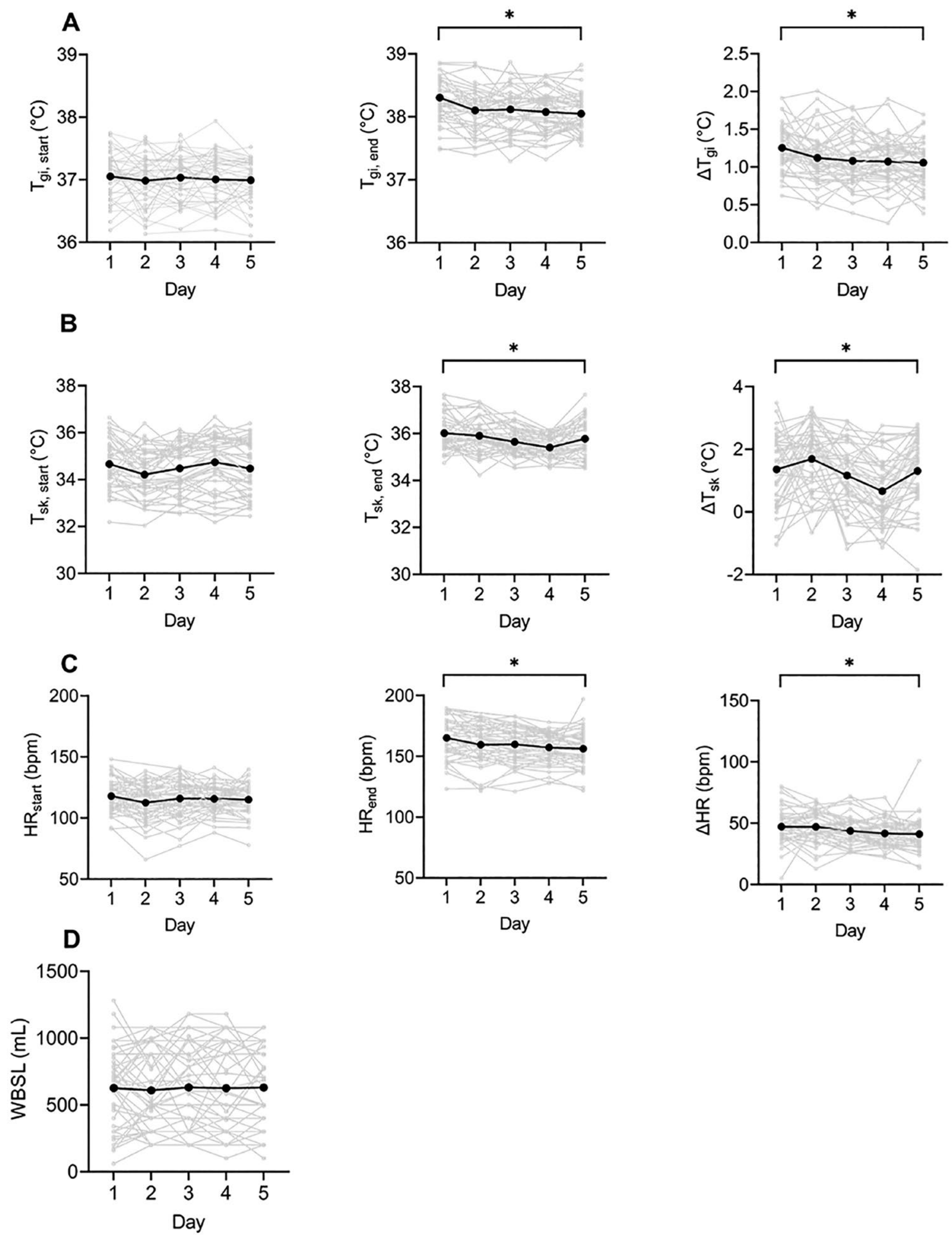

Figure 2. Physiological responses: (A) start, end-of-exercise, and change from start to end-of-exercise (i.e. Δ) gastrointestinal temperature (T_{gi}). (B) Start, end-of-exercise, and Δ mean skin temperature (T_{sk}). (C) start, end-exercise, and Δ heart rate (HR). (D) Whole-body sweat loss (WBSL). Grey symbols and lines represent individual data. Black symbols and lines represent the group average. Asterisks indicate day number is a statistically significant predictor ($p < 0.05$) in the corresponding mixed-effects model (Section 3.3).

38.0 ± 0.3 °C ($d = 0.76$), $T_{sk,end}$ from 36.0 ± 0.7 to 35.8 ± 0.8 °C ($d = 0.31$), and HR_{end} from 165 ± 16 to 156 ± 15 bpm ($d = 0.56$), respectively. ΔT_{gi}, ΔT_{sk}, and ΔHR decreased from 1.3 ± 0.3 to 1.1 ± 0.3 °C ($d = 0.64$), from 1.4 ± 1.1 to 1.3 ± 1.1 °C ($d = 0.05$), and from 47 ± 14 to 41 ± 14 bpm ($d = 0.43$), respectively.

3.2. Subjective scores

Each scale of the subjective scores showed a significant reduction (i.e. improvement) from day one to day five of heat acclimation (Figure 3). RPE decreased over time from 4.8 ± 2.0 (i.e. in between 'somewhat hard' and 'hard') on the first day to 3.6 ± 1.6 (i.e. in between 'moderate' and 'somewhat hard') on the fifth day ($d = 0.64$). TS decreased from 2.2 ± 0.9 (i.e. in between 'warm' and 'hot') on the first day to 1.9 ± 1.0 (i.e. in between scores 'slightly warm' and 'warm') on the fifth day ($d = 0.28$). Thirdly, TC decreased from 2.2 ± 0.9 (i.e. between 'uncomfortable' and 'very uncomfortable') on the first day to 1.7 ± 0.9 (i.e. in between 'slightly uncomfortable' and 'uncomfortable') on the fifth day of heat

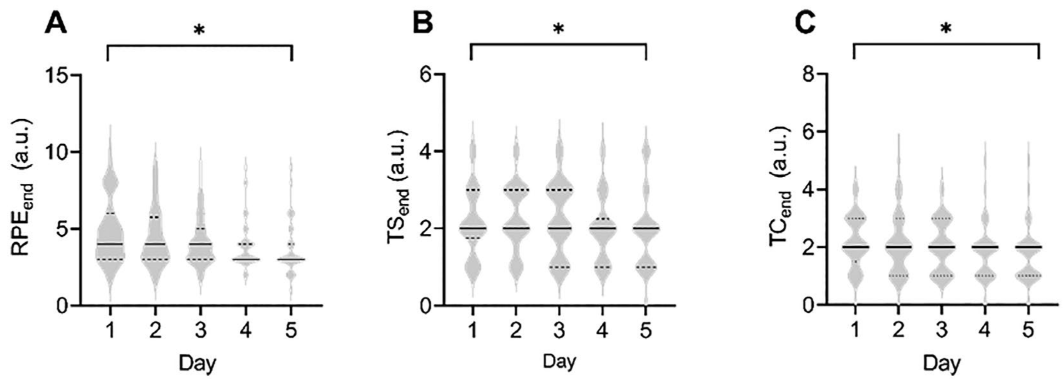

Figure 3. Perceptual responses: end-exercise (A) rating of perceived exertion (RPE), (B) thermal comfort (TC), and (C) thermal sensation (TS). The solid horizontal lines represents the median. The dashed horizontal lines represent third quartiles. Asterisks indicate day number is a statistically significant predictor ($p < 0.05$) in the corresponding mixed-effects model (Section 3.3).

acclimation ($d = 0.48$). Accordingly, day number was a statistically significant predictor for RPE, TS, and TC (see Table 2 for details).

3.3. Linear mixed-effects models

The linear mixed-effect models resulting from the forward stepwise process, as described in Section 2.5, are summarised in Table 3. The table shows the (directional) relationship between the outcome and predictors, the *p*-value of each predictor, and both the marginal and conditional R^2. None of the models were improved by adding a random slope instead of a random intercept.

With the exception of WBSL ($p = 0.156$), all outcome measures related to either the end of exercise or the difference between the start- and end-of-exercise showed a significant relationship with the day number ($p < 0.05$). Various outcomes also showed a significant relationship with work rate. Some outcome measures showed a significant relationship with one or more of the individual characteristics, namely, fat percentage and BSA-to-mass ratio with $T_{gi,start}$ ($p < 0.05$), body mass with ΔT_{sk} ($p < 0.05$), sex with ΔHR ($p < 0.05$) and WBSL ($p < 0.05$), age with HR_{start} ($p < 0.001$), and HR_{end} ($p < 0.01$). For all mixed-effects models except $T_{sk,start}$, ΔT_{sk}, and WBSL, the marginal R^2 values were low (0.015–0.223), whereas the conditional R^2 values were comparatively high (0.464–0.902).

Note that the absence of a statistically significant interaction between day number and work intensity indicates that the rate of change in the outcome measures over the days (the adaptation rate) was not statistically different between the two intensities [1.5 W kg^{-1} ($n = 21$) or 1.75 W kg^{-1} ($n = 25$)]. This indicates that both groups adapted at a similar rate across the five days.

Table 2. Physiological and subjective outcomes where day number is a statistically significant predictor, including its (unscaled) β coefficient, confidence interval, and *p*-value.

Variable	β Coefficient	95% Confidence interval	*p*-Value
$T_{gi,end}$	−0.05	[−0.07, −0.03]	$<10^{-6}$
ΔT_{gi}	−0.04	[−0.07, −0.02]	$<10^{-4}$
$T_{sk,end}$	−0.10	[−0.15, −0.05]	$<10^{-4}$
ΔT_{sk}	−0.11	[−0.19, −0.02]	0.011
HR_{end}	−2.15	[−2.84, −1.46]	$<10^{-9}$
ΔHR	−1.75	[−2.60, −0.90]	$<10^{-4}$
RPE	−0.29	[−0.38, −0.20]	$<10^{-9}$
TS	−0.08	[−0.14, −0.02]	0.005
TC	−0.12	[−0.16, −0.08]	$<10^{-6}$

$T_{gi,end}$: end-of-exercise (i.e. 30-min fixed work-rate cycling) gastrointestinal temperature; ΔT_{gi}: change in gastrointestinal temperature during fixed work-rate; $T_{sk,end}$: end-of-exercise skin temperature; ΔT_{sk}: change in skin temperature during fixed work-rate; HR_{end}: end-of-exercise heart rate; ΔHR: change in heart rate during fixed work-rate; RPE: rating of perceived exertion; TS: thermal sensation; TC: thermal comfort.

Although AIC-based stepwise modelling reduces false positives compared to significance testing alone, it remains prone to inflated Type I error (Mundry and Nunn 2009). Marginal predictors may not be robust under stricter controls. As no interaction was found between day number and personal characteristics, suggesting no modulation of STHA effectiveness due to personal characteristics, further analysis was deemed unnecessary.

4. Discussion

This study aimed to examine how individual characteristics influence both physiological adaptations and subjective scores resulting from a five-day STHA protocol. Inducing controlled hyperthermia via the STHA protocol resulted in physiological and perceptual benefits during heat exposure. Specifically, physiological improvements over the five days were found in $T_{gi,end}$, ΔT_{gi}, $T_{sk,end}$, ΔT_{sk}, HR_{end}, and ΔHR using mixed-effects

Table 3. Best mixed-effects models for each outcome measure.

Outcome	Relationship	Marginal R^2	Conditional R^2
ΔT_{gi}	$\sim I^{*} - Day^{***} + Intensity^{**}$	0.123	0.503
$T_{gi,start}$	$\sim I + Fat_{\%}^{***} + BSA - to - mass ratio^{*}$	0.135	0.528
$T_{gi,end}$	$\sim I - Day^{***} + Age^{*}$	0.125	0.598
ΔT_{sk}	$\sim I^{***} - Intensity^{***} - Day^{*} + Body mass^{*}$	0.305	0.387
$T_{sk,start}$	$\sim I^{***} + Intensity^{***}$	0.638	0.749
$T_{sk,end}$	$\sim I^{***} + Intensity^{***} - Day^{***}$	0.223	0.464
ΔHR	$\sim I^{*} + Intensity^{***} - Day^{***} + Sex^{*}$	0.210	0.472
HR_{start}	$\sim I - Age^{***}$	0.169	0.615
HR_{end}	$\sim I - Day^{***} - Age^{**}$	0.158	0.763
WBSL	$\sim I^{***} + Intensity^{***} - Sex^{*}$	0.364	0.584
RPE	$\sim I - Day^{***} + Intensity^{*}$	0.114	0.902
TC	$\sim I^{*} - Day^{***} + Intensity^{**}$	0.160	0.751
TS	$\sim I - Day^{**}$	0.015	0.830

Directionality of the effect is denoted using the sign of the predictor. Sex is a categorical variable with male as baseline. I is the intercept and Intensity is activity level (1.5 or 1.75 W/kg). Significance is denoted using asterisks for each predictor (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). Marginal R^2 represents proportion of variance explained only by fixed effects of the model. Conditional R^2 represents the proportion of variance explained by both fixed and random effects in the model.

analysis. Subjective measures, including RPE, TC, and TS, also improved over time.

4.1. Direction and magnitude of heat acclimation

Previous studies have identified reductions in core temperature and HR as two classic markers of heat acclimation (Périard, Racinais, and Sawka 2015; Sawka et al. 2011; Ashworth, Cotter, and Kilding 2020; Tyler et al. 2024; Brown et al. 2024; Garrett et al. 2009). In the present study, all outcomes that indicated either the end-of-fixed work rate exercise or the difference between the start- and end-of-exercise exhibited a statistically significant association with the day number, with the exception of WBSL. Based on these findings, STHA was considered successful as it induced reductions in the two classic markers. In addition to physiological adaptations, participants also reported subjective improvements throughout the STHA. Participants perceived the same exercise protocol as progressively less strenuous, as indicated by a lower RPE, and thermal discomfort and perceived warmth gradually decreased. The elicited changes in physiology and subjective scores mimicked the responses observed during heat acclimatisation in a military field setting (unpublished data, Dutch Ministry of Defense). Given the observed heat acclimation adaptations in both physiological and subjective scores, the current STHA regimen appears to be an effective way to reduce heat stress. In professions such as the armed forces, where time and logistical constraints limit the feasibility of prolonged acclimation protocols, STHA may offer advantages as adaptations are effectively initiated and the time to achieve full acclimation upon deployment to hot environments can potentially be reduced. This is particularly relevant in high-humidity environments, where the most beneficial heat acclimation adaptations are primarily vasomotor in nature (i.e. less effective evaporative cooling due to humidity) and tend to occur early in acclimation.

Périard, Racinais, and Sawka (2015) described the typical adaptive responses to heat acclimation as a percentage of change relative to the first day. Compared to these expected adaptations, this study found relatively small magnitudes of adaptation. For example, the expected core temperature decrease during exercise at a given work rate should be ~6% on the fifth day of heat acclimation (Périard, Racinais, and Sawka 2015). However, the end-exercise T_{gi} reduction after five days was <1% in this study. A recent meta-analysis reported a comparable time-point reduction in core temperature of −0.34 ± 0.24 °C following STHA ($n = 181$, Tyler et al. 2024). Another study on STHA in a military population reported a reduction in end-exercise core temperature from 38.1 ± 0.34 to 37.9 ± 0.3 °C on day 5 (Saillant, Charkoudian, and Salgado 2022). Results of the present study align with that as $T_{gi,end}$ lowered from 38.3 ± 0.4 °C on day 1 to 38.0 ± 0.3 °C on day 5. Likewise, according to Périard et al., the typical HR reduction on day 5 is expected to be ~15% (Périard, Racinais, and Sawka 2015), whereas the observed end-of-exercise HR here was only 5%. Again, the results of the present study (HR_{end} from 165 ± 16 bpm on day 1 to 156 ± 15 bpm on day 5) align well with Tyler et al.'s meta-analysis (−5 ± 1 bpm compared time-point HR, $n = 60$, Tyler et al. 2024) and adaptations found in a military population (134 ± 17 to 122 ± 13 bpm on day 5, Saillant, Charkoudian, and Salgado 2022). The absence of a statistically significant interaction between day number and work rate on any of the phenotypes indicates that the magnitude of adaptations was not significantly different between the two work rates [1.5 W kg^{-1} ($n = 21$) or 1.75 W kg^{-1} ($n = 25$)]. The lower adaptation rate compared to that of Périard, Racinais, and Sawka (2015) was consistent between the two work rates. The absolute HR and core temperature responses in this study are comparable to other controlled hyperthermia STHA protocols (Garrett et al. 2009; Garrett et al. 2012; Cotter, Patterson, and Taylor 1997; Turk and Worsley 1974), despite the lower thermal stimuli (i.e. controlled hyperthermia ≥38.0 °C rather than ≥38.5 °C core temperature).

T_{sk} followed a decreasing trend from days 1 to 4, but unexpectedly experienced a slight increase on the fifth day. This was statistically different from day 1 (lower) and day 4 (higher), but not from day 2 or 3. A higher T_{sk} is beneficial in terms of maintaining a high water vapour pressure at the skin to overcome the high ambient water vapour pressure (Sawka et al. 2011). This is typically achieved by higher skin blood flow, which requires circulatory adaptations. Increased sweat rates on the contrary, often observed after LTHA, are expected to cool down the skin. A physical analysis indicates the 0.38 °C rise in $T_{sk,end}$ from day 4 to 5 is consistent with ~4W of additional heat storage during the fixed work rate phase (using skin mass and specific heat from Xu, Rioux, and Castellani 2023). The observed reduction in average WBSL from day 4 to 5 accounts for more than a 4W decrease in cooling capacity, but an increase in skin blood flow could also plausibly increase heat transfer to the skin by more than 4W. It is debateable how the interplay of these two mechanisms causes the sudden increase in T_{sk} in this study.

4.2. Individual characteristics

Outcome measures change in relationship to fixed work rate (1.5 or 1.75 W·kg^{-1}). Logically, a higher work rate leads to increased metabolic heat production, resulting in increased temperatures, WBSL, HR, and subjective heat experience. After controlling for intensity, some outcome measures showed a significant relationship with one or more individual characteristics. Some of these are not pertinent to acclimation but are well described in the literature: HR decreases with age (Tanaka, Monahan, and Seals 2001), and women sweat less than men (Yanovich, Ketko, and Charkoudian 2020; Wickham, Wallace, and Cheung 2021). The relationship between body fat percentage and BSA-to-mass ratio with T_{gi} adaptation is not well documented, although Alkemade et al. (2021) found a similar relationship between body fat percentage and resting rectal temperature adaptation during acclimation. Because $T_{gi,start}$ is measured in the first 5 min of the fixed work rate protocol, the relationship with the BSA-to-mass ratio could be related to the thermal inertia of the body. Although it is widely known that age affects thermoregulation, the relationship between age and $T_{gi,end}$ has not been directly reported in the literature.

For all mixed-effects models except $T_{sk,start}$, ΔT_{sk}, and WBSL, the marginal R^2 tends to be small, and the conditional R^2 tends to be relatively large. This indicates that most of the observed variance can be explained by individual differences that were not captured by the measured characteristics. This variance could potentially be explained by characteristics not quantified in this study (e.g. fitness level), but they may also be reflective of an individual's inherent acclimation capability (e.g. due to genetics), or short-term physical or mental condition (e.g. sleep, diet).

No reported individual characteristics were found to interact with day number, suggesting that physiological and subjective adaptations were not moderated by any of the variables included in this study. Stronger still, the mixed-effects models were not improved by adding random slopes for each participant, suggesting that adaptations over the days were uniform for the entire sample population.

We acknowledge the study was aimed at military populations and executed with a sample population that is representative of the Dutch Military. As such, the findings may not extend to the general population. Nevertheless, we did find significant adaptations and it can be concluded that the military population in this study experienced benefits from the STHA protocol. Furthermore, those benefits were uniform over the sample population. Practically speaking, this is a convenient finding because the reason for performing an STHA protocol is usually logistical constraints. The uniform benefit suggests that additional personalisation of the STHA protocol would not provide additional benefits; we do not find evidence that a 'one size fits all' approach would have large impact on acclimation outcomes due to individual variation.

4.3. Limitations

The current controlled hyperthermia protocol aimed at a core temperature of >38.0 °C for 60 min (Figure 1) rather than the recommended 38.5 °C (Périard, Racinais, and Sawka 2015; Ashworth, Cotter, and Kilding 2020; Périard, Eijsvogels, and Daanen 2021; Moss et al. 2020). This was done in accordance with physiological responses quantified during heat acclimation in an actual military field setting (unpublished data, Dutch Ministry of Defense). It could be that adaptations in phenotypes and their potential relationship with individual characteristics would have been more explicit during a 38.5 °C controlled hyperthermia protocol. In this study, pre- and post-constant heat stress tests were not administered to measure the magnitude of adaptations. While including identical forcing function tests before and after heat acclimation would have been relevant, the approach is justified by taking the fixed work rate (in W·kg^{-1}) part of the protocol. Further, a mixed-effects linear model was chosen for data analysis, as it is well-suited for the repeated-measure nature of the experiment and accounts for individual variation. Given the exploratory nature of the study and uncertainty regarding the role of individual characteristics in STHA, multiple outcome measures were evaluated using a forward stepwise procedure guided by AIC. Although this approach penalises overly complex models, the combination of numerous outcome measures and stepwise selection can still inflate Type I errors (false positives). Consequently, relationships identified at lower *p*-values should be considered as an indication of possible relationships and areas of interest for future studies.

Although this study included a substantial sample size, it focused on a military cohort representative of the Dutch Military, which is not reflective of the general population. The sample predominantly consisted of men, younger adults, mostly Caucasian, and generally fit individuals. As such, it is uncertain whether the observed uniform adaptations would apply to non-military groups. Especially of note is that the lower number of female participants compared to male participants may have reduced the statistical power for analysing gender-related differences. Finally, future studies should gather information on the fitness level of the participants, as this might affect heat adaptation. Initially, we expected to be able to use results from the yearly endurance test as a proxy for fitness level, but the way this test is administered is by verifying personnel can achieve minimum benchmarks within predetermined timespans. Therefore, the yearly test is not an adequate all-out test and was deemed not usable as a proxy for fitness level. For future research, we recommend establishing fitness level of the individuals in a lab setting before measurements. Furthermore, no additional testing was done to evaluate the retention of adaptations over time. Since STHA is usually done shortly before going to a hot environment, retention over longer periods tends to be of less practical interest.

4.4. Conclusions

A 5-day short-term heat acclimation protocol resulted in significant physiological and perceptual benefits during heat exposure. Although some outcome measures show a relationship with one or more individual characteristics, most of the variance is attributable to individual differences that are not captured in the measured characteristics. The military population in this study adapted uniformly to heat during the STHA protocol, as evidenced by the absence of interaction effects between time and any individual characteristic, along with random slopes for time. As such as 'one size fits all' short-term acclimation protocol appears to be effective in Dutch military populations.

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Author contributions

CRediT: **Lisa Klous**: Conceptualization, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing; **Koen van der Sanden**: Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing; **Floris Paalman**: Conceptualization, Investigation, Writing – review & editing; **Pim Scheiberlich**: Data curation, Investigation, Writing – review & editing; **Sam Ballak**: Conceptualization, Investigation, Methodology, Project administration, Writing – review & editing; **Marc Duineveld**: Investigation, Writing – review & editing; **Mariëlle Besselink-Weghorst**: Conceptualization, Investigation, Methodology, Project administration, Writing – review & editing; **Nicholas Godman**: Investigation, Writing – review & editing; **Marijne de Weerd**: Conceptualization, Investigation, Writing – review & editing; **Boris Kingma**: Conceptualization, Formal analysis, Funding acquisition, Methodology, Supervision, Writing – review & editing; **Koen Levels**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Writing – review & editing.

Disclosure statement

The authors declare no conflicts of interest. The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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Data availability statement

The datasets generated and/or analysed during the current study are not publicly available because of participant consent limitations but are available from the corresponding author via e-mail.

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