A novel approach to characterise the energy cost of human cool-seeking behaviour and its individual variability during heat stress

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Abstract

Behavioural thermoregulation (e.g. cool-seeking) is thought to proceed autonomic heat-loss responses (e.g. sweating), due to energy-conservation requirements. However, the energy cost of cool-seeking behaviours in humans has been rarely quantified. Here we present a novel approach to characterise the energy cost of a common human cool-seeking behaviour (i.e. manual fanning) and its individual variability during heat stress. Ten healthy males (20±1y) participated in two 60-min trials (*CONTROL* and *FAN*) consisting of resting exposure to 37(±0.4)°C and 44(±6)% RH. During *FAN*, participants freely used a hand-held fan instrumented with an accelerometer, to offset thermal discomfort. During *CONTROL*, no fan was provided. We measured energy expenditure (breath-by-breath gas analysis), core temperature (T_c), mean skin temperature ($\bar{T}_{sk}$), forehead T_{sk}, microclimate (next-to-skin) relative humidity ($\overline{RH}_{sk}$), heart rate (HR), and thermal discomfort during both trials; and used FAN accelerometery data to characterise cool-seeking behaviour's onset, duration, bout frequency, and work rate. Seven participants engaged with self-fanning, which varied individually in onset time (mean: 12:30 mm:ss [range: 00:49-30:19]), total duration (05:54 mm:ss [01:04-17:53]), and bouts (6 [1-17]), but not work rate (308±51 strokes·min^{-1}). Energy expenditure did not differ between *FAN vs. CONTROL* in those who fanned (433±28 vs. 447±64 KJ; *p*=0.993), nor time-dependent changes in T_c, $\bar{T}_{sk}$, $\overline{RH}_{sk}$, and *HR*. Our results indicate that our novel approach, which combine accelerometery (to quantify movement patterns) and indirect calorimetry (to measure associated energy expenditure), is both feasible and effective in quantifying the energetic cost of voluntary, behaviourally mediated thermoregulatory actions, and their individual variability during heat stress.

New and Noteworthy

We present a novel approach to characterise the energy cost of a common human cool-seeking behaviour (i.e. manual fanning) and its individual variability during heat stress. Results indicate that our novel approach, which combine accelerometery (movement patterns) and indirect calorimetry (energy expenditure), is feasible and effective. This approach could be applied to a variety of thermal behaviours, thereby broadening the methodological toolkit available to researchers to study the relationship between behavioural and autonomic human thermoregulation.

Keywords: Thermoregulatory behaviour; Heat exposure; Voluntary Cooling; Temperature regulation; Energy Cost

Introduction

As global temperatures rise and extreme heat events increase in frequency and severity, there is an ever-growing need to broaden our understanding of human heat tolerance and adaptation (1). Human thermal homeostasis is maintained through a coordinated interplay of behavioural, autonomic, and endocrine responses (2), occurring in an optimised sequence to reduce the physiological impact on other bodily systems (3). Behavioural thermoregulation represents humans' first and most effective line of defence against heat, such that when performed it may reduce the requirement of autonomic thermoeffector activation such as sweating (3).

When body temperature increases due to heat and/or physical activity, an autonomic reduction in sympathetic cutaneous vasoconstriction occurs, passively increasing skin blood flow and skin temperature to promote dry heat dissipation (3). This change in body temperature also activates thermoreceptors in the skin leading to conscious warm sensations, often in conjunction with skin wetness perception if sweating occurs (4, 5). These perceptual signals can in turn drive thermal discomfort (6). This experience is believed to largely drive cool-seeking behaviours—i.e. a voluntary action performed to alleviate increases in body temperatures and thermal discomfort during heat stress and/or physical activity—such as fanning, drinking, shade-seeking, reducing clothing insulation, and pacing (7, 8).

These behavioural responses will typically precede the onset of active cutaneous vasodilation and sweating—which are predominately dependent on changes in core temperature (9). This "orderly recruitment" of behavioural and autonomic heat-defence responses is believed to be dependent on energy-conservation principles, whereby the body favours behaviour before it engages more energy consuming processes such as sweating (which incurs in water loss) (3). Numerous studies exist which have investigated human thermoregulatory behaviours, typically in attempt to establish the contribution of core temperature, skin temperature, thermal discomfort, and thermal sensitivity on humans' decision to engage in cool-seeking behaviour (3, 6, 10). These studies commonly utilise methods including the shuttle-box model (parallel cold and hot chambers where participants can freely move between) (11, 12), changes in self-selected exercise work rate during heat stress (13-15), observations on the addition/removal of clothing (16, 17), and on the interaction with electronic cooling devices (18-21). However, the energy cost of such cool-seeking behaviours in humans—which has implications to understand energy conservation mechanisms for thermoregulation—has been rarely quantified and characterised, particularly under controlled laboratory settings.

The evidence above highlights a critical knowledge gap in our understanding of the relationship between behavioural and autonomic human thermoregulation. Indeed, it is often suggested that energy conservation mechanisms underlie the orderly recruitment of behavioural and autonomic thermoregulatory responses, whereby humans may naturally engage behaviour (e.g. cool-seeking) prior to the activation of energy-consuming heat loss responses (e.g. sweating) (22). Yet, as far as these authors know, limited evidence is available on the actual energy cost of such behaviours, likely due to a limited availability of methodological studies exploring approaches to quantify inherently variable responses such as individual (thermal) behaviours.

The importance of understanding the energy cost of human thermal behaviours is two-fold: on the one hand, if cool-seeking behaviour requires active movement (e.g. consider the act of fanning one-self, removing clothing, or seeking shade), then it could heighten the heat stress if the resulting cooling is not sufficient to offset the additional metabolic heat production arising from the behaviour itself; on the other hand, if the behaviour incurs a perceived effort, then the motivation to engage may be attenuated (23, 24). For example, Snopkowski et al. (25) recently employed a model where participants had to perform low-intensity handgrip exercise in order to receive transient cooling during heat stress. They reported that physical effort attenuated engagement in cool-seeking behaviour, owing to the motivational conflict of whether the physical effort required was worth the potential reductions in warm sensations and discomfort (25). However, energy expenditure during the handgrip exercise protocol was not assessed in the cited study.

The aim of this study was therefore to develop and test a novel approach to characterise the energy cost of human cool-seeking behaviour and its individual variability during heat stress. Specifically, our novel approach consisted in the integration of two well-established methodologies, i.e. accelerometery (to quantify movement patterns) (26, 27) and indirect calorimetry (to measure associated energy expenditure) (28)—both of which have been extensively validated—to characterise the energy cost of a common human cool-seeking behaviour in a cohort of healthy young adults exposed to heat stress. We selected manual fanning as an exemplar cool-seeking behaviour to establish the feasibility of our approach (**Figure 1**), due to its accessibility and familiarity (i.e. humans have engaged in this a cool-seeking behaviour for millennia (29)).

Methods

Ethical Approval

This study was approved by the University of Southampton Ethics Committee (approval number: 72799) and the West of Scotland Research Ethics Service (IRAS approval number: 308721). The study was carried out in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants prior to commencement of the study. This study was not part of a registered clinical trial.

Participants

The present study utilised a convenience sampling approach, recruiting a total of 10 young, healthy males (age: 20 ± 1 years; height: 183.5 ± 7.6 cm; mass: 78.4 ± 9.2 kg). Inclusion criteria included non-smokers, physically active individuals (regularly performing ≥ 30 min of moderate exercise at least 3 times per week), not heat acclimatised, free from musculoskeletal, cardiovascular and neurological diseases, and not currently undergoing any medical (including pharmacological and non-pharmacological) treatment.

Experimental design

Participants visited the laboratory on two occasions separated by ≥ 48 hours in the months between October and December 2024. Participants underwent two counterbalanced protocols: (*i*) 60-min seated exposure to 37.0 °C (± 0.4 °C) and 43.5 % (± 5.4 %) RH without a fan (CONTROL), and (*ii*) 60-min seated exposure to 37.0 °C (± 0.4 °C) and 44.3 % (± 6.0 %) RH with a fan (FAN) (**Figure 1**). This environmental condition was selected as it is has been reported to be a real-world upper-limit indoor temperature and humidity during heatwaves across the globe (30-33), and has the potential generate significant increases in body temperatures within a 60 min period (34, 35). Both trials took place within a climatic chamber (Design Environmental WIR 22/5H, Weiss Technik, Reiskirchen-Lindenstruth, Germany) with environmental conditions continuously measured by a temperature and humidity probe (Testo 440, Testo, Baden-Württemberg, Germany).

During both protocols, participants sat quietly in the chamber (**Figure 2**). The FAN protocol was comprised of two sections: FAN_{FREE} and $\text{FAN}_{\text{FIXED}}$. The duration of FAN_{FREE} was 55 min, during which participants had free access to a handheld fan to offset thermal discomfort. The fan was conveniently placed on a side table next to the participant. $\text{FAN}_{\text{FIXED}}$ immediately proceeded FAN_{FREE}, with the protocol involving 5 min of compulsory, continuous self-fanning. The $\text{FAN}_{\text{FIXED}}$ protocol was included in the study as a contingency measure to ensure the availability of self-fanning data, allowing us to explore the metabolic cost of self-fanning even if participants did not engage in the cool-seeking behaviour during FAN_{FREE}. Physiological data was measured continuously apart from blood pressure and forehead skin temperature (T_{sk}) which were collected every 5 min. During $\text{FAN}_{\text{FIXED}}$, forehead T_{sk} was measured every

2.5 min. For CONTROL, a near-identical protocol was carried out with the sole difference being the exclusion of a handheld fan.

Experimental procedures

On the day of their scheduled visits, participants were advised to drink ≥500 mL of water at least 2 h before their arrival to ensure adequate hydration. Upon their arrival to the laboratory, participants provided a urine sample for the assessment of their urine specific gravity (Digital refractometer, KERN, Balingen, Germany). If their urine specific gravity was >1.025 g/mL, then participants were asked to drink ~500 mL of water. Following 30 min, they were tested again prior to resuming with the study to ensure adequate hydration (36). Participants were instructed to bring a lose-fitting t-shirt, shorts, and ankle-length socks to wear for the protocol (*clo*: ~0.3). The clothes reserved for the study were weighed before participants changed into them. Participants then had their height and body mass measured via a free-standing stadiometer (SECA 213, SECA, Hamburg, Germany) and a high precision scale (KERN 150K2DL, Balingen, Germany), respectively. Subsequently, participants were provided with the hand-held fan to allow for familiarisation. While participants practiced using the fan, researchers did not correct technique or make any comments on fan speed as changes in technique can paradoxically have negative implications on movement economy (37). Familiarisation was considered successful when participants verbally confirmed that they were satisfied and understood how to utilise the fan. Participants were informed that during the FAN_{FREE} protocol, they would have access to the fan and clearly instructed to use the handheld fan as and when needed to offset any thermal discomfort. Participants were then instrumented with a heart rate monitor, blood pressure cuff, wireless temperature and humidity data loggers, and a face mask described below.

Following the completion of both protocols, and the removal of any attached equipment, participants were instructed to wipe off any accumulated sweat and were then weighed wearing all their clothes. After, participants were escorted to the changing room and instructed to remove all of their clothes and place them in a closed plastic bag, this was done to minimise the potential for the evaporation of sweat from their clothes. Once complete, participants were provided with a glass of water to rehydrate and were then discharged based on verbal confirmation alongside no observed issues with their wellbeing.

Body temperatures and microclimate

Core temperature (T_c) was measured through a telemetric pill (BodyCAP, Hérouville Saint-Claire, France) which provided a continuous measurement of gastrointestinal temperature as a surrogate for T_c (sample rate: 0.0667 Hz; accuracy: ± 0.1 °C; operating range: 25 °C to 45 °C). Participants ingested the telemetric pill 3 h prior to their arrival at the laboratory.

Furthermore, eight wireless temperature and humidity data loggers (Hygrochron, iButtons, Maxim, San Jose, USA) were taped in pairs to the skin of the upper-chest, deltoid, thigh and calf on the participant's dominant-hand side. Of each pair, one was taped directly onto the skin to continuously measure T_{sk} (sample rate: 0.0167 Hz; resolution: 11-Bit; accuracy: ± <0.5 °C; operating range: -20 °C to 85 °C), whilst the other was placed in a 3D-printed frame taped to the skin for the continuous measurement of skin microclimate relative humidity (RH_{sk}) (sample rate: 0.0167 Hz; resolution: 12-Bit; operating range: 0% to 100% RH),, as previously described (18). This custom-built frame elevated the data logger by 6 mm and ensured ample airflow around the skin. In doing so, it prevented artificial supersaturation of the sensor due to direct contact with the sweat on the skin (38, 39). Whole-body mean T_{sk} ($\bar{T}_{sk}$) and RH_{sk} ($\overline{RH}_{sk}$) were estimated according to the equations by Ramanathan (40) as illustrated below:

$$\bar{T}_{sk} = (Upperchest\ T_{sk} \times 0.3) + (Deltoid\ T_{sk} \times 0.3) + (Thigh\ T_{sk} \times 0.2) + (Calf\ T_{sk} \times 0.2)$$

$$\overline{RH}_{sk} = (Upperchest\ H_{sk} \times 0.3) + (Deltoid\ H_{sk} \times 0.3) + (Thigh\ H_{sk} \times 0.2) + (Calf\ H_{sk} \times 0.2)$$

An infrared thermal camera (ER53, FLIR Systems, Wilsonville, OR, USA) was used to capture thermal images of participants' faces. Images were captured every 5 min except during $\text{FAN}_{\text{FIXED}}$ where they were captured every 2.5 min. These images were then analysed offline on a specialist software (ResearchIR, FLIR Systems, Wilsonville, OR, USA). A digital outline of the forehead was then created on these images, and forehead T_{sk} was determined as the mean temperature of this area.

Fanning behaviour

Fanning behaviour was recorded via a tri-axial accelerometer (AX6, Axivity, UK—Range: ±2-16 g; Resolution: 16-bit) which was retrofitted to a handheld fan, sampling at 25 Hz. The fan was made of bamboo and silk, its dimensions were 38 x 21 cm (width x height) with an approximate surface area of 567 cm^2, and weighed 73.5 g. The raw accelerometer data were processed using a custom MATLAB (Natick, MA, USA) script to quantify participant fanning behaviour. This script is publicly available on GitHub: https://github.com/francescacavallo/fanning_behaviour_analysis.git. Using a graphical interface, researchers manually selected two periods within the trial: (*i*) the FAN_{FREE} section, and (*ii*) the $\text{FAN}_{\text{FIXED}}$ section.

Peak detection was performed on the Euclidean magnitude signal from the $\text{FAN}_{\text{FIXED}}$ section to establish a participant-specific threshold for temporal spacing between fanning strokes. This threshold was then used to segment and identify fanning bouts within the FAN_{FREE} period (**Figure 1**). Each bout was analysed for start time and duration (both reported as mm:ss), stroke count (peak count), work rate (strokes·min^{-1}), and time-magnitude signal area under the curve (AUC) to capture overall fanning. These metrics were tabulated across all identified bouts and exported for downstream statistical analysis. Subsequently, individual participant summary metrics such as total AUC, cumulative bout duration, and mean work rate (across all bouts) were calculated for the entire session.

Energy expenditure

Participants were instrumented with a face mask which was connected to a metabolic cart (Quark CPET Metabolic Cart, Cosmed, Rome, Italy). The flow sensor was calibrated using a 3 L calibration syringe. The O_2 and CO_2 sensors were calibrated with room air and reference gases of known concentration (O_2 16%, CO_2 5%). Inspired and expired gases were assessed by breath-to-breath analysis which, amongst the wide array of parameters, allowed for the calculation of cumulative energy expenditure expressed in either kilojoules (KJ) or AUC, as well as a breath-to-breath rate of energy expenditure (Kcal·min^{-1}). Additionally, metabolic equivalent of task (MET) was calculated using previously reported formulas where $MET = \frac{V\dot{O}_2}{Body\ mass \times 3.5}$ (41).

Thermal discomfort

Participants reported their whole-body thermal discomfort at baseline using a 5-point Likert scale based on previously reported recommendations (42): +1 comfortable; +2 slightly uncomfortable; +3 uncomfortable; +4 very uncomfortable; +5 extremely uncomfortable. These self-reports of thermal discomfort were collected again at 55 min and 60 min. During the FAN protocols, these time points correspond to end of FAN_{FREE}/start of FAN_{FIXED} (55 min) and end of FAN_{FIXED} (60 min). This approach was selected, as opposed to measuring thermal discomfort at regular intervals (e.g., every 5 min), as (a) the increased number of person-votes may introduce intra-individual error (43), and (b) it would be highly unlikely that these specific timepoints would have sufficient temporal resolution to capture any self-reported improvements in thermal discomfort, which are likely to be transient. While, a continuous visual analogue scale (VAS) could have been employed to assess thermal discomfort (44), changes in thermal discomfort would have likely coincide with self-fanning; as such, the dual task of simultaneously fanning and adjusting a continuous VAS rating could have introduced task complexity, potentially hindering cool-seeking behaviour and related energy expenditure. Participants were clearly instructed during the familiarisation phase to use the fan during the FAN_{FREE} condition to offset thermal discomfort. Thus, engagement in this behaviour—particularly as it requires physical work—was interpreted as a proxy of thermal discomfort, as commonly used in rodent models (45-48).

Central haemodynamics

Heart rate was continuously measured through an optical heart rate sensor (Verity Sense, Polar, Kempele, Finland) strapped around participants' non-dominant forearm. The heart rate sensor was then connected to the metabolic cart (Quark CPET Metabolic Cart, Cosmed, Rome, Italy) which recorded the data. Arterial blood pressure was measured via an automated stress test monitor (Tango M2, SunTech, Morrisville, NC, USA) using the machine's non-exercise mode function. The inflatable cuff was placed on the participants' non-dominant upper arm, with systolic (SBP) and diastolic (DBP) blood pressure measurements occurring every 5 min. Mean arterial pressure (MAP) was then calculated as $MAP = \left({}^{1}\!/_{3} \cdot SBP\right) + \left({}^{2}\!/_{3} \cdot DBP\right)$.

Estimated whole-body sweat loss

Participants had their clothes weighed as well as their clothed-body mass, pre- and post-protocol. The difference between clothed-body mass and clothing provided a measure of body mass at these two timepoints. Consequently, estimated whole-body sweat loss was calculated as the difference in pre-protocol body mass and post-protocol body mass.

Statistical analysis

A *priori* sample size calculation was performed using G*Power (version 3.1.9.7) for a two-way repeated measures ANOVA (f = 1.89; α = 0.05; β = 0.8). The premise of the sample size was based on previous data (49) that reported energy expenditure values for young, healthy adults during heat stress (wet bulb globe temperature: 29 ºC) during lying-rest, sitting-reading, and step-exercise (approximate METs: 1, 1.5 and 5.5 METs, respectively (50)). We obtained a minimum sample size of 4–6 participants to detect differences in energy expenditure between trials. However, since we could not guarantee that every participant would engage in the cool-seeking behaviour during FAN_{FREE}, we increased the sample size by ~50%; thus, bringing the minimum sample size of 10 participants.

Data were checked for outliers and assessed for normality via Shapiro-Wilk test and Mauchly's test of sphericity, with no corrections required. Differences in measured continuous variables were assessed using ANOVA with linear mixed-effects models. Linear mixed models are more appropriate for the analysis of nested and crossed structures of the data, where there are multiple observations within a single subject in a given condition as well as multiple observed conditions for each subject (51). The linear mixed model includes time, protocol, and their interaction as fixed effects. A random intercept accounts for the variation between the participants' baselines. After conducting the mixed-effects ANOVAs, post-hoc tests were conducted for significant time-protocol interactions only, using a

Bonferroni correction. Differences between ordinal data (i.e., thermal discomfort) were evaluated as the delta (Δ) values between key timepoints (55 min – 0 min, and 60 min – 55 min) using a Mann-Whitney U test. Relationships between physiological parameters and fanning behaviour parameters were assessed with Pearson's correlation analyses. In all analyses, P values of < 0.05 were considered statistically significant. Continuous data are reported as Mean ± SD while ordinal data are reported as Median ± IQR. Statistical analyses were performed using R 4.0.5 (52) in RStudio Version 1.2.5033 (Boston, MA, USA).

Results

Self-fanning engagement during FAN_{FREE}

Seven out of the 10 participants engaged with self-fanning during FAN_{FREE}, displaying a heterogeneous use of fanning as cool-seeking behaviour (**Table 1**). Specifically, onset time (12:30 ± 12:00; range: 00:49 – 30:19), total duration (05:54 ± 05:35; range: 01:04 – 17:53), and number of continuous fanning bouts (6 ± 6; range: 1-17 bouts) varied greatly at an individual level (**Figure 3**). However, self-fanning work rate was not different between participants (308 ± 51 strokes$\cdot$min^{-1}).

Physiological and perceptual responses during FAN_{FREE}

During FAN_{FREE}, $\bar{T}_{sk}$ and $\overline{RH}_{sk}$ increased by 2.47 ± 0.81 °C ($p < 0.001$) and 35.0 ± 12.8 % ($p = 0.001$), respectively, in the 7 participants that engaged in the cool-seeking behaviour (**Table 2**). These increases were comparable to that observed during CONTROL (all $p = 1.000$), and the magnitude of increase was not correlated to self-fanning parameters ($p \geq 0.119$). During FAN_{FREE} and CONTROL, no changes in T_c ($p = 0.944$), and forehead T_{sk} ($p = 0.239$), HR ($p = 0.946$), and MAP ($p = 0.670$) were observed from baseline to the end of protocol (**Table 2**). During FAN_{FREE}, total energy expenditure was 433 ± 28 KJ (i.e. 1.35 ± 0.04 METs), which was not different to CONTROL (447 ± 64 KJ; $p = 0.993$; **Table 2**). No correlations were found between self-fanning parameters and energy expenditure ($p \geq 0.178$) (**Table S1**). Participants started both protocols reporting a thermal comfort score of +1 ± 0 (i.e. descriptor: "comfortable"). At 55 min, median comfort scores increased to +2 "slightly uncomfortable", with no differences between FAN and CONTROL (i.e. Δ = +1 ± 3 vs +1 ± 2, respectively; $p = 0.968$).

Physiological and perceptual responses during $\text{FAN}_{\text{FIXED}}$

All ten participants continuously fanned for 5 min during $\text{FAN}_{\text{FIXED}}$, doing so at a self-fanning work rate of 305 ± 28 strokes$\cdot$min^{-1}, which was not different to that observed during FAN_{FREE} ($p = 0.941$).

Following the continuous 5 min bout of self-fanning, no changes in T_c, $\bar{T}_{sk}$ and $\overline{RH}_{sk}$, forehead T_{sk}, HR, and MAP were observed between the end of FAN_{FREE} and $\text{FAN}_{\text{FIXED}}$ (i.e., 55 min vs 60 min; all $p > 0.100$). With regards to between-protocol differences, no differences in physiological variables were found between the final values of $\text{FAN}_{\text{FIXED}}$ and CONTROL (all $p > 0.100$). Energy expenditure during $\text{FAN}_{\text{FIXED}}$ was not different to the corresponding final 5 min of CONTROL (48 ± 6 vs 52 ± 8 KJ; $p = 0.886$). The metabolic equivalent for $\text{FAN}_{\text{FIXED}}$ was 1.35 ± 0.05 METs.

At 60 min, thermal discomfort was lowered during $\text{FAN}_{\text{FIXED}}$ in comparison to CONTROL (mean ± SD: $\Delta = -1 \pm 1$ vs 0 ± 0, respectively; $p = 0.025$, **Figure 4**). No differences in estimated whole-body sweat losses were observed between FAN and CONTROL protocols for all participants (214g ± 77 vs 204g ± 87, respectively: $p = 0.816$).

Discussion

The present study sought to develop and test a novel approach to quantitively characterise cool-seeking behaviour and its energy cost during heat exposure in young healthy adults. Our results indicate that our novel approach, which combine accelerometery (to quantify movement patterns) and indirect calorimetry (to measure associated energy expenditure), alongside a suite of commonly used physiological and perceptual methods (i.e. body temperatures, cardiovascular responses, and thermal discomfort) is both feasible and effective when applied to the study of exemplar, common behaviours such as manual fanning.

Characterisation and individual variability in self-fanning behaviour

When exposed to a hot environment and provided with the freedom to engage with self-fanning (i.e. FAN_{FREE}), the majority of our participants ($n = 7/10$) engaged with this cool-seeking behaviour. We believe that this was likely the result of the observed, heat-induced increases in $\bar{T}_{sk}$ (i.e. ~2.5℃), moisture build up on the skin (i.e. ~35% increase in $\overline{RH}_{sk}$), and thermal discomfort (i.e. rated "slightly uncomfortable"), as recorded at the end of FAN_{FREE}. This observation is aligned with previous empirical evidence that has repeatedly demonstrated the role of increases in $\bar{T}_{sk}$ and $\overline{RH}_{sk}$—with the latter being a surrogate for physical skin wetness—as important drivers of thermal behaviour (4, 11, 53, 54). This observation also aligns with previous work showing that thermal discomfort can independently drive thermal behaviours (7, 8, 55), even during non-thermal warming via capsaicin (56).

While most of our participants engaged in self-fanning when given the opportunity, it is important to note that they did so in a highly individual manner, i.e. participants' engagement in self-fanning varied in onset time, total duration of fanning, and number of fanning bouts (**Figure 3**). Yet, those that engaged in self-fanning predominately did so for multiple bouts (**Figure 3**) and at a similar work rate (308 ± 51 strokes·min^{-1}). An advantage of our novel approach is that it allowed us to characterise such individual variability, which is also commonly seen during exercise (57). In accordance with the literature (58), it is plausible to hypothesise that the heterogeneity in responses and why participants did/did not engage with self-fanning could be related to individual variations in the extent of changes in $\bar{T}_{sk}$ and $\overline{RH}_{sk}$ amongst our fanners, given that no reductions in T_c, $\bar{T}_{sk}$, forehead T_{sk}, $\overline{RH}_{sk}$, physiological strain, and thermal discomfort were observed during FAN$_{\text{FREE}}$ (**Table 2**). However, correlation analysis revealed no relationships between self-fanning and changes in $\bar{T}_{sk}$, and $\overline{RH}_{sk}$. One alternative explanation for the heterogeneity of the self-fanning engagement may be related to the relatively modest level of heat stress experienced by participants which did not result in any meaningful increase in their T_c. Under the present acute, passive heat exposure conditions—where only minimal changes in T_c were observed—alterations in skin temperature and wetness are arguably the primary drivers of thermal behaviours (58). In contrast, when heat stress and/or physical activity are sufficient to increase T_c, T_c typically accounts for the greatest proportion of variance in the magnitude of cool-seeking behaviours resulting from endogenous and exogenous heat stress (18-21). Under such conditions of more severe heat stress, it is plausible to hypothesise that participant engagement with the cool-seeking behaviour would be more homogenous, reflecting the stronger and more uniform thermoregulatory challenge. Future studies should therefore consider evaluation of our self-fanning paradigm under more severe heat stress levels that are likely to increase T_c.

We also believe that there are important considerations to be made regarding the transient nature of any convection-mediated changes in local skin temperature and airflow during the act of self-fanning. Specifically, these effects are likely to be very transient and localised. As such, these may have not been well captured by e.g. our IR measurements of face skin temperature (sampled every 5 minutes) nor our continuous thermistor measurements (i.e. the measured skin area would have been covered by the sensor). Hence, the fact that our measurements did not capture such physiological changes, does not necessarily mean that these did not occur at a time and in a magnitude sufficient to be perceived as potentially beneficial to drive repeated engagement. Equally, we cannot exclude that the perception of airflow itself (mediated via mechanoreceptors in the skin) may have provided some form of relief in the absence of actual skin cooling (59), aspects of which could have driven the observed individual variation in behaviour.

Understanding the drivers of individual variability in autonomic and behavioural thermoregulatory responses continues to be an important research priority, particularly when one aims to understand variability in adaptation to heat stress under real-life scenarios. In this context, we believe that the findings and observations above indicate that our novel approach can be used effectively to broaden the range of methods available to our community to characterise ecologically relevant cool-seeking behaviours and their individual variability.

Energy cost of self-fanning behaviour

With the present study, we selected a common and wide-spread cool-seeking behaviour, i.e. self-fanning, as we believed it offered ecological validity and a relevant motivational scenario: we expected that individual engagement with fanning may at least partly involve (whether consciously or unconsciously) an evaluation of whether the physical effort—and possible metabolic energy cost—required to self-fan was worth the potential reductions in thermal discomfort and additional heat load (25). Whilst this approach had been widely used in other animal models (60, 61), to our knowledge, it has received limited empirical evaluation in humans to date. We also recognise that other cool-seeking behaviours may have offered greater "cooling power"—consider the use of electric fanning as described in the recent paper of Wang et al. (62). However, many of these strategies do not require continuous active movement and may therefore have provided an inferior model for the examination of the energetic cost associated with an actively generated cooling response.

In relation to the above, in this study we recorded no meaningful differences in energy expenditure between FAN and CONTROL (**Table 2**). This observation is relevant, as it may help better contextualise a societal belief claiming that self-fanning may paradoxically makes one hotter due to the associated metabolic heat production (63-67). Indeed, our physiological measurements (**Table 2**) indicated that self-fanning did not make participants any hotter than sitting quietly, neither during FAN_{FREE} nor $\text{FAN}_{\text{FIXED}}$.

It is important to highlight that self-fanning requires muscular work to move the fan, which is inherently associated with a metabolic cost. Based on our measurements, we estimated this to be 1.35 METs, which was comparable to sitting quietly in the heat (1.3 METs), but less costly than, for example, light housework (2.0 METs) (41, 50). One could argue that the metabolic energy cost of self-fanning may have gone unnoticed due to it being lower than the sensitivity of the metabolic cart to detect a change in energy expenditure. If that were the case, it would further support the view that the metabolic cost of self-fanning is still extremely low, as the measurement error for energy expenditure using the Quark CPET Metabolic Cart (Cosmed, Rome, Italy) is ~0.68 ± 0.99 % (68). Given that participants did not fan continuously for more than 5 min and that the metabolic cost of self-fanning appears to be very low, it is therefore not entirely surprising that self-fanning would have not been sufficiently metabolically taxing to induce substantial increases in body temperature.

Notably, during $\text{FAN}_{\text{FIXED}}$, thermal discomfort was reduced during the 5 min period of continuous self-fanning compared to CONTROL (**Figure 4**), suggesting that self-fanning may offer a transient improvement in thermal comfort. It is reasonable to assume that a similar reduction in thermal discomfort may have occurred under FAN_{FREE} but that it was not captured due to the assessment of thermal comfort occurring at pre- and post-FAN_{FREE}. Given that participants were instructed to use the fan to "offset thermal discomfort," engagement in this behaviour—particularly instances involving frequent or prolonged fanning—provides additional support for its potential to elicit transient improvements in thermal comfort, consistent with how thermal comfort is often inferred from rodent models (45-48).

Altogether, we believe that the considerations above further highlight the potential of using the novel approach presented here to more directly interrogate questions related to metabolic energy-management models, their application to human thermal behaviour, and their relevance to decision making associated with heat adaptation strategies.

Experimental considerations

There are several experimental considerations for this study. First, only healthy, young males participated in this study. Whilst there is a call for greater inclusion of females in physiological research (69-72), the primary aim of the present study was to assess the feasibility of a novel approach to characterise cool-seeking behaviour and its energy cost. There are well-established sex-differences in thermal comfort, perception and body temperatures during heat stress (43, 62, 73), as well as the effect of menstrual cycle on body temperature, energy expenditure, thermal perception and thermal behaviour (74-79). Hence, future research is warranted to establish whether sex-dependent differences in this type of behaviour occur.

In addition, we believe that the potential of self-fanning to reduce forehead T_{sk} and thermal discomfort may be under-represented due to the use of a CPET mask. The use of the mask not only limited the cooling area to the side of the face and forehead but also, likely created a warm and humid microclimate around the participants' nose and mouth (80). It is therefore possible that the (a) potential improvements in thermal discomfort were attenuated, and (b) engagement in this cool-seeking behaviour was limited due to a possible reduction in perceived/actual cooling benefits. Nonetheless, we believe that this does not directly affect the rigor or validity of the present findings, given that the primary aim of this study was not to evaluate the efficacy of self-fanning as a cooling strategy, but rather, to develop a novel approach for characterising this cool-seeking behaviour and quantifying its associated energy cost—an objective that was achieved, given that the majority of participants (70%) engaged in the behaviour during FAN_{FREE}.

Since there are strong links between facial fanning and thermal comfort (81, 82), and between thermal discomfort and cool-seeking behaviour (56), future studies may consider alternative approaches that do not cover the face (e.g. direct calorimetry) to measure energy expenditure and associated thermal loads during cool-seeking behaviour. Our laboratory is in the process of utilising our fan methodology without a face mask in vulnerable groups, with preliminary findings indicating comparable cool-seeking behaviour engagement and T_{sk} profiles to those observed in the present study (83).

Finally, future studies may also consider implementing evaluation of the Rate of Perceived Exertion associated with the active behaviour, to better understand the relationship between motivation to engage and behaviour's efficacy (25).

Conclusion

Our results indicate that our novel approach, which combine accelerometery (to quantify movement patterns) and indirect calorimetry (to measure associated energy expenditure), is both feasible and effective to characterise the energy cost of a common human cool-seeking behaviour (i.e. manual fanning) and its individual variability during heat stress. This approach could be used to more directly interrogate questions related to performance energy-management models, their application to human thermal behaviour, and their relevance to decision making associated with heat adaptation strategies, under controlled laboratory conditions.

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Conflict of interest

None declared.

Data Availability Statement

Data will be made available upon publication at the University of Southampton data repository (PURE; URL to be activated upon publication).

Supplemental Material

Supplementary Table 1 DOI: http://dx.doi.org/10.5258/SOTON/D3780.

Author Contributions

Nuno Koch Esteves, Daisy Luck and Davide Filingeri conceived and designed research. Nuno Koch Esteves, Daisy Luck and Hannah Blount performed experiments. Nuno Koch Esteves, Francesca R Cavallo, and Peter R Worsley analysed data. Nuno Koch Esteves and Davide Filingeri interpreted results of experiments. Nuno Koch Esteves prepared figures. Nuno Koch Esteves and Davide Filingeri drafted manuscript. Nuno Koch Esteves, Hannah Blount, Peter R Worsley, Justin Sheffield, Ian Galea and Davide Filingeri edited and revised the manuscript. Nuno Koch Esteves, Daisy Luck, Hannah Blount, Peter R Worsley, Justin Sheffield, Ian Galea and Davide Filingeri approved final version of the manuscript.

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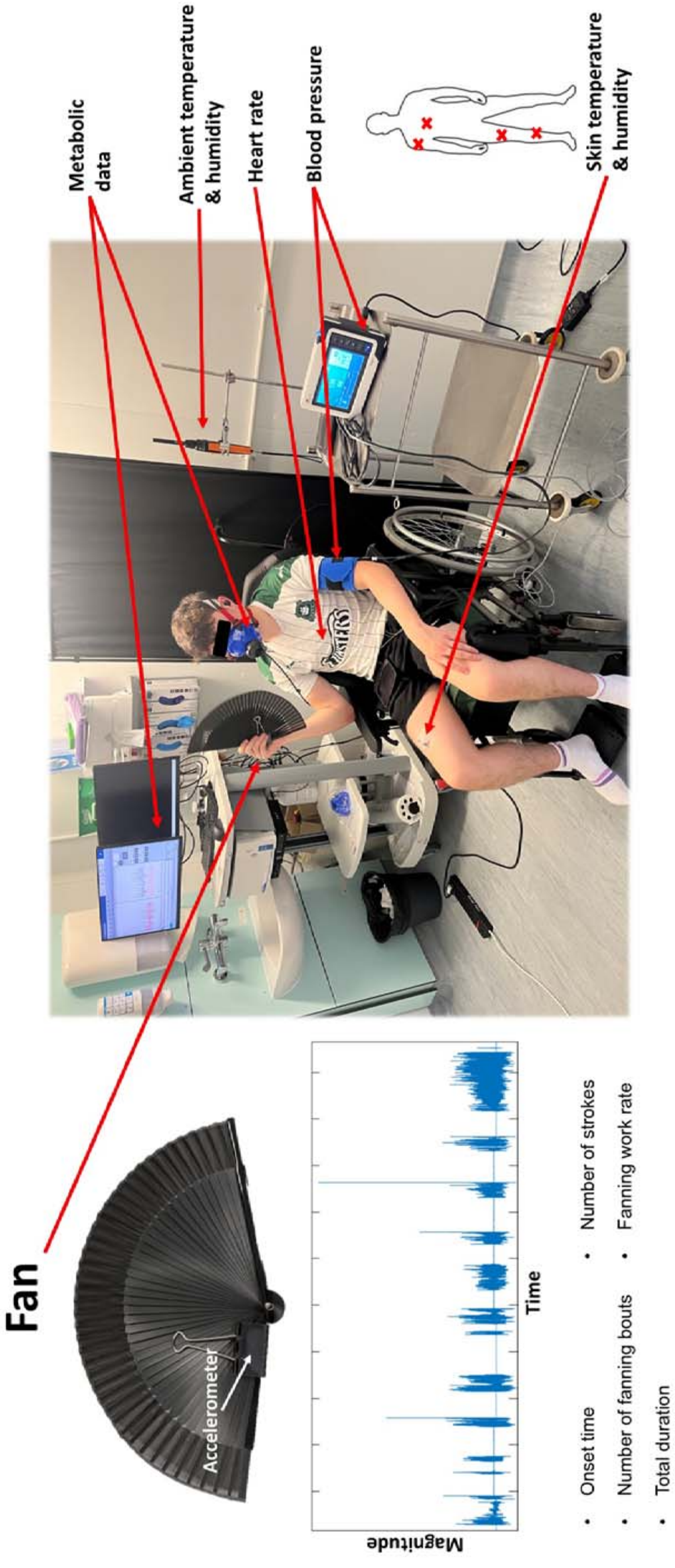
Figure Legends

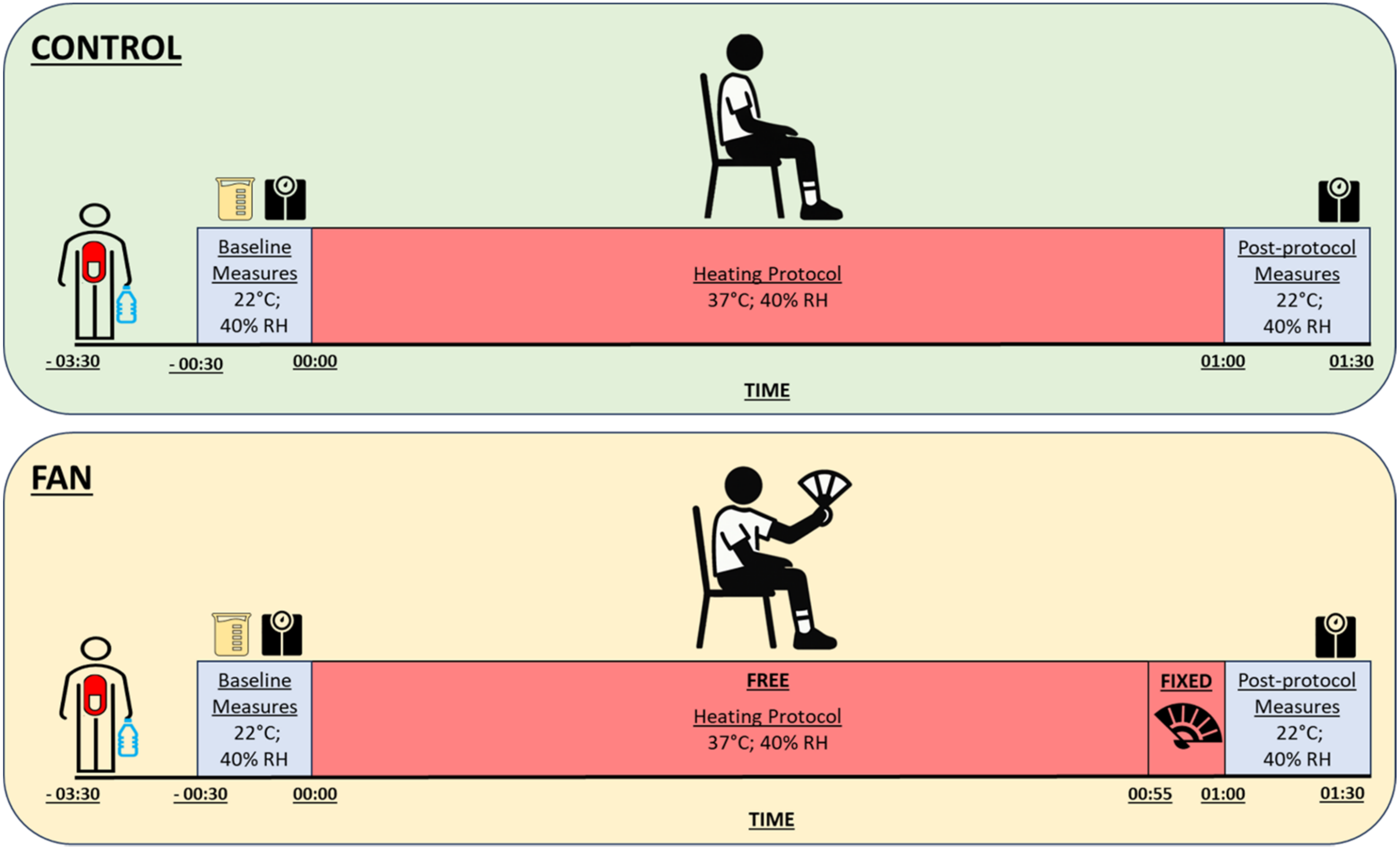
Figure 1. Experimental set up of the study for the FAN protocol. This figure illustrates the instrumentation used to assess physiological and behavioural responses during the FAN protocol. A handheld fan equipped with an accelerometer measuring fanning activity, including onset time, number of fanning bouts, total duration, number of strokes, and fanning work rate. A participant is shown actively fanning while undergoing continuous monitoring of multiple physiological variables. Metabolic data are collected via a metabolic cart connected to a face mask. Ambient temperature and humidity are recorded near the participant. Heart rate is monitored via chest strap, and blood pressure is measured with an automatic cuff. Skin temperature and humidity are recorded from multiple sites on the body via wireless thermistors (iButtons). This integrated setup enables comprehensive analysis of the participant's thermoregulatory behaviour and physiological responses during manual self-fanning.

Figure 2. Schematic of the experimental design.

Figure 3. Engagement with self-fanning during FAN_{FREE}. Engagement reported as a cumulative frequency of the number of fan strokes. Lines represent individual responses. N = 7, solely representing those who engaged with the cooling-seeking behaviour.

Figure 4. Changes in thermal discomfort during $\text{FAN}_{\text{FIXED}}$ and the final 5 min of CONTROL. Bars reported as Mean ± SD along with individual data points for n = 10.


Fan
Accelerometer
Magnitude
Time
Onset time
Number of fanning bouts
Total duration
Number of strokes
Fanning work rate
Metabolic data
Ambient temperature & humidity
Heart rate
Blood pressure
Skin temperature & humidity


CONTROL
Baseline Measures
22°C;
40% RH
Heating Protocol
37°C; 40% RH
Post-protocol Measures
22°C;
40% RH
- 03:30
- 00:30
00:00
01:00
01:30
TIME
FAN
Baseline Measures
22°C;
40% RH
FREE
Heating Protocol
37°C; 40% RH
FIXED
Post-protocol Measures
22°C;
40% RH
- 03:30
- 00:30
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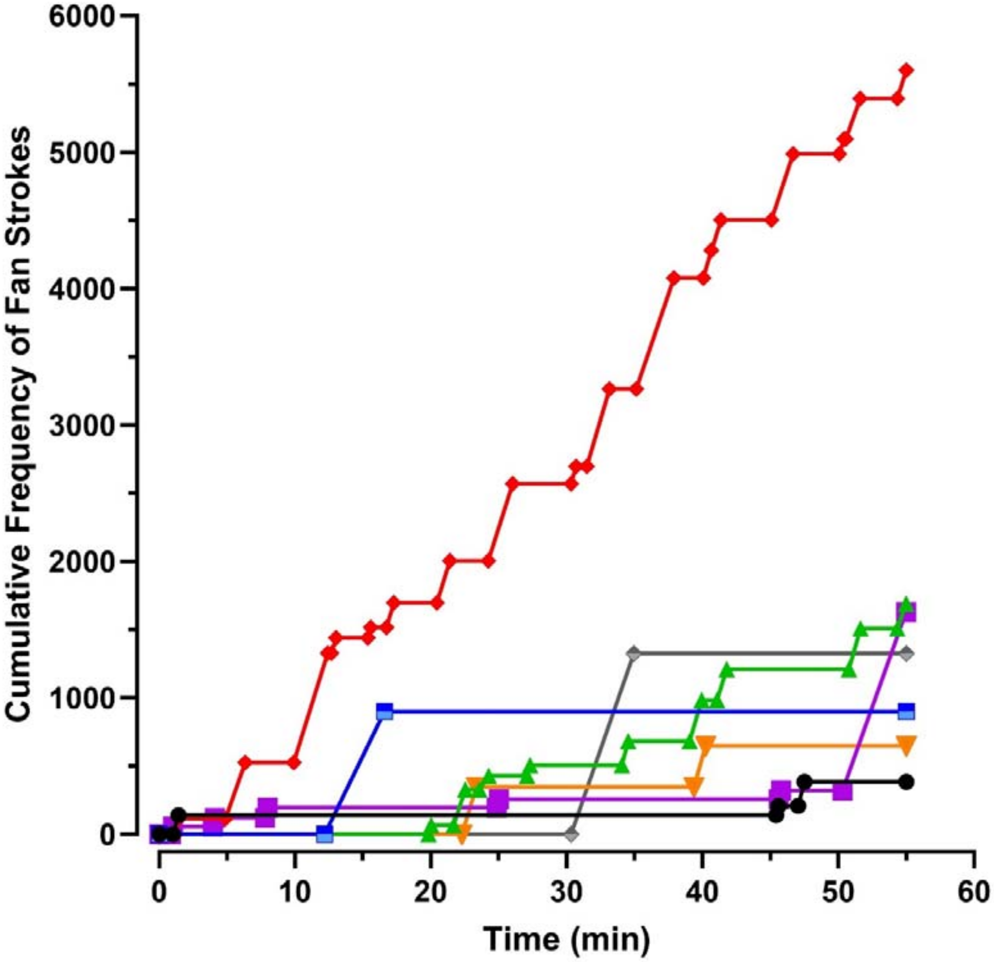
TIME


6000
5000
4000
3000
2000
1000
0
Cumulative Frequency of Fan Strokes
0
10
20
30
40
50
60
Time (min)

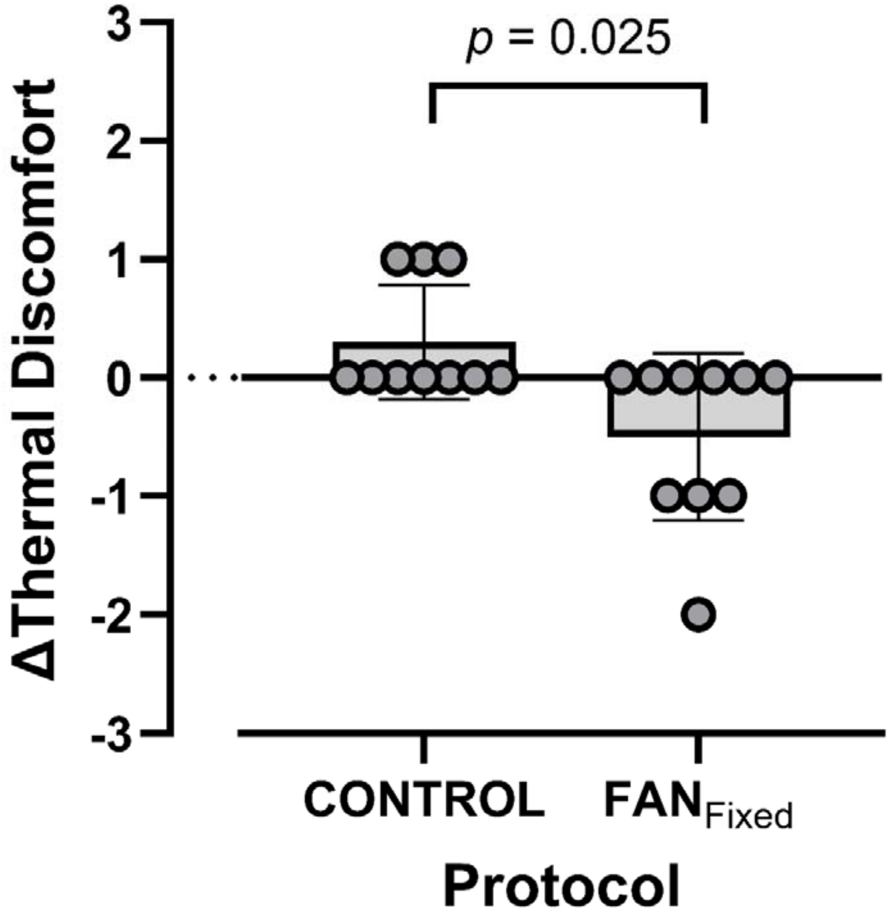

p = 0.025
3
2
1
0
-1
-2
-3
ΔThermal Discomfort
CONTROL
FAN$_{Fixed}$
Protocol

Table 1**.** Cool-seeking behaviour (self-fanning) responses during FAN_{Free} (n = 7).

Variables	Mean ± SD	Min – Max
Onset of fanning (mm:ss)	12:30 ± 12:00	00:49 – 30:19
Total duration of fanning (mm:ss)	05:54 ± 05:36	01:04 – 17:53
Number of continuous fanning bouts (frequency)	6 ± 6	1 – 17
Fanning work rate ($strokes \cdot min^{-1}$)	308 ± 51	205 – 362

Table 2. Physiological and perceptual responses during FAN_{FREE} and CONTROL trials.

Variable	Timepoint	FAN_{FREE}	CONTROL	*p* values
T_c (°C)	Baseline	37.2 ± 0.3	37.0 ± 0.1	Time: 0.926 Protocol: < 0.001 Interaction: 0.944
	End	37.0 ± 0.3	37.0 ± 0.2	
$\bar{T}_{sk}$ (°C)	Baseline	32.9 ± 1.06	32.8 ± 0.73	Time: < 0.001 Protocol: 0.078 Interaction: 0.993
	End	35.4 ± 0.31	35.5 ± 0.31	
$\overline{RH}_{sk}$ (%)	Baseline	53.6 ± 9.8	48.0 ± 6.9	Time: < 0.001 Protocol: < 0.001 Interaction: 0.977
	End	85.3 ± 7.7	79.0 ± 11.1	
Forehead T_{sk} (°C)	Baseline	36.0 ± 0.86	35.7 ± 0.62	Time: 0.126 Protocol: 0.850 Interaction: 0.239
	End	36.6 ± 0.43	36.8 ± 0.15	
HR (bpm)	Baseline	71 ± 16	72 ± 12	Time: 0.014 Protocol: 0.218 Interaction: 0.946
	End	77 ± 13	78 ± 10	
MAP (mmHg^{-1})	Baseline	95 ± 7	96 ± 7	Time: 0.1792 Protocol: 0.0943 Interaction: 0.670
	End	95 ± 10	94 ± 7	
Total energy expenditure (KJ)	Baseline	0 ± 0	0 ± 0	Time: < 0.001 Protocol: 0.249 Interaction: 0.993
	End	433 ± 28	447 ± 64	

Data reported as mean ± SD. P values obtained following a linear mixed-effects model. Baseline values represent resting, normothermic values at timepoint 0m. End values represent end of FAN_{FREE} protocol values at 55m.

Novel Approach to Characterise Cool-seeking Behaviour

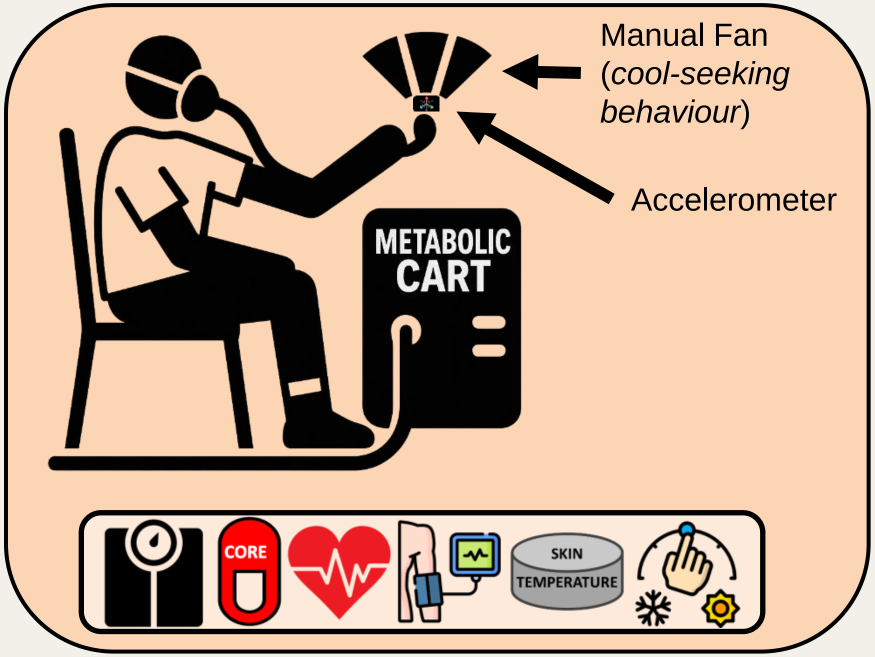
METHODS

→

Two 1h conditions at 37°C/44%RH

FAN
Access to handheld fan
(55’ free + 5’ fixed fanning)

CONTROL
No access to handheld fan



OUTCOMES

Mean skin temperature

Δ = +2.5 °C

No difference between FAN vs CONTROL

Energy expenditure

447 KJ / 1.4 METs

No difference between FAN vs CONTROL

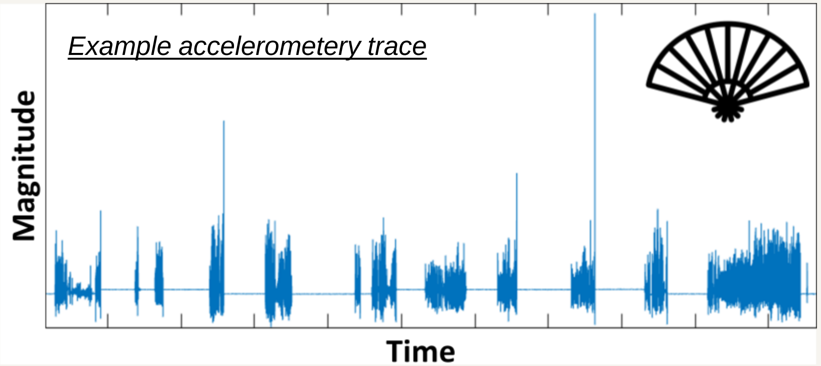
Fanning behaviour

- 7/10 engaged
- Onset time: 12’30”
- Duration: 5’54”
- Frequency: 6
- Work rate: 308 strokes·min^{-1}

Thermal discomfort

Δ = Comfortable to Slightly Uncomfortable

1 vote lower in FAN vs CONTROL



CONCLUSION

Findings show that combining accelerometery with indirect calorimetry is a feasible, effective way to quantify the energetic cost of behaviour-driven thermoregulation and its individual variability under heat stress.