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METHODS AND RESOURCES

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

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Abstract

Behavioral 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 behaviors in humans has been rarely quantified. Here, we present a novel approach to characterize the energy cost of a common human cool-seeking behavior (i.e., manual fanning) and its individual variability during heat stress. Ten healthy males (20 ± 1 yr) participated in two 60-min trials (CONTROL and FAN) consisting of resting exposure to 37(±0.4)°C and 44(±6)% relative humidity (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 ($\overline{T}_{sk}$), 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 characterize cool-seeking behavior's onset, duration, bout frequency, and work rate. Seven participants engaged with self-fanning, which varied individually in onset time [mean: 12:30 min:s (range: 00:49–30:19)], total duration [05:54 min:s (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, $\overline{T}_{sk}$, $\overline{RH}_{sk}$, and HR. Our results indicate that our novel approach, which combines 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, behaviorally mediated thermoregulatory actions and their individual variability during heat stress.

NEW & NOTEWORTHY We present a novel approach to characterize the energy cost of a common human cool-seeking behavior (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 behaviors, thereby broadening the methodological toolkit available to researchers to study the relationship between behavioral and autonomic human thermoregulation.

energy cost; heat exposure; temperature regulation; thermoregulatory behavior; voluntary cooling

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 behavioral, autonomic, and endocrine responses (2), occurring in an optimized sequence to reduce the physiological impact on other bodily systems (3). Behavioral thermoregulation represents humans' first and most effective line of defense 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

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sweating occurs (4, 5). These perceptual signals can in turn drive thermal discomfort (6). This experience is believed to largely drive cool-seeking behaviors—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 behavioral responses will typically precede the onset of active cutaneous vasodilation and sweating—that are predominately dependent on changes in core temperature (9). This "orderly recruitment" of behavioral and autonomic heat-defense responses is believed to be dependent on energy-conservation principles, whereby the body favors behavior before it engages more energy consuming processes such as sweating (which incurs in water loss) (3). Numerous studies exist that have investigated human thermoregulatory behaviors, typically in an attempt to establish the contribution of core temperature, skin temperature, thermal discomfort, and thermal sensitivity on humans' decision to engage in cool-seeking behavior (3, 6, 10). These studies commonly utilize 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 behaviors in humans—which has implications to understand energy conservation mechanisms for thermoregulation—has been rarely quantified and characterized, particularly under controlled laboratory settings.

The evidence mentioned earlier highlights a critical knowledge gap in our understanding of the relationship between behavioral and autonomic human thermoregulation. Indeed, it is often suggested that energy conservation mechanisms underlie the orderly recruitment of behavioral and autonomic thermoregulatory responses, whereby humans may naturally engage behavior (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 behaviors, likely due to a limited availability of methodological studies exploring approaches to quantify inherently variable responses such as individual (thermal) behaviors.

The importance of understanding the energy cost of human thermal behaviors is twofold: on the one hand, if cool-seeking behavior 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 behavior itself; on the other hand, if the behavior incurs a perceived effort, then the motivation to engage may be attenuated (23, 24). For example, Snopkowski et al. (25) recently used a model where participants had to perform low-intensity handgrip exercise to receive transient cooling during heat stress. They reported that physical effort attenuated engagement in cool-seeking behavior, 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 characterize the energy cost of human cool-seeking behavior 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 characterize the energy cost of a common human cool-seeking behavior in a cohort of healthy young adults exposed to heat stress. We selected manual fanning as an exemplar cool-seeking behavior to establish the feasibility of our approach (Fig. 1), due to its accessibility and familiarity [i.e., humans have engaged in this a cool-seeking behavior 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 No. 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 utilized a convenience sampling approach, recruiting a total of 10 young, healthy males (age: 20 ± 1 yr; height: 183.5 ± 7.6 cm; mass: 78.4 ± 9.2 kg). Inclusion criteria included nonsmokers; physically active individuals (regularly performing ≥30 min of moderate exercise at least 3 times per week); not heat acclimatized; free from musculoskeletal, cardiovascular, and neurological diseases; and not currently undergoing any medical (including pharmacological and nonpharmacological) treatment.

Experimental Design

Participants visited the laboratory on two occasions separated by ≥48 h in the months between October and December 2024. Participants underwent two counterbalanced protocols: *1*) 60-min seated exposure to 37.0°C (±0.4°C) and 43.5% (±5.4%) relative humidity (RH) without a fan (CONTROL) and *2*) 60-min seated exposure to 37.0°C (±0.4°C) and 44.3% (±6.0%) RH with a fan (FAN) (Fig. 1). This environmental condition was selected as it 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 to 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).

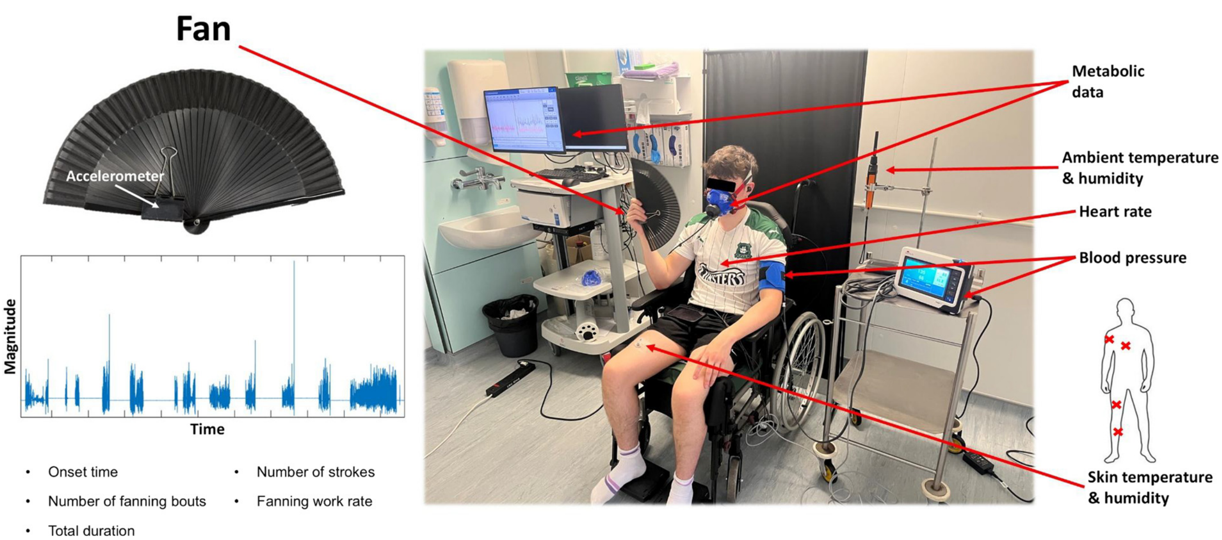

Figure 1. Experimental setup of the study for the FAN protocol. This figure illustrates the instrumentation used to assess physiological and behavioral responses during the FAN protocol. A handheld fan was equipped with an accelerometer measuring fanning activity, including onset time, number of fanning 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 (HR) is monitored via an optical HR sensor, 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 behavior and physiological responses during manual self-fanning.

During both protocols, participants sat quietly in the chamber (Fig. 2). The FAN protocol comprised 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,

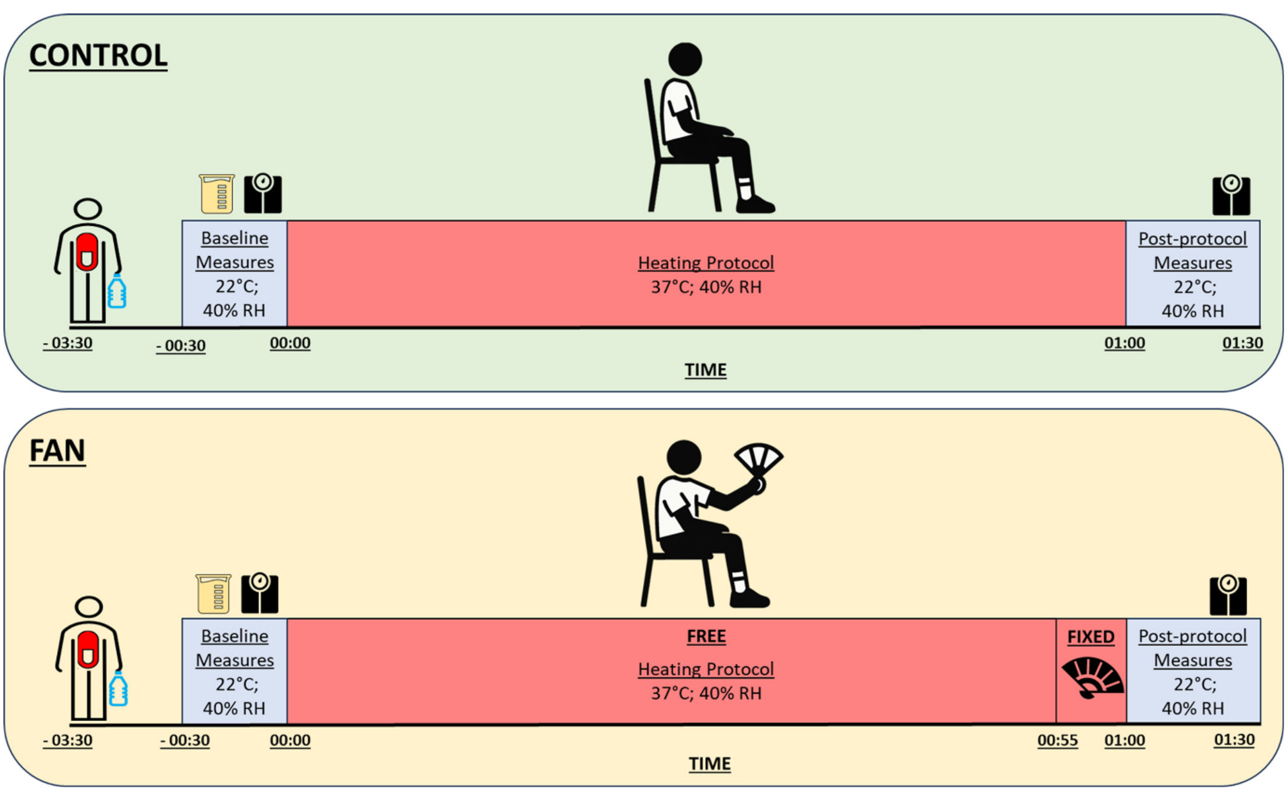

Figure 2. Schematic of the experimental design.

allowing us to explore the metabolic cost of self-fanning even if participants did not engage in the cool-seeking behavior during FAN_{FREE}. Physiological data were measured continuously apart from blood pressure and forehead skin temperature (T_{sk}) that were collected every 5 min. During FAN_{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 loose-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 handheld fan to allow for familiarization. Although 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). Familiarization was considered successful when participants verbally confirmed that they were satisfied and understood how to utilize 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 (HR) monitor, blood pressure cuff, wireless temperature and humidity data loggers, and a face mask.

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 minimize 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: 25–45°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, CA) 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), whereas the other was placed in a three-dimensional (3-D) 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%–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} ($\overline{T}_{sk}$) and RH_{sk} ($\overline{RH}_{sk}$) were estimated according to the equations by Ramanathan (40) as illustrated below:

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

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

An infrared thermal camera (ER53, FLIR Systems, Wilsonville, OR) was used to capture thermal images of participants' faces. Images were captured every 5 min except during FAN_{FIXED}, where they were captured every 2.5 min. These images were then analyzed offline on a specialist software (ResearchIR, FLIR Systems, Wilsonville, OR). 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 behavior.

Fanning behavior 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 × 21 cm (width × 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) script to quantify participant fanning behavior. 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: *1*) the FAN_{FREE} section and *2*) the FAN_{FIXED} section.

Peak detection was performed on the Euclidean magnitude signal from the FAN_{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 (Fig. 1). Each bout was analyzed for start time and duration (both reported as min:s), 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 that 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, among 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 ($kcal \cdot min^{-1}$). In addition, metabolic equivalent of task (MET) was calculated using previously reported formulas, where $MET = \frac{\dot{V}O_2}{\text{Body mass} \times 3.5}$ (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 *1*) the increased number of person-votes may introduce intra-individual error (43), and *2*) 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. Although a continuous visual analogue scale (VAS) could have been used to assess thermal discomfort (44), changes in thermal discomfort would have likely coincided 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 behavior and related energy expenditure. Participants were clearly instructed during the familiarization phase to use the fan during the FAN_{FREE} condition to offset thermal discomfort. Thus, engagement in this behavior, particularly as it requires physical work, was interpreted as a proxy of thermal discomfort, as commonly used in rodent models (45–48).

Central hemodynamics.

HR was continuously measured through an optical HR sensor (Verity Sense, Polar, Kempele, Finland) strapped around participants' nondominant forearm. The HR 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) using the machine's nonexercise mode function. The inflatable cuff was placed on the participants' nondominant upper arm, with systolic (SBP) and diastolic (DBP) blood pressure measurements occurring every 5 min. Mean arterial pressure (MAP) was then calculated as $MAP = (⅓ \times SBP) + (⅔ \times DBP)$.

Estimated whole body sweat loss.

Participants had their clothes weighed and their clothed-body mass, pre- and postprotocol. 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 preprotocol body mass and postprotocol body mass.

Statistical Analysis

A priori sample size calculation was performed using G*Power (v.3.1.9.7) for a two-way repeated measures ANOVA ($f = 1.89$; $\alpha = 0.05$; $\beta = 0.8$). 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°C) 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 behavior 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-effects 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-effects model includes time, protocol, and their interaction as fixed effects. A random intercept accounts for the variation between the participants' baselines. After conducting the linear 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 behavior 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, whereas 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).

RESULTS

Self-Fanning Engagement during FAN_{FREE}

Seven of the 10 participants engaged with self-fanning during FAN_{FREE}, displaying a heterogeneous use of fanning as cool-seeking behavior (Table 1). Specifically, onset time (12:30 ± 12:00; range: 00:49–30:19), total duration

Table 1. *Cool-seeking behavior (self-fanning) responses during FAN$_{Free}$ (n = 7)*

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

(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 (Fig. 3). However, self-fanning work rate was not different between participants (308 ± 51 strokes·min^{-1}).

Physiological and Perceptual Responses during FAN$_{FREE}$

During FAN$_{FREE}$, $\overline{T}_{sk}$ 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 seven participants who engaged in the cool-seeking behavior (Table 2). These increases were comparable with 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 ($P = 0.944$), 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 ($P \geq 0.178$) (Supplemental Table S1). Participants started both protocols reporting a thermal comfort score of +1 ± 0 (descriptor: "comfortable"). At 55 min, median comfort scores increased to +2 "slightly uncomfortable," with no differences between FAN and CONTROL (Δ = +1 ± 3 vs. +1 ± 2, respectively; $P = 0.968$).

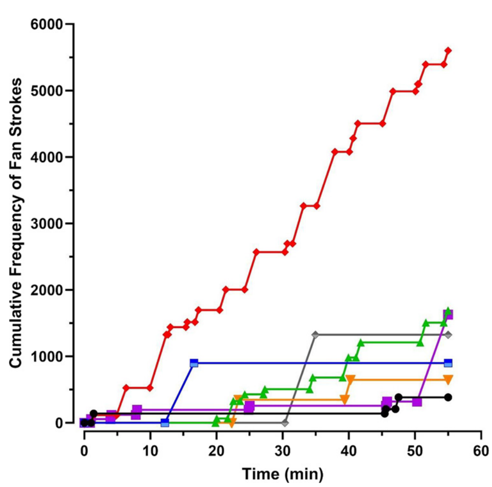

Figure 3. Engagement with self-fanning during FAN$_{FREE}$. Engagement reported as a cumulative frequency of the number of fan strokes. Lines represent individual responses. $n = 7$, solely representing those who engaged with the cooling-seeking behavior.

Physiological and Perceptual Responses during FAN$_{FIXED}$

All 10 participants continuously fanned for 5 min during FAN$_{FIXED}$, doing so at a self-fanning work rate of 305 ± 28 strokes·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, $\overline{T}_{sk}$, and $\overline{RH}_{sk}$, forehead T_{sk}, HR, and MAP were observed between the end of FAN$_{FREE}$ and FAN$_{FIXED}$ (i.e., 55 min vs. 60 min; all $P > 0.100$). With regard to between-protocol differences, no differences in physiological variables were found between the final values of FAN$_{FIXED}$ and CONTROL (all $P > 0.100$). Energy expenditure during FAN$_{FIXED}$ was not different to the corresponding final 5 min of CONTROL (48 ± 6 vs. 52 ± 8 kJ, respectively; $P = 0.886$). The metabolic equivalent for FAN$_{FIXED}$ was 1.35 ± 0.05 METs.

At 60 min, thermal discomfort was lowered during FAN$_{FIXED}$ compared with CONTROL (mean ± SD: Δ = −1 ± 1 vs. 0 ± 0, respectively; $P = 0.025$, Fig. 4). No differences in estimated whole body sweat losses were observed between FAN and CONTROL protocols for all participants (214 g ± 77 vs. 204 g ± 87, respectively: $P = 0.816$).

DISCUSSION

The present study sought to develop and test a novel approach to quantitively characterize cool-seeking behavior 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 behaviors such as manual fanning.

Characterization and Individual Variability in Self-Fanning Behavior

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 behavior. We believe that this was likely the result of the observed, heat-induced increases in $\overline{T}_{sk}$ (i.e., ∼2.5°C), 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 $\overline{T}_{sk}$ and $\overline{RH}_{sk}$—with the latter being a surrogate for physical skin wetness—as important drivers of thermal behavior (4, 11, 53, 54). This observation also aligns with previous work showing that thermal discomfort can independently drive thermal behaviors (7, 8, 55), even during nonthermal warming via capsaicin (56).

Although 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

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

Data reported as means ± SD. *P* values obtained following a linear mixed-effects model. Baseline values represent resting, normothermic values at timepoint 0 m. End values represent end of FAN_{FREE} protocol values at 55 m. HR, heart rate; MAP, mean arterial pressure.

duration of fanning, and number of fanning bouts (Fig. 3). Yet, those that engaged in self-fanning predominately did so for multiple bouts (Fig. 3) and at a similar work rate (308 ± 51 $strokes \cdot min^{-1}$). An advantage of our novel approach is that it allowed us to characterize such individual variability, which is also commonly seen during exercise (57). In accordance with the literature (58), it is plausible to hypothesize 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 $\overline{T}_{sk}$ and $\overline{RH}_{sk}$ among our fanners, given that no reductions in T_c, $\overline{T}_{sk}$, forehead T_{sk}, $\overline{RH}_{sk}$, physiological strain, and thermal discomfort were observed during FAN_{FREE} (Table 2). However, correlation analysis revealed no relationships between self-fanning and changes in $\overline{T}_{sk}$ 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 behaviors (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 behaviors resulting from endogenous and exogenous heat stress (18–21). Under such conditions of more severe heat stress, it is plausible to hypothesize that participant engagement with the cool-seeking behavior would be more homogeneous, 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.

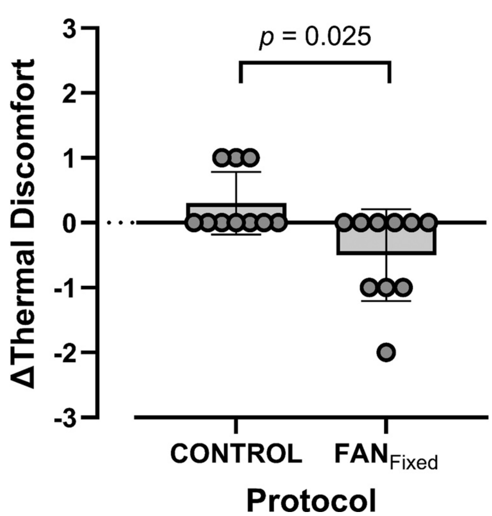

Figure 4. Changes in thermal discomfort during FAN_{FIXED} and the final 5 min of CONTROL. Bars reported as mean ± SD along with individual data points for $n = 10$.

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 localized. As such, these may have not been well captured by our infrared measurements of face skin temperature (sampled every 5 min) 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 behavior.

Understanding the drivers of individual variability in autonomic and behavioral 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 aforementioned indicate that our novel approach can be used effectively to broaden the range of methods available to our community to characterize ecologically relevant cool-seeking behaviors and their individual variability.

Energy Cost of Self-Fanning Behavior

With the present study, we selected a common and wide-spread cool-seeking behavior, 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). Although 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 recognize that other cool-seeking behaviors 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.

Specifically, 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 contextualize 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 FAN_{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 $\sim$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 FAN_{FIXED}, thermal discomfort was reduced during the 5-min period of continuous self-fanning compared with CONTROL (Fig. 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 behavior—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 aforementioned 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 behavior, 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. Although 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 characterize cool-seeking behavior 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 behavior (74–79). Hence, future research is warranted to establish whether sex-dependent differences in this type of behavior occur.

In addition, we believe that the potential of self-fanning to reduce forehead T_{sk} and thermal discomfort may be underrepresented 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 *1*) potential improvements in thermal discomfort were attenuated and *2*) engagement in this cool-seeking behavior 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 characterizing this cool-seeking behavior and quantifying its associated energy cost, an objective that was achieved, given that the majority of participants (70%) engaged in the behavior during FAN_{FREE}.

Since there are strong links between facial fanning and thermal comfort (81, 82), and between thermal discomfort and cool-seeking behavior (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 behavior. Our laboratory is in the process of utilizing our fan methodology without a face mask in vulnerable groups, with preliminary findings indicating comparable cool-seeking behavior 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 behavior, to better understand the relationship between motivation to engage and behavior's efficacy (25).

Conclusions

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 characterize the energy cost of a common human cool-seeking behavior (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 behavior, and their relevance to decision making associated with heat adaptation strategies, under controlled laboratory conditions.

DATA AVAILABILITY

Data will be shared upon reasonable request via the University of Southampton data repository (PURE).

SUPPLEMENTAL MATERIAL

Supplemental Table S1: http://doi.org/10.5258/SOTON/D3780.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

N.K.E., D.L., and D.F. conceived and designed research; N.K.E., D.L., and H.B. performed experiments; N.K.E., F.R.C., and P.R.W. analyzed data; N.K.E. and D.F. interpreted results of experiments; N.K.E. prepared figures; N.K.E. and D.F. drafted manuscript; N.K.E., H.B., F.R.C., P.R.W., J.S., I.G., and D.F. edited and revised manuscript; N.K.E., D.L., H.B., F.R.C., P.R.W., J.S., I.G., and D.F. approved final version of manuscript.

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