The relationship between radiant heat, air temperature and thermal comfort at rest and exercise

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Abstract

The aims of the present work were to investigate the relationships between radiant heat load, air velocity and body temperatures with or without coincidental exercise to determine the physiological mechanisms that drive thermal comfort and thermoregulatory behaviour. Seven male volunteers wearing swimming trunks in 18°C, 22°C or 26°C air were exposed to increasing air velocities up to 3 $m.s^{-1}$ and self-adjusted the intensity of the direct radiant heat received on the front of the body to just maintain overall thermal comfort, at rest or when cycling (60 W, 60 rpm). During the 30 minutes of the experiments, skin and rectal temperatures were continuously recorded. We hypothesized that mean body temperature should be maintained stable and the intensity of the radiant heat and the mean skin temperatures would be lower when cycling. In all conditions, mean body temperature was lower when facing winds of 3 $m.s^{-1}$ than during the first five minutes, without wind. When facing winds, in all but the 26°C air, the radiant heat was statistically higher at rest than when exercising. In 26°C air mean skin temperature was lower at rest than when exercising. No other significant difference was observed. In all air temperatures, high correlation coefficients were observed between the air velocity and the radiant heat load. Other factors that we did not measure may have contributed to the constant overall thermal comfort status despite dropping mean skin and body temperatures. It is suggested that the allowance to behaviourally adjust the thermal environment increases the tolerance of cold discomfort.

Key Words: Thermal comfort; Behavior; Radiant heat; Skin temperature; Deep body temperature

Introduction

The thermal environment consists of a combination of air temperature, air velocity, relative humidity and radiation. These parameters influence skin temperature through conductive, convective, evaporative and radiant routes of heat exchange. Under normal circumstances, humans will respond to cutaneous thermal sensations by adjusting their behavior in order to maintain an overall thermally comfortable state, reflecting satisfaction with the thermal environment [1]. Adding or removing clothing layers, changing body position, or adjusting the heating system in a room conserves the resources (fluid, substrate) used by the autonomic responses when maintaining deep body temperature within its narrow range [2].

The conscious, subjective behavioural responses of humans to the thermal environment have been investigated by allowing volunteers to self-adjust the temperature of a liquid conditioning garment (and hence their skin temperature), at rest or when exercising in cold air [3]. It was shown that such adjustments related to changes in mean body temperature, as the rise in deep body temperature was counteracted by drops in skin temperature such that mean body temperature remained stable. Previous work revealed that thermoregulatory behaviour was driven by both deep body and skin temperatures [4, 5]. As skin and deep body temperatures equally contribute to thermal comfort [6], in situations where deep body temperature remains stable, thermal comfort (and thermoregulatory behavior) should be determined by skin temperatures. In support of this, in a recent study the decision to move between a warm and cool place was initiated before deep body temperature was affected [7]. At rest, the cutaneous thermoreceptors may thus provide the primary input for thermoregulatory behaviour.

Amongst the main parameters defining the thermal environment, wind speed has been reported to be a better predictor of behavioural adjustments to the environment than ambient temperature [8]. However, in this study, skin temperatures were not recorded and therefore their impact on the thermoregulatory behaviour could not be estimated. Other investigations observed a liner relationship between thermal sensations and the intensity of simulated solar radiation [9]. Nevertheless, the authors did not consider air velocity. It is also important to note that in both studies, participants had no control over their thermal environment.

Although their work was conducted without wind or direct radiant heat, and in a very cold air temperature (-20°C), Flouris and Cheung [3] demonstrated an accurate and objective way of collecting data on behavioural thermoregulation: if people are given some control over the environment in order to maintain their overall thermal comfort, they should provide relevant information regarding the satisfactory thermal profile (absolute and rate of change of body temperatures) required for that particular state of mind.

The present study investigated the previously unexplored relationship between radiant heat load and air velocity with and without coincidental exercise to try to determine the physiological mechanisms that drive thermal comfort and, thus, thermoregulatory behaviour in such situations.

If, in agreement with earlier findings [3], mean body temperature is the adjusted parameter in our study, we hypothesized that mean body temperature should be maintained relatively stable and the intensity of the radiant heat and the mean skin temperatures would be lower in the exercising conditions.

Methods

This study was approved by the University of Portsmouth BioSciences Research Ethics committee and was performed in accordance with the ethical standards of the 1964 Declaration of Helsinki (2008). The participants gave their written informed consent to participate.

Volunteers

Seven male volunteers were recruited for this study (mean [SD]; Age 23.2 [5.1] yr; height 1.77 [0.061] m; mass 75 [14.2] kg). They were instructed to avoid performing any vigorous physical activity and consuming alcohol for 24 hours prior to each test, and to avoid caffeine and hot food three hours before data collection.

Experimental design

The experiment was a repeated measures design in which each volunteer completed six tests, on three separate days (two tests per day, one at rest and the other during exercise). The order of presentation of conditions (to which each volunteer was randomly allocated) was influenced by practical considerations and could only be partially balanced.

Experimental procedures and set-up

Wearing minimal clothing (swimming trunks) in three different moderate air temperatures and relative humidity of 50 p. 100, volunteers were exposed to increasing air velocities and self-adjusted the intensity of the direct radiant heat received to just maintain thermal comfort, at rest or during a low intensity exercise.

During the entire experiment (30 minutes), the volunteers faced a panel of halogen lights simulating solar radiation. The intensity of the radiant heat produced was similar across the whole area of their body’s front side. Where the volunteers stood, the maximum intensity received from the radiant system was 1000 $W.m^{-2}$, as established with a pyranometer, and in agreement with the maximum direct solar radiation one would get on earth at sea level [10]. During all six tests, volunteers wore dark glasses to reduce the total irradiance by 80 p. 100 and protect them against UV radiation.

The experiment started with the radiant system off but, at anytime, the volunteers could accurately adjust the heat received by 10 $W.m^{-2}$ from 0 to 1000 $W.m^{-2}$ by using a computer mouse wheel with their right hand. They were asked to adjust the intensity so that they received the minimal radiant heat required to maintain their overall thermal comfort, as defined by the category "just comfortable" on the scale they had been familiarized with prior to each test. The delay between the control and the change in the intensity of the radiant heat produced was considered to be insignificant. The volunteers could not see any of the data recorded.

Environmental conditions

Throughout each of the six conditions, the air temperature was set at 18°C, 22°C or 26°C. Based on pilot studies the lowest air temperature was defined as that minimal temperature in which it was possible to just maintain thermal comfort with maximal radiant heat and maximum wind speed. The highest air temperature was defined as that minimal temperature in which thermal comfort was just achievable without wind and simulated solar radiation.

At all times, volunteers faced a fan simulating wind. Air velocities were set by the investigator for five minutes before being increased as follows: 0, 1.5, 2, 3, 0 and 3 $m.s^{-1}$. These air velocities correspond to a range of wind speeds going from "calm" to "light breeze" on the Beaufort scale.

Exercise

Each of the three air temperature conditions were completed at rest and when undertaking a low intensity physical activity on a bike (60 Watts, 60 rpm), to induce a moderate raise in deep body temperature and stay within comfortable limits (body in heat balance and skin wetness kept minimal). Cycling started five minutes before data collection to let volunteers habituate and make sure deep body temperature was already rising when the experiment started. This pre-test exercise did not involve any wind or solar radiation. In the three resting experiments, volunteers stood still, faced the fans and the solar panel. This position was adopted in order to get a finer control of the radiant heat system, as the face is known to be a highly sensitive region to thermal stimuli ([11], [12] and [13]).

Following the first test of the day, volunteers stayed equipped but rested for one hour in their own clothes, in a thermoneutral environment. Once thermal balance was recovered (as determined by a continuous monitoring of their rectal temperature and thermal comfort state), they entered the chamber for their second and last test of the day.

Measurements

Skin and rectal temperatures

Deep body temperature was continuously recorded using a self-inserted rectal thermistor (Edale Instruments Ltd., UK) 15 cm beyond the anal sphincter. Once volunteers had changed into a swimming costume, they entered the climatic chamber. Whole body front (directly exposed) surface temperatures were recorded using an infra-red camera (FLIR systems, Thermovision A320, UK). Local skin temperatures were determined by data acquisition on the largest body surface area possible on the face, upper chest, abdomen, arm, forearm, hand and thigh. Throughout the experiment, rectal and skin temperatures were recorded at 30 second intervals on electronic data loggers (Squirrel 1000 and 2040 series meter loggers; Grant Instruments [Cambridge] Ltd., UK). Thermal images were recorded at five second intervals using an acquisition and analysis program (ThermaCAM Researcher Pro v2.9, FLIR systems, UK).

Thermal comfort

Before each test, volunteers were familiarized with the thermal comfort scale, consisting of six categories (A4 size), from bottom to top: very uncomfortable, uncomfortable, just uncomfortable, just comfortable, comfortable and very comfortable.

Calculations

The individual skin temperature recorded on the different body sites were combined to produce a mean skin temperature (T_{sk}) using an adjusted version of Hardy and Du Bois [14] to exclude the regions which were not directly exposed to the simulated solar radiation.

$$T_{sk} = (0.07T_{face} + 0.0875T_{chest} + 0.0875T_{abdomen} + 0.035T_{arm} + 0.035T_{forearm} + 0.05T_{hand} + 0.095T_{thigh})/0.46$$

Mean body temperature (T_b) was estimated by extrapolating findings of Frank *et al*., [6], who showed that skin (T_{sk}) and rectal temperatures (T_{re}) equally contribute to thermal comfort:

$$T_b = 0.5\ T_{re} + 0.5\ T_{sk}$$

Ambient temperature

The ambient temperature was estimated using the Wet Bulb Globe Temperature, recorded with the appropriate thermometer placed between the volunteer and the solar panel, as close as possible to the volunteer's position. The following formula was used:

$$WBGT = 0.7\ T_{nw} + 0.2\ T_g + 0.1\ T_{a},$$

with T_{nw} the natural wet-bulb temperature, T_g the globe temperature and T_a the air temperature.

Air velocity

Wind speeds were measured during pilot testing using an anemometer (Anemometer TMA10, Meterman Test Tools, USA) placed as close as possible to the volunteer, at a standardized and fixed position.

Simulated solar radiation intensity

The intensity received on the skin was continuously recorded using a pyranometer sensor (LP02 thermopile pyranometer, Campbell scientific, UK) attached to the chest.

Data analyses

All tests were conducted using SPSS 18 (Statistical Package for the Social Sciences, version 18, Chicago, USA). Before any analysis was conducted, it was confirmed that the data met the requirements and assumptions of each statistical test used. Paired-sample t-tests were used to compare temperatures or radiant heat intensities between resting and exercising experiments, within air temperatures and velocities conditions, or when comparing initial and final data sets within each of the six conditions. The alpha level was set at 0.05.

Results

General observations

Seven male participants were recruited for this study. They all completed the six conditions. Overall thermal discomfort was never reported, and on the rare occasions when the irradiance reached the maximum intensity of 1000 $W.m^{-2}$ it was for very short periods.

Irradiance

To maintain their overall thermal comfort, volunteers adjusted the intensity of the radiant heat received on the front of their body (Fig. 1). As the air velocity increased, volunteers required more irradiance to maintain their overall thermal comfort. The sudden increase in air velocity at the end of the experiments did not influence the intensity of the radiant heat required; no significant difference was observed between the two high wind periods (3 $m.s^{-1}$).

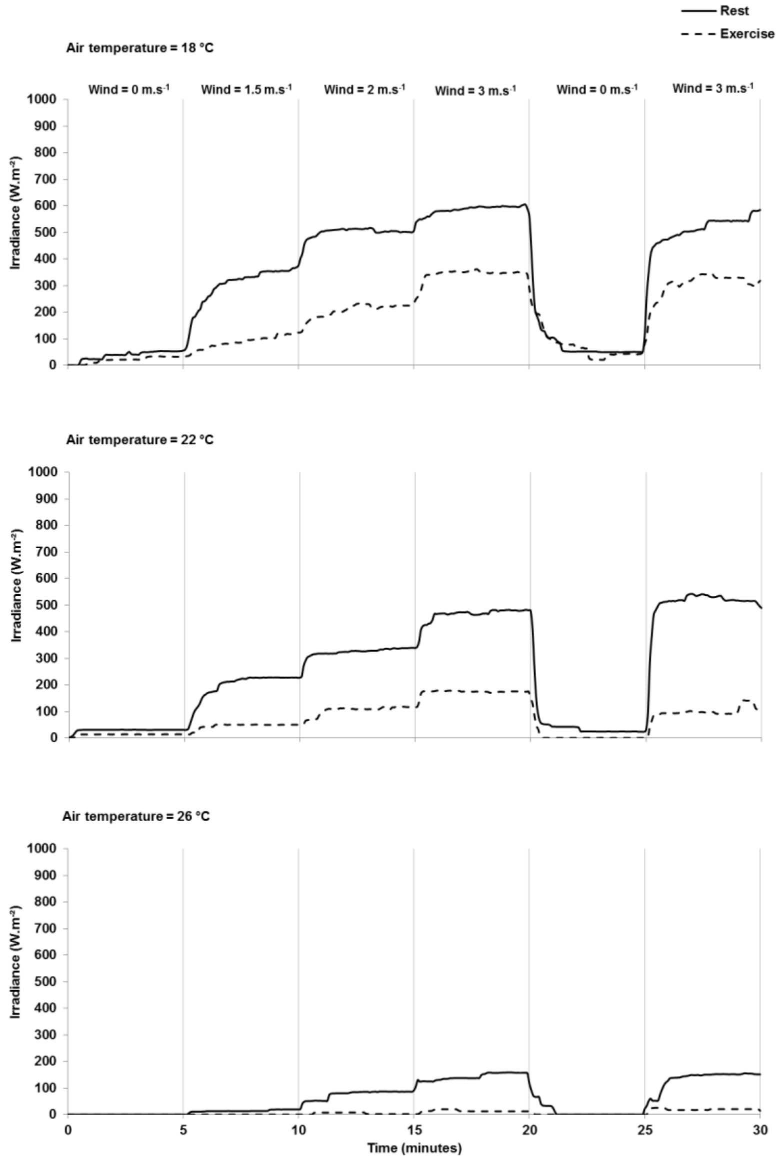

Fig. 1. Mean irradiance required to maintain overall thermal comfort in swimming trunks, at rest or when exercising in three air temperatures when facing different air velocities (n=7).

In 18°C and 22°C air temperatures, when facing winds, the irradiance was almost always significantly greater at rest than when exercising (Fig. 2). In 26°C, the irradiance at rest was not significantly different from that when exercising.

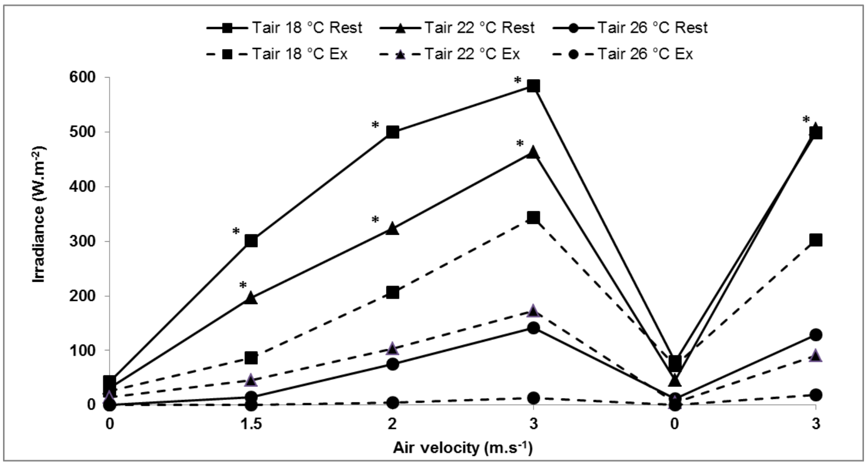

Fig. 2. Mean incident thermal radiation required to just maintain thermal comfort in different ambient temperatures with and without exercise. Each air velocity was set for five minutes and is presented on the axis in the same order as during the experiments: starting with 0 m.s^{-1}, and 3 m.s^{-1} from the 25th to the 30th minute. Within each ambient temperature, **s**ignificant differences between rest and exercise are indicated with * $P < 0.05$ ($n = 7$).

High correlation coefficients were observed between the air velocity and the irradiance required to maintain thermal comfort (Table 1). These strong relationships can be described by linear trend lines between the air velocity and the irradiance (data not shown here).

Table 1. Correlation coefficients between the air velocity and the irradiance (averaged over each five-minutes wind increments) required to maintain overall thermal comfort at rest or when exercising, in different air temperatures (n=7).

		REST	EXERCISE
Air temperature	18°C	0.97	0.94
	22°C	0.99	0.89
	26°C	0.93	0.85

Skin temperatures

Overall, mean skin temperatures dropped over the 30 minutes of each condition (Fig. 3). Every time the air velocity was increased, mean skin temperature dropped.

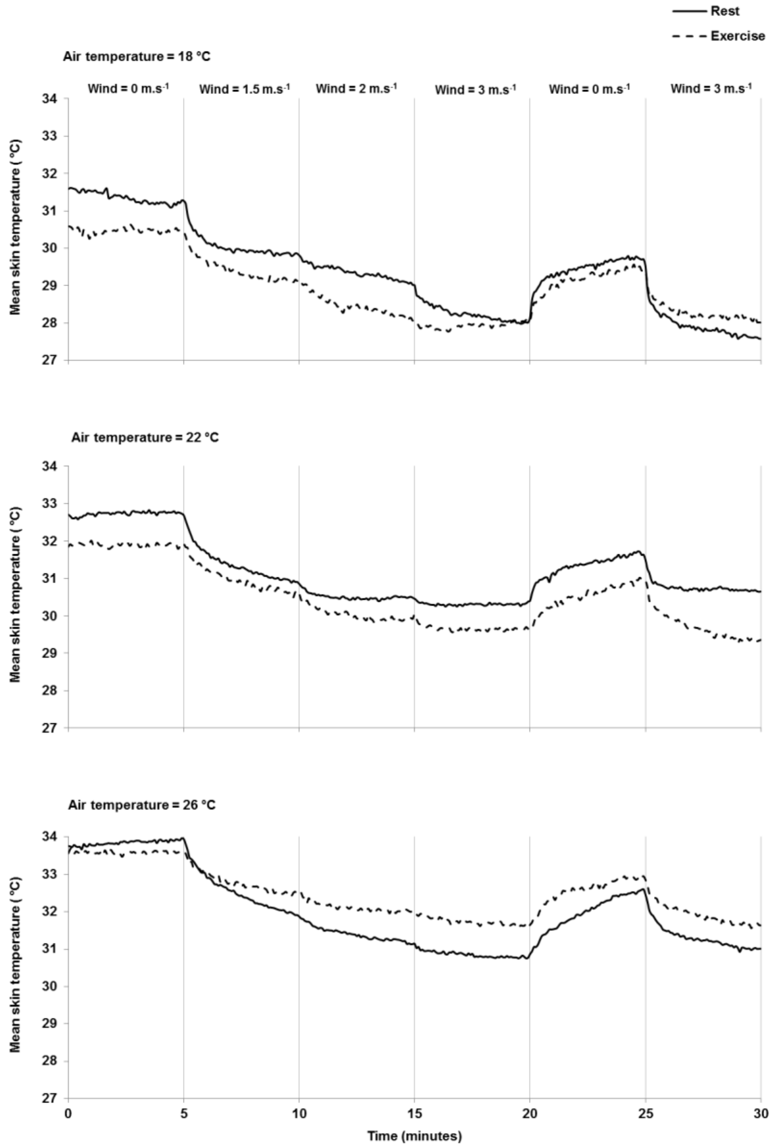

Fig. 3. Average mean skin temperature of volunteers exposed to various wind speeds at rest or when exercising, in swimming trunks, in three different air temperatures (n=7).

Table 2 indicates that when facing most air velocities in 26°C air, mean skin temperature was significantly higher when exercising than when at rest. No significant difference was observed in the 18°C and 22°C air temperatures.

Table 2. Average (SD) mean skin temperature of volunteers exposed to various air velocities at rest or when exercising, in swim trunks, in 26°C air temperature. Significant differences between rest and exercise are indicate with * $P < 0.05$; ** $P < 0.01$ ($n = 7$).

Time (minutes)	Air velocity ($m.s^{-1}$)	Average (SD) mean T_{sk} (°C)		Sig diff
		Rest	Exercise	
0-5	0	33.87 (0.62)	33.58 (0.81)	/
5-10	1.5	32.51 (0.42)	32.78 (0.74)	/
10-15	2	31.40 (0.45)	32.12 (0.72)	*
15-20	3	30.85 (0.61)	31.73 (0.66)	**
20-25	0	31.99 (0.64)	32.59 (0.62)	*
25-30	3	31.36 (0.77)	31.98 (0.64)	*

Rectal temperature

In all experimental conditions, rectal temperature rose throughout the 30 minutes of each test, whilst remaining within normal states. Table 3 shows that the mean (SD) rise in T_{re} over the 30 minutes of all resting conditions was 0.07 (0.16) °C. Across all exercising conditions, the mean (SD) rise in T_{re} was 0.36 (0.16) °C.

Table 3. Data sample of the rectal temperatures recorded throughout the 30 minutes of the experiments. The data presented are the temperatures averaged across the three air conditions (18, 22 and 26°C) at rest or when exercising ($n = 7$).

	Rest	Exercise
Mean (SD) initial T_{re}	37.0 (0.2)	37.0 (0.3)
Mean (SD) final T_{re}	37.1 (0.2)	37.4 (0.2)
Mean (SD) rise	0.07 (0.16)	0.36 (0.16)
Max rise	0.42	0.62
Max drop	0.24	0.03

Mean body temperature

In all conditions, mean body temperatures dropped every time the air velocity was increased (Fig. 4). Statistical analyses revealed that in all six experimental conditions, mean body temperatures were significantly lower when facing air velocities of 3 $m.s^{-1}$ (from the 15th to the 20th minute) than with no wind, during the first five minutes of the experiment (Table 4).

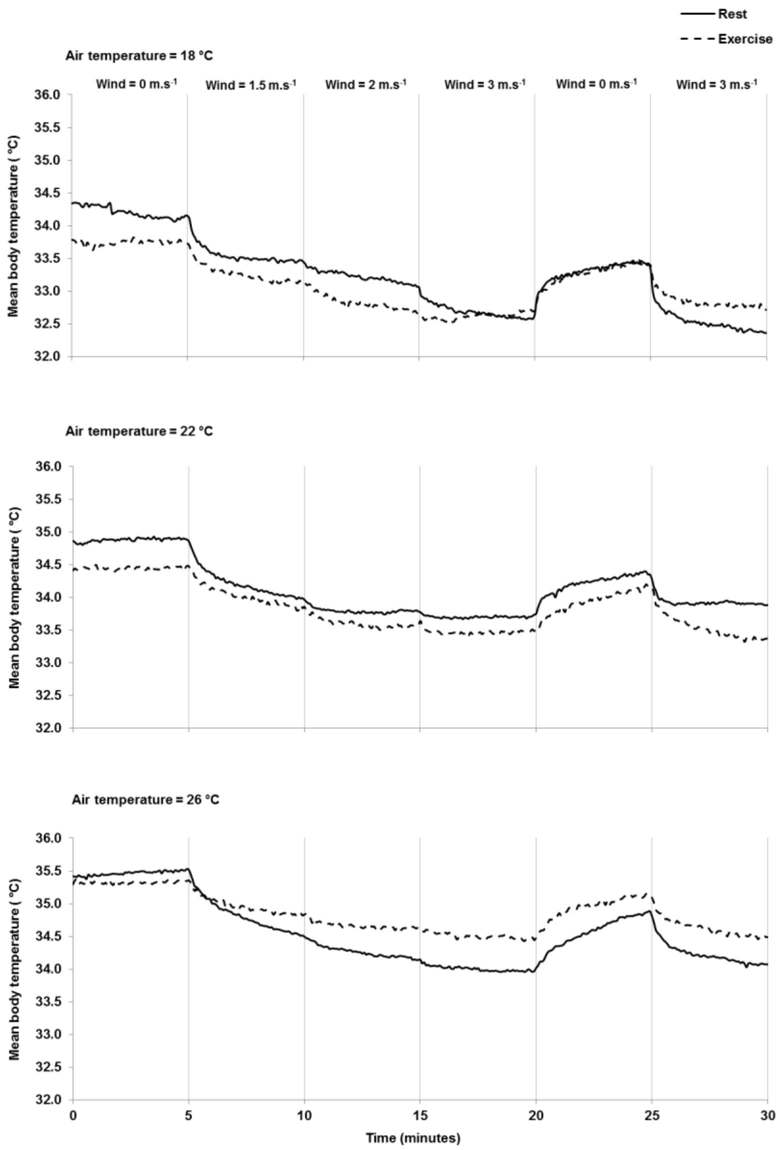

Fig. 4. Average mean body temperature of volunteers exposed to various air velocities at rest or when exercising, in swimming trunks, in three different air temperatures (n=7).

Table 4. Average (SD) mean body temperature of volunteers exposed to air velocities of 0 or 3 $m.s^{-1}$ at rest or when exercising, in swimming trunks, in various air temperatures.

Significant differences between rest and exercise are indicate with * $P < 0.05$; **** $P < 0.0001$ ($n = 7$).

Air temperature		Average (SD) mean T_b (°C) Wind=0 m.s^{-1}	Wind=3 m.s^{-1}	Sig diff
18°C	Rest	34.08 (0.60)	32.69 (0.83)	*
	Exercise	33.75 (0.64)	32.62 (0.60)	*
22°C	Rest	34.89 (0.11)	33.70 (0.91)	*
	Exercise	34.56 (0.43)	33.82 (0.72)	*
26°C	Rest	35.48 (0.30)	34.00 (0.29)	****
	Exercise	35.32 (0.43)	34.51 (0.34)	****

Discussion

The aims of the present work were to investigate the relationships between radiant heat load, air velocity and body temperatures with or without exercise to determine the physiological mechanisms that drive thermal comfort and thermal behaviour.

When facing winds, in all but the 26°C air temperature, the radiant heat required to just maintain overall thermal comfort was statistically higher at rest than when exercising, and we accept our hypothesis. In addition, we reject the hypothesis that mean skin temperature is higher at rest than when exercising as no significant difference was found in 18°C or 22°C. On the contrary, in 26°C mean skin temperature was significantly higher when cycling. At rest, in the warmest air temperature, rectal temperature was almost constant throughout the 30 minutes whereas it was continuously rising in the exercise condition. This moderate but consistent rise in rectal temperature when exercising may have been sufficient to avoid peripheral vasoconstriction and thus maintain skin temperature at higher levels when compared to the resting condition.

In all three air temperatures, the intensity of the radiant heat required to maintain overall thermal comfort was strongly related to air velocity. This relationship was refined and it seemed that linear trend lines could best reflect the patterns observed. When air velocities increased from 0 to 3 $m.s^{-1}$, volunteers proportionally increased the radiant heat load received on the front of their body. The impact of radiant heat on thermal comfort has been investigated in very few studies. However, our observations support previous work from Hodder and Parsons [9] who noted that the thermal sensation votes of volunteers increased by one scale unit for each increase of simulated solar radiation of 200 $W.m^{-2}$. Nevertheless, the experiment from Hodder and Parsons was conducted in hot conditions only, which were rapidly perceived as uncomfortably warm. Furthermore, volunteers had no control over the thermal environment, as a consequence of which no behavioural adaptation was investigated. In addition, the authors did not consider air velocity, or the impact of coincidental exercise on thermal responses. To the authors' knowledge, the present study is the first to describe the relationships between radiant heat, body temperatures, wind speeds and thermal comfort in three different air temperatures.

When responding to a cooling stimulus, cold receptors will first exhibit high frequencies of discharge, rapidly followed by a partial adaptation: for the same linear stimulus, the afferent signal will be lower [15]. Therefore, it was expected that each of the wind increments would be followed by an increase in the intensity of the radiant heat before it is reduced to lower levels. Surprisingly, when air velocity was suddenly increased (causing a rapid fall in mean skin temperature), no overshoot was observed in the intensity of the radiant heat required to maintain thermal comfort. In addition, when immediately increasing the air velocity from 0 to 3 $m.s^{-1}$, the same behavioural adaptation was observed as when the increase occurred over 15 minutes; the radiant heat load was similar in both high wind periods. Although rectal temperatures were continuously rising, the very low rates of change in some conditions (0.1°C in 30 minutes) suggest that other factors may have been involved.

Deep body and skin temperatures equally contribute to thermal comfort [6], and it is possible that they also equally contribute to thermal behaviour. We thus investigated mean body temperature responses based on the formula attributing identical weighting factors for rectal and skin temperatures. Although rectal and skin temperatures seemed to have opposite patterns, the rise of the former was not sufficient to compensate the fall of the latter. As a consequence, in all experimental conditions, mean body temperature was lower when facing air velocities of 3 $m.s^{-1}$ (from the 15^{th} to the 20^{th} minute) than without wind, during the first five minutes of the experiment. We reject our hypothesis that mean body temperature is the definitive variable and is maintained relatively stable. As opposed to what can be observed in the present study, Flouris and Cheung [3] showed that conscious responses to thermal inputs were adjusted to changes in mean body temperature. However, these authors used the more classical formulae from Burton [16], where, on the basis of calorimetric considerations, rectal temperature accounts for 70 percent in the average body temperature. Not only this estimation may not be appropriate for thermal comfort investigations, but it would not be sufficient to explain why in our resting conditions, with near-stable rectal temperature, overall thermal comfort was maintained despite falling mean skin temperatures.

The cutaneous thermal sensitivity is not uniform across the body ([17], [18]). The constant thermal comfort status with continuously falling mean skin temperatures may therefore be partially explained when looking at local skin temperatures. It appeared that in almost all six experimental conditions, the face and the chest were the body regions showing the smallest fall in skin temperature over the first 20 minutes, from 0 to 3 $m.s^{-1}$ wind (data not presented here). Conversely, the change in local skin temperature was greatest for the hands. The face and the chest have been reported to be highly sensitive to thermal stimulus ([13], [19]) and it is possible in our study that they had a disproportionate influence on overall thermal comfort, and in turn on behavioural adjustment. The present experiment did not provide the data to fully test this statement; the fact that skin temperatures on some body sites remained more stable than others may just be coincidental, and related to local physiological characteristics such as vasomotor responses [15]. To further investigate this result, it would be necessary to allow volunteers to adjust skin temperature of each body region independently. It is thus proposed that further research concentrates on the impact of local skin temperatures on behavioural adjustments.

Finally, other factors that we did not measure may have contributed to the constant overall thermal comfort status despite falling mean skin and body temperatures. Hormonal mechanisms, inhibitory mechanisms on the synaptic system or psychological aspects such as attention have been proposed to explain the influence of exercise on thermal sensitivity ([20], [21], [22]). We cannot exclude that such factors contributed to lower the threshold for thermal discomfort, thus delaying and/or reducing the initiation of behavioural adjustments. However, if they did it is only partially, as similar situations were observed in the resting conditions. It is possible that allowing direct and precise control of the thermal environment had a positive influence on thermal comfort. Already suggested by Paciuk [23], such influence of personal control was later investigated by Brager *et al*., [24]. These authors reported that when allowed to control some thermal conditions of their workplace (in particular, the operable window in buildings) participants were more tolerant of the thermal environment.

The present experiment was the first to explore the relationships between radiant heat load, air velocity and body temperatures with or without exercise in several thermal environments to determine the physiology behind thermal behaviour. It was expected that behavioural thermoregulation would rely on thermal comfort through cutaneous thermal afferents mainly. In natural situations, this conscious adaptation would tend to prevent or delay large variations in deep body temperatures. We conclude that factors that we did not measure account for the responses observed in our study, and that the allowance to behaviourally adjust the thermal environment increases the tolerance of cold discomfort.

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