



# Higher comfort temperature preferences for anthropometrically matched Chinese and Japanese versus white-western-middle-European individuals using a personal comfort / cooling system

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## ABSTRACT

**Purpose:** To investigate potential differences in preferred Personal Comfort Systems (PCS) settings of Japanese and Han-Chinese versus white-western-middle-Europeans.

**Method:** A series of five experiments (n=167) with similar methodology is reported that allowed participants to self-select their preferred PCS outlet air temperature in a warm controlled climatic chamber setup with and without solar radiation. Test groups were matched for age, height, weight, body-surface-area and body-mass-index to remove the influence of these confounding factors on the results. Participants were first exposed to solar radiation (exp-1-4; simulating glazed building without proper shading or a car) before starting to control the outlet temperature of the PCS, or (exp-5, simulating warm building) were exposed to a warm room temperature and immediately could control the PCS. Ethnicity effects were studied through the chosen preferred PCS outlet temperatures and the microclimate temperature close to the participants' chest.

**Results:** In all experiments, Asian groups selected a PCS outlet temperature significantly higher, on average by 5 °C, leading to a 1.9 °C higher microclimate temperature at chest level. While absolute selected temperatures of the PCS differed between experiments, related to different designs of the PCS and climate conditions, no interaction between ethnicity and experiment was present.

**Conclusions:** Despite removing important confounding factors that could explain earlier observed differences between Asian and white western middle-European ethnicities tested, a substantial, consistently higher thermal preference temperature of the PCS was found in the two Asian groups. This has implications for the design parameters of PCS for use in offices or air-conditioning systems in cars.

## 1. Introduction

Personal cooling/comfort systems (PCS) in offices are gaining popularity to improve individual comfort while providing potential savings in overall energy consumption of the building [1–3]). A recent review by Ref. [4] describes a multitude of studies on various types [(a) Heating b) Heating and ventilation c) Cooling d) Cooling and ventilation e) Ventilation]. Car climate systems are similar in principle, as many allow the settings to be adjusted for individual occupants. Especially with cooling systems and air conditioning systems, the design capacity (lowest temperature achievable) directly affects overall energy use.

Most systems, in cars and offices, have similar design targets (personal space temperature) with either similar cooling capacity for different markets, or cooling capacity adjusted to the local climate. Feedback from users (car industry, personal communication) suggests that for certain climatic regions (i.e. a fixed cooling capacity) customer complaints on the effectivity of air conditioning systems may be related to the ethnicity of the user. Hence the purpose of this paper is to look at possible ethnicity effects on the preferred temperature setting of such systems to inform their designers of a potential variation in design requirements which can impact satisfaction with such systems, but also may impact/optimize their energy requirements [5] as well as affect

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worker productivity and health [6].

Standards for the determination of thermal comfort (ASHRAE standard 55 [8], ISO 7730 [71]) based on the work by Fanger [7]) are used worldwide for all individuals irrespective of their ethnicity, nationality or country of origin. ASHRAE Standard 55 [8] recognises that there is a thermal comfort difference in winter and summer months within the same country, but it does not consider thermal preference differences of individuals from different countries. More recently comfort standards have been extended with the addition of the 'adaptive model' which suggests that comfort temperatures in naturally ventilated buildings vary for different climatic regions. Ref. [61] suggested adaptation to occur via adjustment (behavioural/technical adjustments to heat balance), habituation (psychological adaptation & changing expectations) or acclimatisation (long term physiological adaptation to climate). Whether such differences are indeed related to long term adaptation of individuals to the local climate or are actual ethnic differences is so far unclear, as most data is obtained in field studies, which typically cannot exclude all potentially confounding factors.

Individual differences play an important role in temperature regulation [9–11] and individual physiological responses to cold and heat [12,13]. Similarly, perceptual responses and thermal preference may be influenced by many individual factors (sex, age, body characteristics [height, weight, obesity]), as well as by external factors (climate, noise, light, education level, job roles and personal behaviour) [5,14–22]. Age can simultaneously affect thermoregulatory mechanisms for sweating and thermal sensation during passive heat exposure [23]. The effect of gender is less conclusive. Ref. [24,25] showed preferred temperature of males to be lower than that of females while [26] showed female occupant satisfaction levels were significantly lower than male occupants for fifteen indoor environmental quality factors. Fanger's classical work suggests that the thermal neutral temperature, if adjusted for metabolic rate and clothing, is the same irrespective of nationality, geographic location, gender and age [27]. The observed differences between sexes may indeed be caused by the lower metabolic rate in females [28]. Using this information, Fanger's model indeed predicts a difference for males and females in the same space with females having a higher preference temperature.

Thermal comfort in buildings, vehicles, outdoor environments or in climate chambers has been studied in many different climate areas, mostly in field studies with limited control. Those studies in buildings have focussed around the method of control of the whole environmental space, which fall into two categories: climate controlled/air conditioned (HVAC) or naturally ventilated buildings. While the neutral temperature in air-conditioned buildings in hot humid areas was found to be 24.7 °C in Bangkok, Thailand [14], 24.2 °C in Singapore [29,30], 23.7 °C in Hong Kong [31] and 25.6 °C in Taiwan [32] this tended to be partially explained by variations in activity and clothing level (Clothing 0.26–0.6clo and Activity 1.0–1.2met).

For naturally ventilated buildings, this variation can also be seen in the temperatures that people report being thermally comfortable at. Ref. [33] showed a positive correlation of comfort temperatures in free running buildings with mean outdoor temperature, which was not explained by clothing and activity differences. Comfort temperatures in hot dry and hot humid climates were much higher than those in temperate climates. This can be related to adaptations to the local climate, but may also have an ethnicity component. For example, anthropometric differences, like the body size and body tissue composition, between ethnicities can affect heat exchanges inside the body and with the environment and thereby change comfort temperatures.

Numerous studies have observed thermal preference differences between different ethnicities. [34] Observed that Malays preferred a thermal environment which was 2 °C warmer than the optimum for Europeans in Singapore. A 2 °C increase in preferred temperature was also seen in a field study by Ballantyne et al. in Papua New Guinea, where the comfort temperatures of Melanesians and "Caucasians"<sup>1</sup> were compared [35]. None of these field study data controlled for anthropometrics, activity and clothing however. Comparisons of thermoregulatory responses to heat between Japanese Brazilians and Japanese show that Japanese Brazilians felt cooler and more comfortable in a 40 °C environment than the Japanese. The thermoregulatory responses observed in Japanese Brazilians may be largely attributed to the climate in Brazil, located on the Tropic of Capricorn [36], i.e. reflecting long term adaptation to heat (>20 years) rather than ethnicity as the contributing factor. Long term 'thermal history' is indeed considered a potential factor [37]. Ref. [38] observed a higher sensitivity to skin wettedness in "Caucasians" versus Japanese. while [39] found that Malaysian males (on average warmer climate than Japan) tended to be less sensitive to detecting warmth than Japanese males. Finally, Ouzahra, in Ref. [40] compared the response to a cold stimulus between British, Chinese and Nigerian students studying in England and observed a stronger cold sensation response in the Chinese and Nigerian groups to a cool stimulus put on the skin.

In most of these studies, ethnicities were tested in their typical geographical location, without matching the groups for body anthropometrics, acclimatisation etc., or just defining one group as 'foreigners' [41], thus potentially confounding ethnicity with adaptation and individual characteristics. It is known that heat acclimatisation influences a person's physiology [42]. Particularly in the heat, human ability to produce sweat is increased following repeated exposure to the environment, but also a downward shift in resting body temperature and in the sweating threshold as well as increased cardio-vascular stability is observed [43]. Whether thermal sensitivity or preference is altered by this process is unclear.

Given the various issues indicated above, a study of ethnic differences without confounding factors would ideally need to control for several factors: Age; Activity level; Body surface area (heat loss potential); Body mass (heat generation); Surface to mass ratio (heat loss potential/heat generation volume); Obesity (tissue insulation); Heat acclimatisation level; and Clothing insulation. A further factor, discussed by Ref. [44]; is that of health in general, related to socio-economic status. For acclimatisation, comparing ethnic groups who have been living for a substantial period in the same geographical location to remove differences in short term climate adaptation should provide clearer evidence for ethnic factors. Such studies are difficult to perform in the field, and most past field studies suffer from potential confounding differences in populations. Hence, a smaller scale highly controlled laboratory study may be more appropriate for the present research question than the typical large-scale field study approach used so far.

Apart from the potential physical/anthropometrical and physiological confounding factors listed above, another confounding factor in most studies investigating ethnic variation in thermal comfort is that of the language and semantics in which the subjective scales are presented [5,45]. Predominately, most comfort studies use the standardised scales of thermal sensation, comfort and thermal preference of ISO 10551 [70] and for comparisons of ethnicities these are translated into the respective languages. However, the wording for these scales, e.g. 'warm' or 'hot' in different languages may have different meanings/notations

<sup>1</sup> NOTE: "Caucasians" is used between inverted commas here to reflect its contentious definition. The term is only used in this paper to refer to its historic use in the literature. Recent evaluations of the term indicate it to be imprecise and based on an inappropriate racial definition. See e.g. <https://www.sapiens.org/column/race/caucasian-terminology-origin/>.

in different regions/cultures [45]. Also, comfort is linked to different thermal sensation scores in different areas, e.g. 'cool' and 'cold' are linked to a vote of 'comfort' in Nigeria and Malaysia [5]. This complicates comparisons of subjective responses of different ethnic groups to the same condition. An alternative for this is to allow people to adjust the climate they are exposed to, to their preferred setting. Fanger used this type of approach in a series of studies in the 1970's, [46–48]. In these studies, the participant could control and select their preferred comfort temperature for the environment. This experimental protocol style allows the quantification of the participants actual comfort temperature without language bias. An additional benefit of this approach is that a greater precision can be achieved in determining the preferred comfort temperature compared to studies where climates are fixed at multiple levels and the preferred point is analysed by regression of the comfort and sensation votes and subsequent interpolation to the neutral point [49,50].

These studies determined preference temperatures under uniform conditions (mean radiant temperature ( $t_r$ ) = air temperature ( $t_a$ )). In real-world scenarios this is rarely the case. Vehicles in particular, often expose the occupant to considerable radiant asymmetry [51], and with the growth in glass clad buildings more and more workers are exposed to solar radiation indoors if the building is not well designed with adequate, preferably outdoor, shading.

Over a period of around 10 years, our laboratory has performed a series of five studies on this topic, comparing Asian and British/western-middle-European individuals. These studies were very similar in experimental setup, using almost identical equipment. This paper summarises the results of these studies. Based on the earlier mentioned considerations, the presented studies aimed to determine preferred comfort temperatures of the air flow of a personal comfort/cooling system for two Asian groups: Chinese and Japanese versus British/western-middle-European individuals in a non-uniform and in a uniform radiant environment, i.e. a simulated vehicle or office space with and without the addition of solar radiation. A personal cooling/heating system (similar to a car air conditioning and ventilation system or personal climate system nowadays found in modern offices) allowed the individual to adjust their local climate. The self-selected outlet temperature of the air vents pointing at the participants was measured as proxy for preferred temperature. All groups were selected from a population that resided a minimum of two months in the same climatic conditions (UK) to avoid short term heat acclimatisation effects. In four experiments, the participants were exposed to simulated solar radiation (i.e. making them feel uncomfortably warm) prior to them being able to select their preferred comfort temperature. One experiment was without radiation but with a high room air temperature. Clothing and activity were matched, and from the recruited groups subsets were selected to match the Asian and western European groups for anthropometric differences for each of the five experiments (age, height, weight, body surface area and body-mass-index (BMI)). The choice of comparing Asians versus western European (British and west-middle Europeans) was related to questions from car manufacturers exporting cars to both these markets, considering customer feedback and complaints.

## 2. Materials and method

For details on measuring equipment, please refer to Table 1.

### 2.1. Environmental conditions of the five individual studies

This study summarises outcomes of five individual studies (Table 2), all focussing on comparing responses between two Asian groups: Japanese and Han-Chinese versus white western-middle-European participants (European). The majority and largest of the studies (2–5) compared Han-Chinese and Malaysians of Han-Chinese decent (3rd and 4th generation Chinese immigrants; further identified as Malay) to Europeans. A separate study (1) was performed on Japanese. All studies

**Table 1**  
Details of measuring equipment with accuracy and resolution.

variable	unit	Equipment	accuracy	precision
Air temperature	$T_a$ (°C)	Testo Ltd, model 453 & 435-2 Alton, Hampshire, UK (high precision probe)	0.2 °C	0.1 °C
PCS outlet temperature	$T_{pcs}$ (°C)	Thermistors; Grant Instruments, Cambridge, UK	0.1 °C	0.1 °C
Microclimate temperature	$T_{mc}$ (°C)	Thermistors; Grant Instruments, Cambridge, UK & Testo Ltd, model 453 & 435-2 Alton, Hampshire, UK	0.1/0.2 °C	0.1 °C
Relative Humidity	rh (%)	Testo Ltd, model 453 & 435-2 Alton, Hampshire, UK & Vaisala	1 %	0.1 %
Air speed	m. $s^{-1}$	Testo Ltd, model 453 & 435-2 Alton, Hampshire, UK & TSI, Biral, Bristol, UK	0.03 m $s^{-1}$ /2%	0.01 m $s^{-1}$
Radiation	W. $m^{-2}$	Pyranometer CM11; Kipp & Zonen		
Mean Radiant Temperature	$T_{mrt}$ (°C)	Thermistor, derived from 15 cm Black Globe; Testo Ltd, model 453 using CBE comfort calculator	0.5 °C	0.1 °C
Skin Temperature	$T_{sk}$ (°C)	Thermistors; Grant Instruments, Cambridge, UK & iButtons DS1922T	0.1 °C/0.5 °C (0.2 °C after local calibration)	0.1 °C/ 0.06 °C
Tympanic body core temperature	$T_{ty}$ (°C)	ThermoScan Pro 4000, Braun, Germany	0.2 °C	0.1 °C
Body Mass	kg	Mettler Toledo model CC150	5 g	1 g
Height	cm	Marsden Stadiometer UK	0.5 cm	0.5 cm
Heart Rate	HR	Polar, Tampere, Finland	2bpm	1bpm

were performed between late autumn and early spring to avoid heat acclimatisation effects.

The setup of the experiments was based on the same principles and used most of the same equipment. However, as over the years some equipment, mainly the design of the PCS, was updated and the setup optimised, it is acknowledged that the data cannot be compared between experiments; only within. Therefore, an overall analysis needs to be performed as a two-way ANOVA with ethnicity and experiment as independent factors.

### 2.2. Test facility

The studies were undertaken in climate chambers in the Environmental Ergonomics Research Centre at Loughborough University. The ambient air temperature for the different studies was set at 24, 25, or 30 °C, relative humidity 40, or 50% and a chamber air velocity of 0.1–0.2  $ms^{-1}$  (Table 2). In addition, in all but one experiment, two simulated solar radiation lamps (Thorn OQI 1000), provided a radiant heat load on the participants torso and upper legs of 540–714  $Wm^{-2}$ . All climates were fixed and stable for each individual experiment but differed between experiments. The solar simulation lamps were turned on for at least 30 min prior to the start of the experiment to allow them to reach their steady state operating conditions. Environmental conditions (Table 2) were monitored and measured in the climatic chamber throughout the experiment. Shielded air temperature,  $T_a$  was measured in front of, and behind the participant. Where Globe temperatures were

**Table 2**

Overview of environmental conditions averaged over the test period (Air temperature (shielded)  $T_a$  ( $^{\circ}\text{C}$ ), Relative humidity RH (%), Chamber and PCS air speed at location of persons upper body ( $\text{m}\cdot\text{s}^{-1}$ ), Solar radiation heat flux ( $\text{W}\cdot\text{m}^{-2}$ ) and mean radiant temperature  $T_{\text{mrt}}$  ( $^{\circ}\text{C}$ ) and total number of participants in the five studies comparing Asian to white western-middle-European participants (M, male and F, female). @ = estimated value. \*significant difference between ethnicity of 0.2  $^{\circ}\text{C}$  [Chinese higher]).

Experiment #	groups	Köppen climate classification	N tested	# European selected	# Asian selected	$T_a$ ( $^{\circ}\text{C}$ )	RH (%)	Air speed ( $\text{m}\cdot\text{s}^{-1}$ ) chamber/PCS	Solar Radiation ( $\text{W}\cdot\text{m}^{-2}$ )	$T_{\text{mrt}}$ ( $^{\circ}\text{C}$ )
1 CHI-MALAY	Chinese -Malaysian	Af vs. Cfb	23	6 M/4F	6 M/4F	$24.0 \pm 0.3$	$40.0 \pm 3.2$	0.2/0.65	$540 \pm 18$	$34.1@$
2 JAP	Japanese	Dfa & Cfa vs. Cfb	21	6 M/3F	6 M/4F	$24.2 \pm 0.3$	$40.9 \pm 2.5$	0.2/0.65	$665 \pm 15$	$35.6@$
3 CHI-Male	Chinese -Males	Cfa, Cwa, Dwa vs. Cfb	51	18 M	22 M	$25.0 \pm 0.2^*$	$48.1 \pm 0.5$	0.15/0.70	$621 \pm 20$	$36.1 \pm 0.9$
4 CHI-Female	Chinese - Females	Cfa, Cwa, Dwa vs. Cfb	36	18F	18F	$25.3 \pm 0.3$	$48.3 \pm 1.1$	0.15/0.78	$717 \pm 18$	$37.3 \pm 1.1$
5 CHI-Female, NR	Chinese - Females No Solar added	Cfa, Cwa, Dwa vs. Cfb	36	18F	18F	$29.9 \pm 0.4$	$39.6 \pm 1.7$	0.15/0.78	0	$28.6 \pm 0.5$
	Total		167	73	78					

measured, mean radiant temperature,  $T_{\text{mrt}}$ , was calculated using the CBE comfort tool at the position of the participant's torso, pre and post experiment from measurements using a black globe. Where no globe data were available,  $T_{\text{mrt}}$  was estimated based on our available data for measurements of radiation intensity, air temperature and air speed. Air velocity,  $v$ , was measured with a hot wire anemometer in front of the participant. Relative humidity,  $rh$  (%), was measured in front of the participant with a hygrometer. Direct simulated solar radiation was measured 'normal' to the participants' chest at the start and the end of the test with a Pyranometer.

A Personal Climate System (PCS, Fig. 1 & Fig. 2) was constructed which enabled the participant to control the temperature of an airflow directed towards their upper legs and upper body. The PCS was constructed as an insulated box which incorporated an air conditioning unit/chiller (Inverter KFR-34 GW-BP, exp 1–3 or a chilled heat exchanger radiator, exp 4,5) and a 2 kW electric fan heater, which both fed into a baffled mixing chamber. The chiller unit was set at maximum fixed cooling and the temperature of the air was controlled by the variation of the amount of heat added to the mixing chamber, giving a range of air temperatures at the outlets between approximately 5–12 and

41  $^{\circ}\text{C}$ . The PCS temperature was controlled by the participant using an analogue dial, with markers that indicated the direction of colder and warmer temperatures. There was a fixed air flow through the system, which exited through a set of 4 (exp 1,2) or 8 (exp 3–5) adjustable (by experimenter during setup only) air vents (120 or 80 mm diameter, exp 1,2 and exp 3–5 respectively) on the upper front vertical face of the PCS. Vents were set up so that the air flow covered the participant's upper legs, chest and face. Vent settings were identical for all participants within an experiment, but due to developments over time, differed slightly between experiments. The temperature of the air flow from the PCS ( $T_{\text{PCS}}$ ) was recorded at four of the air vents using thermistors. In CHI-Males, the temperature of the mixed microclimate air,  $T_{\text{MC}}$ , was measured just in front of the participants. In experiments CHI-FEMALES the relation between  $T_{\text{MC}}$ , at the chest and  $T_{\text{PCS}}$  was determined in separate calibration runs, in which the experiment was replicated without participant in the chair, and the relation between the whole range of  $T_{\text{PCS}}$  and  $T_{\text{MC}}$  was determined.

The experimental set up and chair height was arranged for each individual to maintain the same solar radiation load and air flow at the participants' upper body. After entering the climatic chamber, the seat



**Fig. 1.** Experiment setup in the Climate Chamber (experiment 3), shown with solar radiation lamps on. Front of the Personal Climate System (PCS) with the 8 adjustable air vents. Air temperature was measured using thermistors at the four air vents shown.

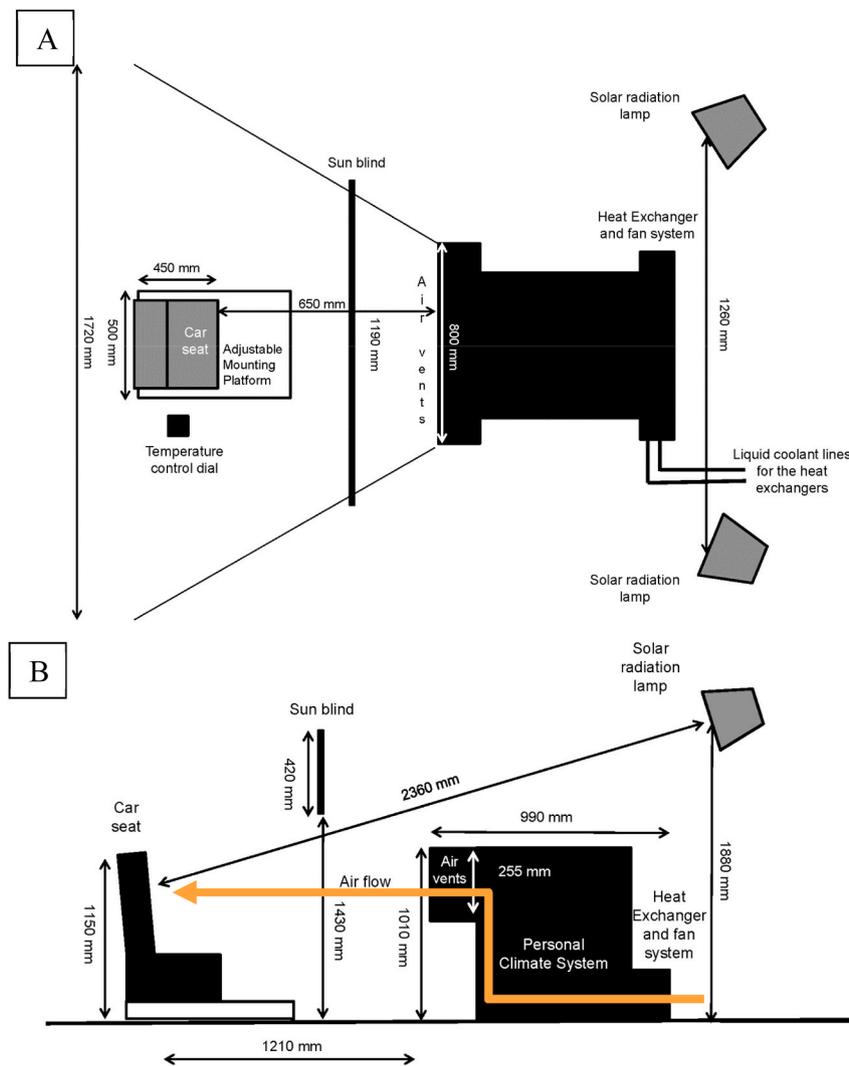


Fig. 2. Schematic of the typical set-up [experiment 4 and 5] (not to scale A: aerial and B: side view) of the climatic chamber for both conditions. No sunblind was used in exp 1–3.

height was adjusted to ensure the shoulder height of each participant was at the same level as the air vents. Participants were asked to maintain a set position throughout with hands on their thighs and feet flat on the floor with their knees close to 90°. In experiment 4 and 5, a sunblind was used to reduce the direct radiation/glare on the face. In experiment 1–3 sunglasses were worn against the glare of the solar lights. Air velocity from the system to the participant was typically around  $0.65\text{--}0.78\text{ m}\cdot\text{s}^{-1}$

### 2.3. Participants & clothing

Participants provided written, informed consent before participating in these studies, which were approved by the Loughborough University Human Ethics Committee. They all filled in a health questionnaire, confirming they were in good health and non-smokers. Female groups were tested across different phases of the menstrual cycle. All Asian participants had been living in the UK for a minimum of 2 months (ensuring loss of any short-term heat acclimation; maximum observed was two years).

Participants wore a specified clothing ensemble of white cotton/polyester (65/35%) long sleeve shirt, beige cotton/polyester (65/35%) trousers in the appropriate size, and their own under garments and shoes, including seat giving an estimated intrinsic insulation of  $0.11\text{ m}^2\text{ }^\circ\text{C W}^{-1}$  (0.7 Clo).

### 2.4. Matching groups for anthropometrics

The goal was to have the two ethnic groups in each individual study matched for potential confounding characteristics. The focus for this was a match in: 1: Age, 2: Body mass; 3: Body Height; 4: Body Surface Area and 5: Body Mass Index (BMI), the latter as a proxy for body composition. For this purpose, the leanest/lightest/smallest or the most obese/heaviest/tallest person(s) for each group were removed from the dataset without consideration of the responses to create the matched group datasets.

### 2.5. Physical and physiological measurements

A series of objective anthropometric and physiological measures were taken on each participant. Body mass, height and BMI. Skin temperatures at six to ten sites were recorded in the different studies with thermistors or iButtons. Mean skin temperature was calculated using ISO 9886:2004 [72]. Heart rate was recorded every 5 min throughout the duration of the experiment and in experiment 3–5 tympanic core temperature,  $T_{ty}$ , at start and end of the experiment.

### 2.6. Subjective measurements

Subjective assessment of thermal sensation (TS), thermal comfort

<p style="text-align: center;"><b>热感觉评价表</b> <b>Thermal Sensation Scale</b></p> <p>现在您感觉冷热程度怎么样? How are you feeling now?</p> <table style="margin-left: auto; margin-right: auto;"> <tr><td>Hot 热</td><td>6</td></tr> <tr><td>5</td><td></td></tr> <tr><td>Warm 暖</td><td>4</td></tr> <tr><td>3</td><td></td></tr> <tr><td>Slightly Warm 微暖</td><td>2</td></tr> <tr><td>1</td><td></td></tr> <tr><td>Neutral 合适, 不冷不热</td><td>0</td></tr> <tr><td>-1</td><td></td></tr> <tr><td>Slightly Cool 微凉</td><td>-2</td></tr> <tr><td>-3</td><td></td></tr> <tr><td>Cool 凉</td><td>-4</td></tr> <tr><td>-5</td><td></td></tr> <tr><td>Cold 冷</td><td>-6</td></tr> </table>	Hot 热	6	5		Warm 暖	4	3		Slightly Warm 微暖	2	1		Neutral 合适, 不冷不热	0	-1		Slightly Cool 微凉	-2	-3		Cool 凉	-4	-5		Cold 冷	-6	<p style="text-align: center;"><b>热舒适评价表</b> <b>Thermal Comfort Scale</b></p> <p>现在您的舒适程度怎么样? Do you find this.....?</p> <table style="margin-left: auto; margin-right: auto;"> <tr><td>Comfortable 舒适</td><td>0</td></tr> <tr><td>-1</td><td></td></tr> <tr><td>Slightly Uncomfortable 稍微不适</td><td>-2</td></tr> <tr><td>-3</td><td></td></tr> <tr><td>Uncomfortable 不舒适</td><td>-4</td></tr> <tr><td>5</td><td></td></tr> <tr><td>Very Uncomfortable 很不舒适</td><td>-6</td></tr> </table>	Comfortable 舒适	0	-1		Slightly Uncomfortable 稍微不适	-2	-3		Uncomfortable 不舒适	-4	5		Very Uncomfortable 很不舒适	-6	<p style="text-align: center;"><b>冷热需求评价表</b> <b>Thermal Preference Scale</b></p> <p>您希望环境(或空调)温度如何变化? How would you prefer to be now?</p> <table style="margin-left: auto; margin-right: auto;"> <tr><td>Much Warmer 多升高些</td><td>3</td></tr> <tr><td>Warmer 升高</td><td>2</td></tr> <tr><td>Slightly Warmer 稍微升高</td><td>1</td></tr> <tr><td>No Change 温度不变</td><td>0</td></tr> <tr><td>Slightly Cooler 稍微降低</td><td>-1</td></tr> <tr><td>Cooler 降低</td><td>2</td></tr> <tr><td>Much Cooler 多降低些</td><td>-3</td></tr> </table>	Much Warmer 多升高些	3	Warmer 升高	2	Slightly Warmer 稍微升高	1	No Change 温度不变	0	Slightly Cooler 稍微降低	-1	Cooler 降低	2	Much Cooler 多降低些	-3
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<p style="text-align: center;">■ 温冷感尺度 Thermal sensation scale</p> <p>あなたは今、暑さや寒さをどのように感じていますか? How do you feel at this moment?</p> <table style="margin-left: auto; margin-right: auto;"> <tr><td>暑い</td><td>6 (Hot)</td></tr> <tr><td>5</td><td></td></tr> <tr><td>暖かい</td><td>4 (Warm)</td></tr> <tr><td>3</td><td></td></tr> <tr><td>やや暖かい</td><td>2 (Slightly Warm)</td></tr> <tr><td>1</td><td></td></tr> <tr><td>どちらでもない</td><td>0 (Neutral)</td></tr> <tr><td>-1</td><td></td></tr> <tr><td>やや涼しい</td><td>-2 (Slightly Cool)</td></tr> <tr><td>-3</td><td></td></tr> <tr><td>涼しい</td><td>-4 (Cool)</td></tr> <tr><td>-5</td><td></td></tr> <tr><td>寒い</td><td>-6 (Cold)</td></tr> </table>	暑い	6 (Hot)	5		暖かい	4 (Warm)	3		やや暖かい	2 (Slightly Warm)	1		どちらでもない	0 (Neutral)	-1		やや涼しい	-2 (Slightly Cool)	-3		涼しい	-4 (Cool)	-5		寒い	-6 (Cold)	<p style="text-align: center;">■ 快適感尺度 Thermal Comfort scale</p> <p>あなたは今快適ですか、不快ですか? (Are you comfortable or uncomfortable?)</p> <table style="margin-left: auto; margin-right: auto;"> <tr><td>快適</td><td>0 (Comfortable)</td></tr> <tr><td>-1</td><td></td></tr> <tr><td>やや不快</td><td>-2 (Slightly Uncomfortable)</td></tr> <tr><td>-3</td><td></td></tr> <tr><td>不快</td><td>-4 (Uncomfortable)</td></tr> <tr><td>-5</td><td></td></tr> <tr><td>非常に不快</td><td>-6 (Very Uncomfortable)</td></tr> </table>	快適	0 (Comfortable)	-1		やや不快	-2 (Slightly Uncomfortable)	-3		不快	-4 (Uncomfortable)	-5		非常に不快	-6 (Very Uncomfortable)	<p style="text-align: center;">■ 適温感尺度 Thermal preference scale</p> <p>温度をどのように調整したいですか? How would you want the room temperature to be now?</p> <table style="margin-left: auto; margin-right: auto;"> <tr><td>今より暖かい方がよい (Warmer)</td><td>+2</td></tr> <tr><td>1</td><td></td></tr> <tr><td>このままでよい (No Change)</td><td>0</td></tr> <tr><td>-1</td><td></td></tr> <tr><td>今より涼しい方がよい (Cooler)</td><td>-2</td></tr> </table>	今より暖かい方がよい (Warmer)	+2	1		このままでよい (No Change)	0	-1		今より涼しい方がよい (Cooler)	-2				
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Fig. 3. Subjective scales presented to participants – Chinese top; Japanese bottom.

(TC) and thermal preference (TP) were explained to the participants. The scales were based on those defined in ISO 10551 [70] and included additional Chinese/Japanese translation of the descriptors, (see Fig. 3). In addition to textual descriptors/anchors, scales had numbers the participants could select. One additional number was inserted between the text anchors for sensation and comfort, providing the options of intermediate scores to the participants. The main purpose of the scales, given the potential issues with language/semantics/cultural influences, was to validate whether participants were able to achieve comfort with the PCS. The participants' ratings of thermal sensation, thermal comfort and thermal preference were taken every 5 min throughout the duration of the experiment (see Fig. 4).

## 2.7. Experimental procedure

**Experiment 1–4:** Participants arrived at the laboratory approximately 30 min prior to the experiment for acclimatisation. They had been asked to refrain from exercise on the day of the experiment and from alcohol for 24 h. They were taken to a thermal-neutral (for different studies 21–25 °C, 20–60% rh) preparation room. They completed medical consent forms and were briefed on both the withdrawal criteria and the experimental procedure. This included information regarding the PCS control guide, timetable of PCS adjustment and the subjective scales of thermal sensation (TS), thermal comfort (TC) and thermal preference (TP).

After measuring height & weight, skin sensors were secured with Transpore tape (3 M), and a heart rate monitor was fitted. The participant donned the standard clothing provided, with their own underwear and shoes. Initial subjective ratings were asked at the end of this preparation period.

The participant was then taken into the climatic chamber and sat in a chair (Fig. 1), height adjusted to maintain the same shoulder height for all participants. The participants gave their initial subjective ratings, and measurements of HR and, where applicable,  $T_{ty}$  were recorded, and all of these data were subsequently taken at 5-min intervals for the rest of the experimental session.

In experiment 1–4, at 30 min the PCS' airflow to the participant was activated and the participant was allowed to use the PCS adjustments. They were instructed to adjust the air temperature to maintain their thermal comfort. Time constant of the PCS was approximately 3 min for cooling and 1 min for heating based on a 15 °C step. At the end of 5 min the participant had to stop adjusting the air temperature. From then on, participants were given 30 s in every 2 min to make fine adjustments to the air temperature of the PCS. Participants were instructed to select a temperature that would provide them with long term comfort. The periods of non-adjustment were used to encourage participants to select a longer-term comfort temperature and avoid a multitude of excessive, opposing, adjustments. The period of adjustment lasted for 15 (exp 1 & 2) or 20 min (exp 3 & 4), upon which the experiments ended. Total duration of the experimental exposure was 45/50 min ((30 min heating phase and 15- or 20-min personal adjustment phase).

**Experiment 5:** In experiment 5, without radiation, initial measures of  $T_{ty}$  and HR were recorded, in addition to subjective ratings of TS, TC and TP. Participants were then able to adjust the air temperature for 32 min, referred to as the personal adjustment phase. At the start of the personal adjustment phase, participants were instructed that they had 5 min to adjust the temperature using the dial of the PCS. They were instructed to select a temperature that would provide long term thermal comfort. After the 5 min adjustment period, participants were able to make fine adjustments to the temperature for 1 min in every 3 min. Prior to each

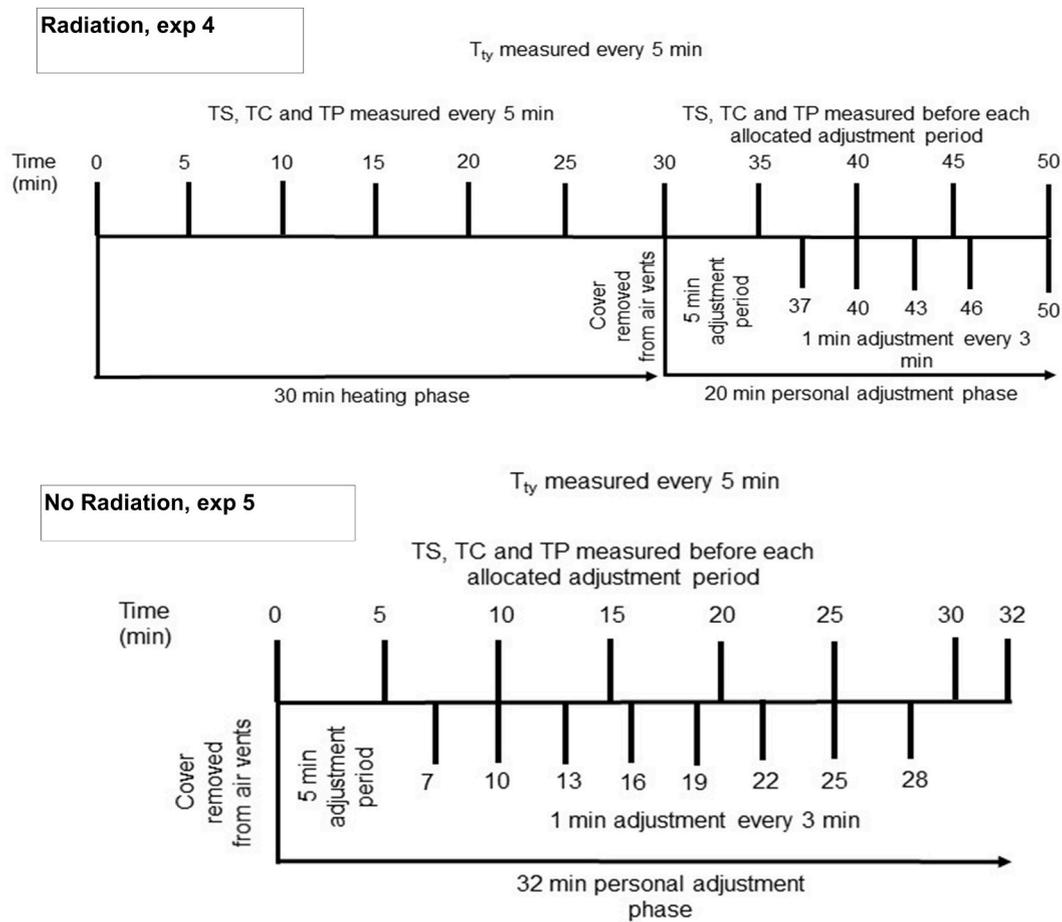


Fig. 4. Comparison of experimental schedule for experiments 4 (top) & 5 (bottom). Experiments 1–3 were almost identical to the top schedule with the only difference a variation in PCS personal adjustment time (15 or 20 min).

adjustment period, ratings of TS, TC and TP were recorded. At the end of the personal adjustment phase, subjective ratings of TS, TC and TP for the whole body and regional sites of chest, legs, arms, hands, feet and face were taken again. The total duration of this experimental procedure was 32 min (no heating phase and 32 min personal adjustment phase).

## 2.8. Statistics

Checks for the level of matching within each individual experiment were done using t-tests on age, mass, height, Body Surface Area (BSA), and BMI. For the overall dataset, variables were analysed using a 2 way (experiment and ethnicity) ANOVA including a test for equality of variance (Levene's Test) focussing on the results at the end of the experiment. Effect sizes were determined with  $\eta^2$  0.01–0.06 'small', 0.06–0.14 'medium' and  $>0.14$  'large'. Subjective scores for thermal sensation, comfort and preference were compared using a non-parametric test Mann-Whitney  $U$  test for independent samples. Tests were performed with SPSS statistics, IBM, Version 23.  $P < 0.05$  was taken as criterion for significance.

## 3. Results

### 3.1. Matching groups for anthropometrics

Table 3 shows the participant characteristics after selecting subsets for each experiment to match both ethnic groups for anthropometric characteristics. By removing a total of 16 participants, two groups were created for each experiment that were matched, i.e. their anthropometrics were not significantly different. The only significant difference

remaining was the age in the CHI-MALE experiment.

### 3.2. Chamber conditions

Chamber temperature, relative humidity and solar radiation levels (Pyranometer) for the two groups are shown in Table 2. Though the air temperature was significantly different between the groups for the CHI-Male experiment, the difference was only 0.2 °C, which is considered irrelevant given the measurement accuracy and the much larger differences in the other results observed. None of the other climate data was different between the Asian and European groups in any experiment ( $p > 0.05$ ).

### 3.3. Scores of thermal sensation (TS), thermal comfort (TC) and thermal preference (TP)

Subjective data in Fig. 5 show a consistent pattern over all experiments. First, when exposed to the radiation, TS, TC and TP changed rapidly and then slower towards warm, uncomfortable and prefer cooler, after which they levelled off until the personal cooling was activated at 30min. In experiment 3 and 4, Chinese initially scored warmer in the heating period, their comfort and preference was not significantly different at that time. After 30min (start of the personal adjustment phase), scores changed rapidly and were all close to 0 ('neutral', 'comfortable' and 'no change') after the first 5 min adjusting. In all experiments, scores of the two groups remained close to "neutral", "comfortable" and "no change" during the last 15/20/32 min of the personal adjustment phase, with score differences between the two groups being very small and also not significant ( $P > 0.05$ ).

**Table 3**

Participant anthropometric characteristics with results of the statistical comparison for ethnicity differences, after matching within each experiment (n: 167 → 151). BSA=Body Surface Area; BMI=Body Mass Index. NR=No Radiation. Significant differences are marked in green shading of the cells.

	number selected	Age (yrs)	SD	Height (cm)	SD	Weight (kg)	SD	BSA (m <sup>2</sup> )	SD	BMI (nd)	SD
<b>1 CHI-MALAY</b>											
EUROPEAN	10	20.6	1.0	169.3	7.1	68.6	7.5	1.78	0.14	23.8	1.0
ASIAN	10	19.8	0.8	171.3	5.5	65.6	8.2	1.76	0.12	22.3	2.4
P value		0.06		0.50		0.41		0.73		0.08	
<b>2 JAP</b>											
EUROPEAN	9	28.8	6.6	168.6	8.8	66.7	14.9	1.75	0.23	23.3	3.4
ASIAN	10	26.9	5.8	171.7	9.9	64.7	11.4	1.76	0.20	21.7	1.7
P value		0.518		0.478		0.737		0.974		0.222	
<b>3 CHI-Male</b>											
EUROPEAN	18	21.7*	2.0	181.6	7.1	77.2	7.5	1.97	0.13	23.4	1.8
ASIAN	22	22.9*	1.6	180.2	4.3	73.0	5.7	1.92	0.09	22.5	1.5
P value		0.03*		0.44		0.06		0.10		0.09	
<b>4 CHI-Female</b>											
EUROPEAN	18	22.5	3.0	164.3	4.6	55.7	5.7	1.60	0.09	20.6	1.7
ASIAN	18	24.0	2.6	163.4	4.8	55.9	5.7	1.59	0.09	20.9	1.8
P value		0.12		0.60		0.92		0.91		0.61	
<b>5 CHI-Female, NR</b>											
EUROPEAN	18	22.5	3.0	164.3	4.6	55.7	5.7	1.60	0.09	20.6	1.7
ASIAN	18	24.0	2.6	163.4	4.8	55.9	5.7	1.59	0.09	20.9	1.8
P value		0.12		0.60		0.92		0.91		0.61	
<b>All</b>											
EUR	73	22.9	3.9	169.9	9.3	64.5	12.2	1.74	0.20	22.2	2.4
ASIA	78	23.5	3.4	170.1	9.0	62.9	10.2	1.72	0.18	21.6	1.9
P value		0.30		0.88		0.37		0.61		0.11	

### 3.4. Mean skin temperature, tympanic temperature and heart rate

For experiments 1–4,  $T_{sk}$  (Table 4) increased continuously during the first 30 min exposure in the chamber and reached its highest value at the end of this period. Maximal skin temperatures were between 34.5 and 37 °C and did not differ between ethnicities. From the start of the personal adjustment phase,  $T_{sk}$  decreased rapidly during the first 5 min of cooling, but for the matched groups it was not different between ethnicities at the end of the personal adjustment period ( $P > 0.05$ ), apart from the JAP experiment where the Japanese participants had a significantly higher skin temperature by 0.8 °C. In general, before matching the groups Asians had a higher skin temperature, which disappeared however once matched for anthropometry. Body core temperature (exp. 3, 4 & 5) was not different between groups, nor was the observed Heart Rate.

### 3.5. Temperature of PCS outlet

The development over time of  $T_{pcs}$  is shown for all individuals and for all experiments in Fig. 6. For experiments shown in Fig. 6 A & B, where  $T_{pcs}$  was pre-set above 25 °C, most participants turned the temperature down. When air temperature from the PCS was pre-set in the range of 15–17 °C (Fig. 6C and D) most of the Chinese participants turned up the temperature of the air flow to keep themselves comfortable, whereas most of the European participants kept or lowered the temperature. Over several experiments, a small number of mainly European participants kept the setting at or close to minimum (about 12–13 °C) but did indicate comfort was achieved and did not prefer cooler temperatures.  $T_{pcs}$  was stable for most of the participants during the last 5–10 min of the cooling period.

Final  $T_{pcs}$  temperatures for all experiments and ethnicities are shown

in Fig. 7. Individual experiments all showed significant differences in final  $T_{pcs}$  between ethnicities ( $P < 0.05$ ; see Table 4) with medium (no radiation) to large (all radiation experiments) effect sizes. The two-way ANOVA (experiment and ethnicity) showed that both differences between experiments ( $P < 0.0001$ ) and the difference between ethnicities ( $P < 0.00001$ ) were highly significant, with effect sizes considered ‘large’ ( $\eta^2 = 0.351/0.187$  resp.). No interaction between experiment and ethnicity was present, indicating a very stable difference between ethnicities over experiments despite variations in conditions and equipment design. The average difference between the air temperatures of all conditions for the two ethnicities was 5.0 °C, ranging from 4.2 to 6.4 °C with the Asian groups always higher.

The significant effect of ‘experiment’ is related to differences in  $T_a$ , PCS design (#outlets and air velocity), presence of radiation and general setup for the different experiments and was expected. Thus, no direct comparisons between experiments’ outcomes can be made, apart from experiment 4 and 5 where the setup was identical, and the only difference was the presence/absence of radiation.

### 3.6. Air temperature in microclimate in front of the participant

The distance from the participant’s chest to front of the PCS was in most experiments approximately 70–80 cm. Hence, cooling air flowing out of the PCS was mixed with room air before arriving at the upper body of the participant. The temperature of this mixed microclimate air,  $T_{mc}$ , was influenced by  $T_{pcs}$ , the systems air speed,  $T_a$  and solar radiation. Air velocity of the chamber (0.1–0.2 m s<sup>-1</sup>), PCS (0.6–0.8 m s<sup>-1</sup>),  $T_a$  and solar radiation were stable during each individual experiment type, so  $T_{mc}$  changed with  $T_{pcs}$ . In experiment CHI-Males, this temperature was continually measured at chest level of the participant.  $T_{mc}$  of the two ethnicity groups during the cooling period in the chamber are shown in

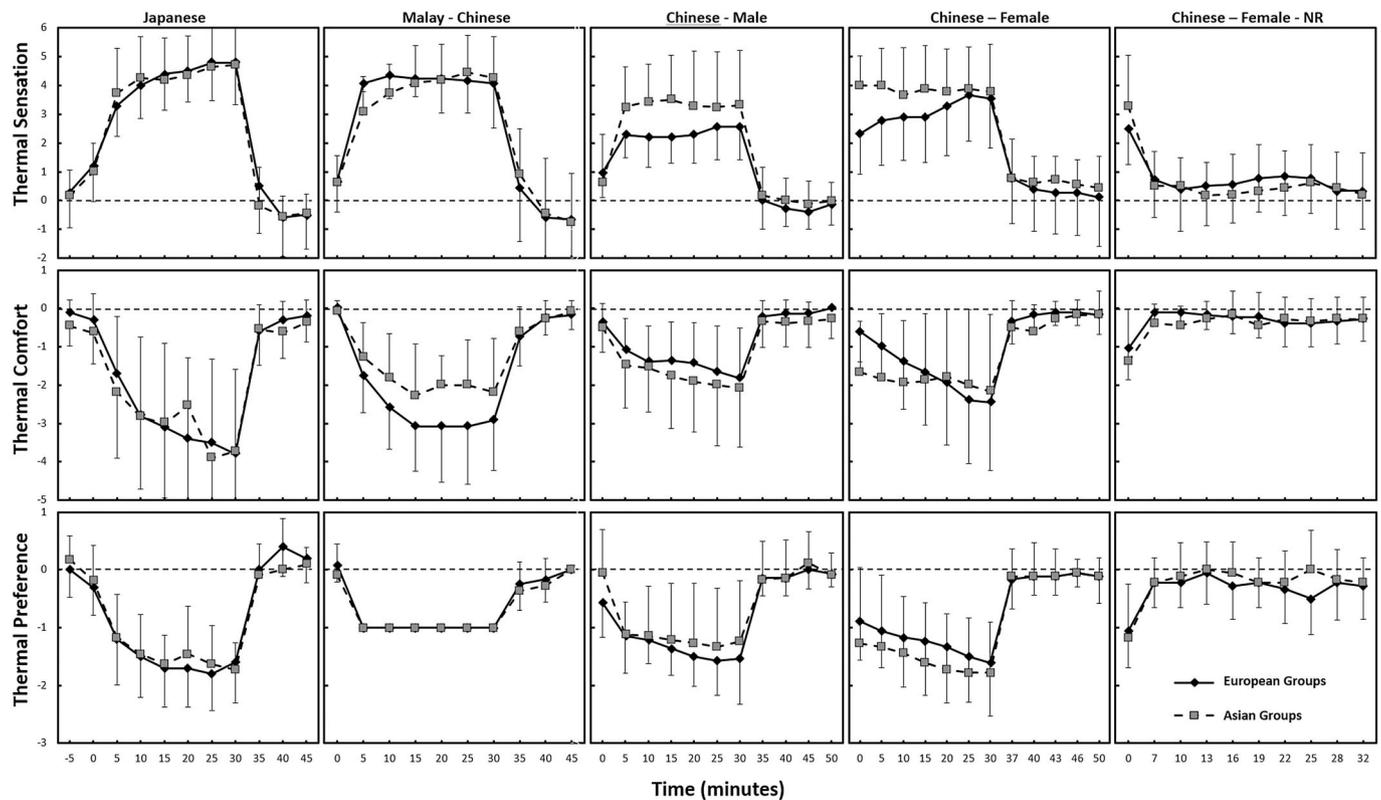
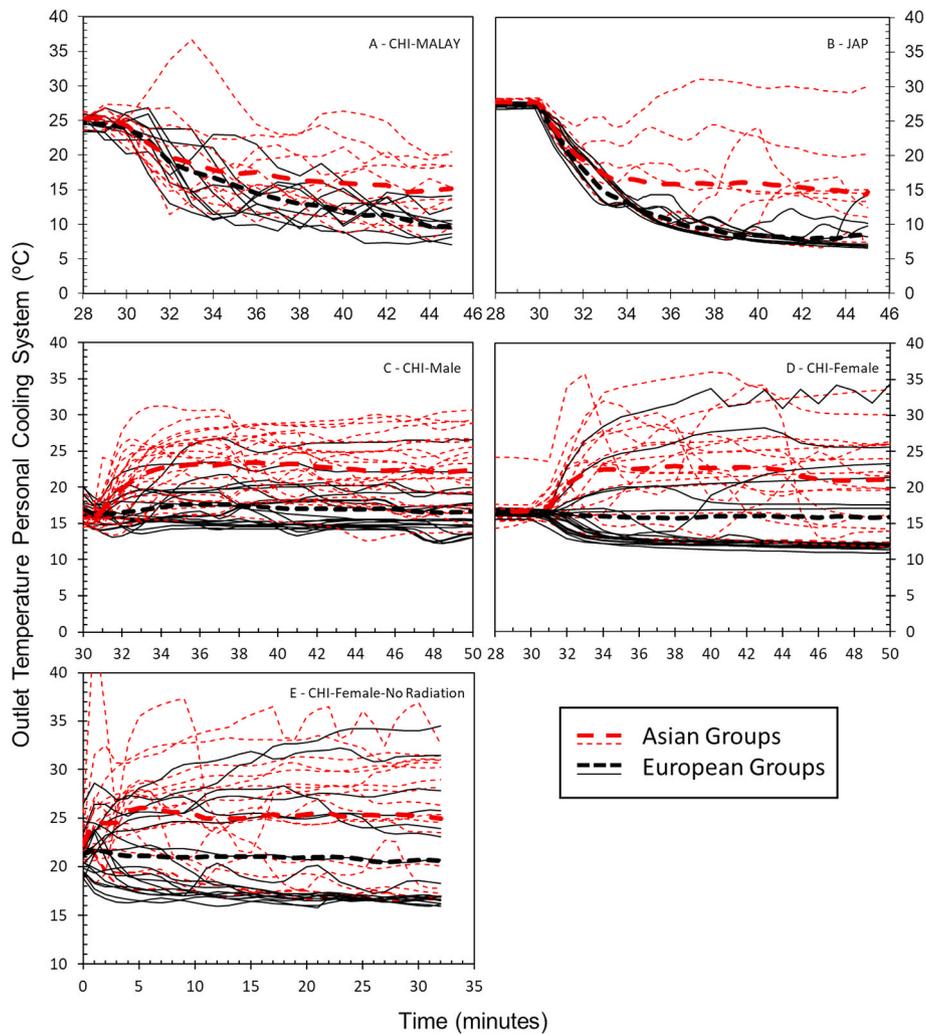


Fig. 5. Rating of thermal environment for Thermal Sensation, Thermal Comfort and Thermal Preference for the groups in all five experiments, matched for age, height, mass, BSA and BMI. In experiment 1–4, Heating was directed towards the front of the participants for 30 min followed by a 15/20 min personal adjustment period. In experiment 5, the adjustment period started immediately after sitting down and lasted for 32 min.

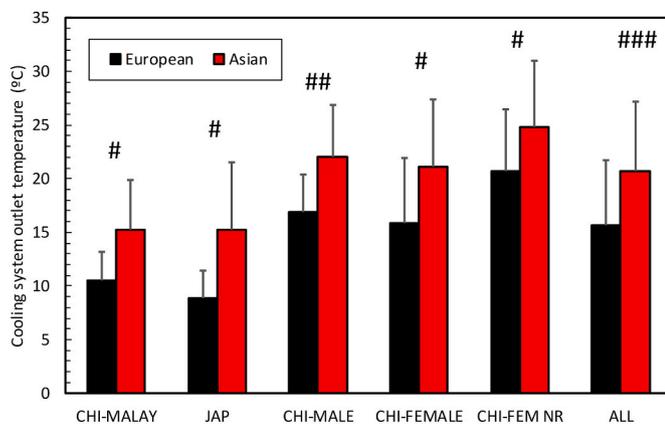
Table 4

Results for final mean skin temperature, personal cooling system (PCS) airflow outlet temperature and air temperature in the microclimate in front of the participant’s chest. Effect size based on  $\eta^2$ . Green shaded areas indicate significance between Asian and European groups in that experiment.

	n selected	T <sub>skin</sub> (°C)	SD	T <sub>mc</sub> at Chest (°C)		T <sub>PCS</sub> final (°C)	SD	effect size T <sub>PCS</sub> final	
<b>1 CHI-MALAY</b>									
EUROPEAN	10	34.7	0.3	-	-	10.6	2.6		
ASIAN	10	34.5	0.6	-	-	15.2	4.6		
P value		ns				0.01		0.30	large
<b>2 JAP</b>									
EUROPEAN	9	33.9	0.7	-	-	8.8	2.6		
ASIAN	10	34.7	0.7	-	-	15.2	6.3		
P value		0.030				0.012		0.318	large
<b>3 CHI-Male</b>									
EUROPEAN	18	33.2	0.6	24.8	1.5	16.9	3.4		
ASIAN	22	33.6	0.5	26.4	1.7	22.0	4.9		
P value		ns		0.00		0.00		0.27	large
<b>4 CHI-Female</b>									
EUROPEAN	18	34.4	0.3	21.8	2.6	15.8	6.1		
ASIAN	18	34.3	0.5	24.1	2.7	21.1	6.3		
P value		ns		0.02		0.01		0.16	large
<b>5 CHI-Female, NR</b>									
EUROPEAN	18	33.5	0.5	26.1	2.6	20.7	5.8		
ASIAN	18	33.5	0.7	28.0	2.8	24.8	6.1		
P value		ns		0.04		0.04		0.12	medium



**Fig. 6.** A–E: Air flow temperatures of the PCS outlet measured at the air vents. Individual and group mean curves. All individual experiments show a significant difference between ethnicities ( $P < 0.05$ ).

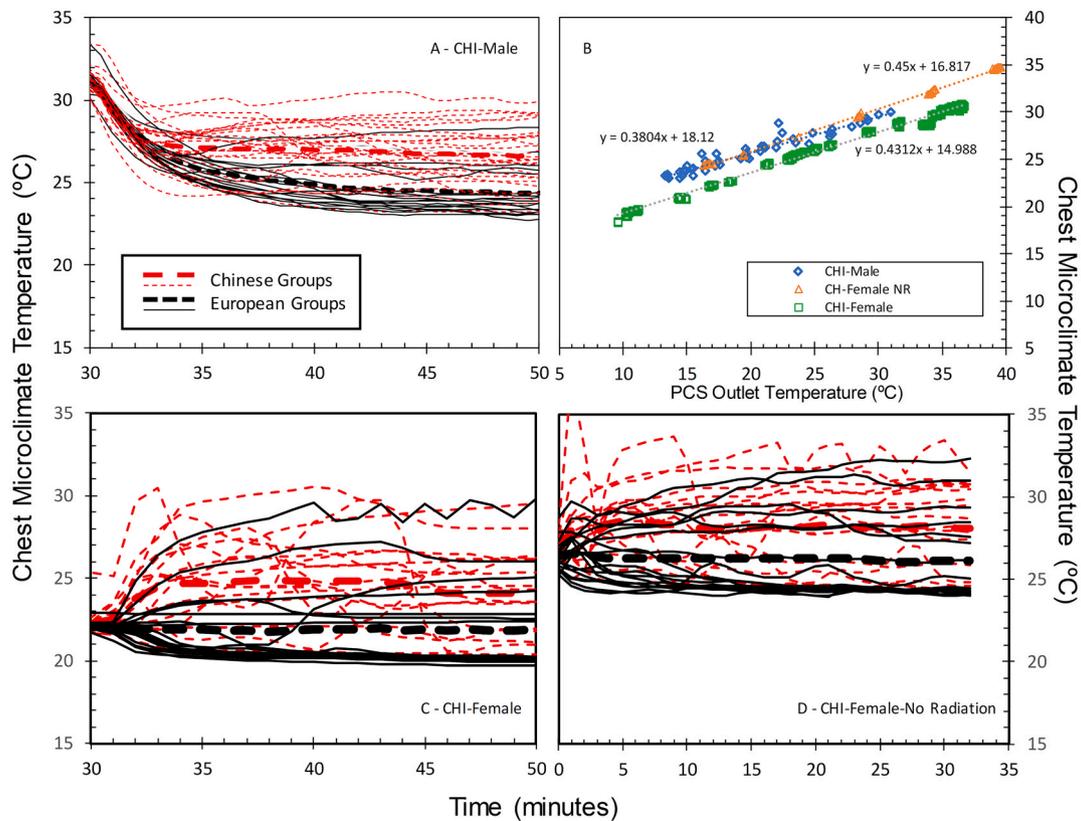


**Fig. 7.** Comparisons of the personal cooling system outlet temperature selected by the participants in individual experiments. Values are taken at end of the experiment. All differences observed in the individual experiments differ significantly between ethnicities ( $\# = P < 0.05$ ;  $\#\# = P = 0.001$ ,  $\#\#\# = P = 7 \cdot 10^{-8}$ ). No comparison between experiments is made as the setup details differed.

**Fig. 8.** After 30 min exposure to the strong solar radiation  $T_{mc}$  was higher than  $30\text{ }^\circ\text{C}$  with most of the participants feeling warm at this moment. When the cooling started, they adjusted cooling air temperature to compensate for the heat load.  $T_{mc}$  decreased continuously during the first 5 min of the personal adjustment phase, with cooling curves for the European group being steeper than those of the Chinese Male group in general.  $T_{mc}$  was stable for most of the participants during the last 5–10 min of the personal adjustment phase, and curves for the two groups kept almost parallel after 10 min of cooling. The  $T_{mc}$  for the Chinese Males being on average  $1.6\text{ }^\circ\text{C}$  higher than for the European for the fully matched groups ( $P = 0.0001$ ). For CHI-Female with and without radiation  $T_{mc}$  was determined in separate calibrations of the PCS (Fig. 8 B), without the participant in the chair. Using these calibrations to estimate  $T_{mc}$  during the main experiments, it was observed that in both experiments the Chinese Female group had significantly higher values ( $P < 0.05$ ). For each  $1\text{ }^\circ\text{C}$  drop from room temperature in  $T_{pcs}$  in the experiments mentioned above,  $T_{mc}$  dropped by approximately  $0.43\text{ }^\circ\text{C}$ . For the lower legs and the head, these changes were lower and varied more per experiment.

#### 4. Discussion

The main outcome of the study is that all five experiments using healthy male and female ethnicity groups matched for clothing, age, body size (height and mass), body mass index (adiposity) and surface



**Fig. 8.** Temperature of the microclimate close to the participants chest for the A: CHI-Male experiment (measured), and C & D: CHI-Female experiments (calculated). B: calibration data of  $T_{mc}$  in relation to  $T_{PCS}$  for CHI-Male and CHI-Female experiments.

area, produced a consistent difference between the Asian groups (Japanese and Han-Chinese) versus the white-western-middle European. The Asian groups selected substantially warmer outlet temperatures of the Personal Comfort System (4.2–6.4 °C, mean 5.0 °C, exp 1–5,  $P < 0.00001$ ), leading to significantly warmer temperatures in the microclimate air next to the skin in the areas targeted by the PCS (1.6 °C - 2.3 °C, mean 1.9 °C in exp 3,4,5;  $P < 0.05$ ).

In addition to this main outcome, the other observations were: In experiments 3 & 4 (CHI-Male and CHI-Female) Chinese participants tended to feel warmer in the heating phase (moderate temperature and solar radiation, but no active temperature control), though this did not lead to significantly higher discomfort or stronger preference for wanting to be cooler than for the Europeans.

A significantly higher mean skin temperature during the heating and the personal adjustment phase (0.8 °C) was observed for the Japanese participants compared to European participants (Experiment 2, JAP). For the Chinese participants, skin temperatures tended to be higher on average when all data were included, but this disappeared when anthropometric data for the groups were fully matched.

The aim of the experimental design was to compare groups of different ethnic background, Han-Chinese and Japanese on the one side and western-middle-European (“Caucasian”) on the other, for their thermal sensation, preference, and thermal comfort in a personal climate adjustment design, allowing the participants to achieve their optimal thermal comfort and thus avoiding known language and semantic issues [5,45] in interpretation of discomfort or sensation scales. The inclusion of the Japanese group in a mainly Chinese study is based on the modern Japanese population (except the aboriginal Ainu people) being seen as a genetic sub-population of “Chinese” people, as the largest fraction of people inhabiting the islands of Japan emigrated from the east Asian (Chinese) mainland over the last 2000 years (Nina Jablonski, personal communication; [52]), thus showing a relevant relation to the Chinese groups.

Matching of the ethnic groupings was based on requirements of various paradigms used in this type of research: 1: All subsets were selected with the same age, as age changes the way humans thermoregulate. While in one experiment there remained a significant age difference, this was extremely small ( $<2$  years) and is not considered biologically relevant, as such age-related changes in thermoregulations only develop beyond 45 years of age and take many years to become visible [53]. 2: All subsets were matched for height/stature. Given the use of radiation in exp 1–4, it was important to provide similar irradiated body areas. This was achieved by matching groups for height and adjusting the seat height for each participant to get the same body parts into the radiation beam and ensure equivalent radiation exposure in the subsets. 3: All subsets were matched for body mass, which with equal height results in equal body surface areas for the groups and with equal adiposity (indicated by the Body Mass Index being matched) results in similar amounts of metabolic active tissue. Thus, heat generation mass and heat loss surface areas are matched. Also, the equivalent BMI pointing to similar body composition ensures that internal body conductive heat exchanges are similar. Any remaining differences, e.g. differences in skin blood flow, would be due to differences in thermoregulatory control, and thus, if present, form real ethnic differences.

Therefore, observing the same result for all five experiments strongly indicates that the ethnic differences observed are a consistent finding related to ethnicity, not due to anthropometric or age differences in the populations tested.

The PCS, designed to allow participants to adjust the temperature of air blown at them to compensate for the heat radiation exposure or the raised room temperature fulfilled its function: As can be seen in Fig. 5, in all experiments participants were able to achieve comfort, and their thermal preference was ‘no change’ by the end of the test. However, the absolute value of temperatures chosen for the PCS differed substantially between experiments, despite showing the same difference between ethnicities. Experiment 1 & 2 had significantly lower PCS temperatures

than experiment 3–5. The main reason for this may be a change in the design of the PCS between these experiments. The first system, used in experiments 1 & 2, only had 4 outlet vents compared to 8 in the later experiments 3–5 and the later systems had more powerful fans. Hence the distribution and speed of the PCS air and the effective cooling was potentially less efficient in the early experiments, explaining the choice of colder temperatures coming out of the PCS. PCS temperatures were highest for experiment 5, without radiation. Here the PCS only had to compensate for the higher air temperature but not for the substantial radiation influx, giving a potential explanation for this observation.

The observed temperature difference at the chest microclimate (average Asian groups 1.9 °C higher) is very close to the observations by Ref. [34] for Malays versus Europeans who observed a 2 °C higher value of the thermal comfort preference of the former. Ref. [35] similarly observed a 2 °C higher preferred temperature of Melanesians versus “Caucasians”. As those studies did not match participants for clothing and activity, a clear conclusion was not possible at that time, however the observed effect is indeed similar to the current, highly controlled lab studies. Ref. [44] also proposed ‘general health’ related to socio-economic status as a potential confounding factor. With the present cohort mainly consisting of University students in the UK, we assume that health/socio-economic status will be above an upper threshold for such effects.

Mixed groups of males and females were chosen in experiment 1 & 2, while experiment 3 was male only and experiment 4 & 5 female only. With close to identical outcomes in terms of PCS temperature difference between the groups for all these experiments, this paper does not provide any indication of sex differences in thermal preference. With experiment 3, male, and 4, female, having quite a similar setup, the results are still very similar (Fig. 7), also in absolute temperature choice. Thus the two experiments do not suggest a male – female difference, despite substantial anthropometric differences between the sexes. Given the differences present in experimental setup between experiments, unfortunately no conclusive formal comparisons between the male and female data can be made.

Finding significant differences in all experiments also suggests a good sensitivity of the ‘self-selected temperature’ research paradigm, consistent with suggestions in the literature that it is superior to testing a paradigm where climates are fixed at multiple levels and the preferred point is analysed by regression of the comfort votes and subsequent interpolation to the neutral point [49,50]. Also, the used approach is not dependent on analysis of differences in the thermal sensation, preference or comfort votes, with its problems of language, semantics etc. [5, 45]. The only use of the subjective votes is to ensure participants had reached the optimal points for comfort and neutral sensations and preferences, which was clearly achieved (Fig. 6) in the adjustment period, indicating that this was of sufficient length. The length is important to consider, given issues with ‘thermal history’; the influence of previous short- or long-term thermal experiences on the current behaviour/sensation. Long term history in terms of heat acclimatisation was avoided by ensuring participants were in the same climate for at least 2 months. Even longer-term history effects [54] could be seen as part of the ethnicity differences that cannot be separated out in this experiment. For effects of short-term thermal history, Ref. [55] suggest a 20-min post transition thermal memory in students in a lecture after an undefined history before the lecture, while Ref. [56] observed very fast transitions (<5 min) to new stable levels of sensation and comfort in people boarding trains or moving between climate chambers. To reduce any impact of this type of short term thermal history and get groups into the same thermal state, participants were instructed to avoid exercise before the test and stayed a minimum of 30 min in a thermoneutral space to ‘acclimatise’ to the same environment before entering the chamber and also reported to be comfortable before the start of the experiment.

The habitual climate (long term thermal history) may be an important factor that could affect thermal comfort preferences of the two

groups. In this paper, all European participants were from areas where the climate is mild, while most of the Asian participants originated from areas with hot summer or hot all-year round conditions, i.e. where summer is substantially hotter by around 10 °C than that of the UK and western middle Europe (for Köppen classification of climate regions see Table 2) Given the vast climate difference between summer in the UK and China/Malaysia/Japan it could be expected that participants of the two groups would have developed a different perspective of a thermally comfortable environment, therefore could be expected to take different compensatory measures to acquire the perception of thermal comfort [54]. Direct heat acclimation effects on the other hand were not expected to affect the results, as the Asian participants were in the UK long enough to remove any lasting heat acclimation effect [43]. Genetic differences, (genotypic or phenotypic adaptations) could be a factor in explaining the differences, although comprehensive research and consistent findings are limited [57], thus this can only be stated speculatively.

Given the use of solar radiation with a component in the visible spectrum, an impact of skin optical properties needs to be considered. While absorptance curves are available across the spectrum from visible to infrared for black and white skin [58], we have been unable to source a similar curve for Chinese or Japanese skin. “Light” European and Chinese skin differ in the amounts of pheomelanin and eumelanin they contain, and in the size of the melanosomes packaging the melanin [59], which would suggest a different absorptance in the visible range. Alaluf et al. provide a skin reflectance value, which showed a difference of 4.5% between Chinese and European skin but this was not statistically significant. The differences between ‘photo-protected’ and ‘photo-exposed’ body parts within each ethnicity was however much bigger (16%) and significant. Also, due to clothing coverage only minor skin areas were exposed to direct radiation. Thus differences between the studied ethnicities may be limited in this aspect.

Evidence from field studies in numerous countries has shown differences in neutral and preferred temperatures for different ethnicities [17,36,60,61]. These studies identify that there are ethnic differences in response to the thermal environment but do not comprehensively determine the physiological basis for the differences. The studies often have confounding factors to which noted differences tend to be attributed; clothing, metabolic activity and body morphology, as well as different methodological approaches.

Several investigators have evaluated the variability of different individual’s perceived comfort. Contrary to our findings, Ref. [62] concluded that age, sex and national-geographic differences did not alter the neutral and preferred temperature of the participant. Moreover, in support of this, Ref. [29,30,63] all observed no significant difference in thermal neutrality between “Caucasian” and Japanese and Singaporeans versus inhabitants of colder regions, though no matching of groups was evident in these studies. Thus confounding factors could have led to a hidden ethnicity effect.

Various studies have looked at ethnic differences in response to heat, rather than comfort. Ref. [64] observed differences in physiological responses (lower sweat rates in Vietnamese compared to Japanese, all living in Japan) they attributed to different body core temperature set points. While the Vietnamese individuals had been living in Japan long enough to be acclimatised to the Japanese climate the responses to heat stress differed. Therefore, it could not have been solely the acclimatisation that is causing individuals of different ethnicity to show different response when exposed to thermal stress. Further evidence for a difference in thermal compensation between individuals of different ethnicity resides in an exercise thermoregulation comparison between Thai and Polish individuals. The researchers found, in exposure to heat, the thermoregulatory mechanisms to be more efficient in Thai’s than in the Polish individuals [65]. A study which looked at thermoregulatory response to desert heat on the other hand found no significant differences between races [66]. Given the different contribution of various thermoregulatory effector systems (blood flow, sweat rate) in the heat

(depending on sweating rate and efficiency) versus comfort (subtle adjustments in skin blood flow), the relevance of these observations in the heat for understanding comfort may be very limited.

In order to judge the results' validity for the three ethnic groups studied, compared to other studies, it is relevant to consider sample size. Sample sizes tend to differ substantially between field studies and lab studies. With increasing experimental control (lab), the time investment per participant increases, making large n numbers difficult to achieve. Also, in field studies, questionnaires tend to be the data collection method of choice, while in the lab more detailed, time consuming, assessments of physiological parameters take place. Compared to most lab studies referenced in this paper, the overall participant number (n = 151 selected out of 167, 73 European vs 78 Asian) is very high. As comparison, Ref. [67]: 10 Malay and 10 Japanese; Ref. [68]: 10 Malay and 10 Japanese; Ref. [39]: 10 Malay and 10 Japanese; Ref. [64]: 7 Malay and 7 Japanese; Ref. [65] used 12 Thai and 14 Polish; Ref. [36]: 8 Japanese Brazilians and 11 Japanese; Ref. [30]: 98 Singaporeans, no control group; and Ref. [35]: 34 Caucasian and 38 Melanese. While field studies have similar ([34] n = 20; [17] n = ~110) n numbers than the present study, they do suffer from the lack of matching the participant groups and outcomes can be confounded by the clothing variation present in the field as well as uncontrolled activity levels. Hence, we conclude that, in addition to the thorough matching of groups, the number of participants used in the present study, while distributed over five smaller experiments, allows a more valid comparison between ethnicities than the earlier studies. Moreover, the participant numbers in the individual studies 1–5 is at a similar level to the previous lab studies, which should give the outcomes of the individual studies at least equal relevance to the previous work.

The observation of a clear ethnicity effect in the absence of any differences in anthropometrics of the groups leaves the question of the potential causes for this observation:

- Differences in heat production/metabolism: a difference in heat production between ethnicities similar to that between sexes would be a potential explanation and would require the Asian groups to have a lower heat generation to explain the higher preference temperature. Metabolic rate was not measured in this experiment, but we recently compared resting metabolic rates between Chinese and British groups (Micheala Lawes, unpublished results) and did not observe such an effect.
- Differences in skin absorptance. As discussed above, differences in absorptance are assumed to be limited between the groups studied here, and if they would contribute, the Asian groups would absorb more of the radiant heat and thus require a cooler PCS temperature, not higher. Also finding the same effect size in the experiment without solar radiation indicates that this effect does not play a relevant role here.
- Differences in long term thermal history. Ref. [69] points to improved cold tolerance in those residing in colder areas and Ref. [54] suggests an impact of the long-term thermal history on the assessment of a warm climate for participants in his study (Nigerian, Turkish & Hungarian). The author links lower preferences to the habitual use of air conditioning in those from warmer countries. While Kalmár's groups were not matched for anthropometrics, which could explain at least part of the observation, such an effect, whether based on habitual air conditioning use, or ethnicity related climate variations cannot be excluded.
- Differences in Physiology: Differences in thermoregulation could affect the thermoneutral zone [11] and differences in e.g. number and distribution of thermoreceptors [40] could affect perceptual measures. While some work is done in this area in terms of heat and cold exposure (e.g. Kuno's classical work on sweat gland distribution), to our knowledge no clear data are available for thermoregulatory control close to the thermoneutral zone or optimal comfort temperature. Similarly, data on thermoreceptor distribution are

sparse, and we are not aware of any ethnicity related study. This would be a relevant area to study further.

One could expect the interpretation/utilisation of the observed results to differ between applications in offices and cars. Given the high levels of radiation in experiment 1–4, the balance between radiative gain and convective losses may be different in offices where appropriate shielding is present. Given however that in the absence of solar influx (exp 5) and quite different air temperature almost identical differences between ethnicities were present suggests the effects observed may be generalised across applications. Most office PCS systems may focus on airflow above the desk rather than both to upper and lower body in cars, which could affect the absolute temperatures chosen, but again may not give a different ethnicity effect.

## 5. Conclusions

To our knowledge, this is the first study on ethnic differences in thermal comfort that removed most known confounding factors from the experimental design. Comparing several groups of Asians ((n = 78, Malaysian, 3rd and 4th generation immigrant Chinese; Japanese; Han-Chinese originating from China (male and female)); to matched western European groups (n = 73) in five different experiments, these were matched as far as possible for age, height, body mass, body surface area, body mass index, activity level and clothing. They were all unacclimatised and were tested in the same climate chamber setup using the same personal climate system (different between experiments). Differences of native climates that the two participant groups were habituated to was large with over 10 °C difference in mean summer temperature.

- Both the Chinese and the Japanese participants selected significantly warmer temperatures of the PCS than the white, middle-western-Europeans.
- The Asian groups consistently selected a PCS airflow temperature 5 °C higher (range 4.2–6.4 °C between experiments), leading to 1.9 °C warmer (1.6 °C - 2.3 °C in experiments 3,4,5) microclimate temperatures close to the person's chest compared to the European groups. These observations are relevant to the development and design of personalised comfort/climate systems for offices, car air-conditioning systems, and the observed ethnicity effect may also be relevant to analysis of thermal comfort in buildings in general.
- In the period of heating (moderate temperature and solar radiation, but no personal control of temperature), Chinese participants felt warmer in some studies, though this difference did not reach significance and was not reflected in a colder preference vote or more discomfort.
- In the matched comparisons, skin temperatures were similar in all experiments with exception of the Japanese group, that had a higher skin temperature.
- While skin temperature differences were observed before groups were matched, which disappeared with the extensive matching, a significant difference in the selected personal cooling temperature remained consistently present for all subgroup comparisons before and after matching, showing no link between skin temperature and selected temperature.

## Author contributions

GH was the senior academic responsible for experiments 2, 4 and 5; supervised exp 1 and jointly with YQ developed exp 3. GH secured funding of exp 4&5 and did the final write-up of this summary paper. KG performed experiments 4&5, analysed the data and wrote the report for these two experiments. YQ was visiting academic in the EERC lab and developed and performed exp 3, followed by data-analysis and writing a preliminary report/paper. LD developed and performed exp 2 and

analysed the data. VK performed exp 1 as part of his studies. SH supported the design of studies 3-5 and contributed to the drafting and development of this paper.

### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Study 4&5 were funded by a car manufacturer.

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