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Dynamic thermal perception under whole-body cyclical conditions: Thermal overshoot and thermal habituation

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ABSTRACT

The emerging *"smart grid"* paradigm with associated demand-management programs, such as demand-response (DR), calls for enhanced building energy flexibility. This can be achieved by time-shifting or -shaving building heating and cooling peak loads through the implementation of heating and cooling set-point temperature modulations. However, designing and controlling comfortable DR-induced set-point variations remains a challenge as the psycho-physiology of dynamic thermal perception is still poorly understood. In this paper, we explored the physiological and subjective responses of 29 male and 35 female adults to whole-body warm and cool cyclical thermal conditions and focused on studying the phenomena of *"thermal overshoot"* and *"thermal habituation"*. We observed that females responded to cooling with a higher rate of cooling of skin temperature and, correspondingly, stronger thermal overshoot responses compared to males. These perceptual differences were explained in terms of skin temperature differences since the relationship between thermal sensation and skin temperature was independent of sex. We tested whether other factors influence the interindividual variability of the sensory response and found that the thermal overshoot response weakens as participants' body mass index increases and their age decreases. Thermal habituation was found to modify skin temperature only after cool exposures. Given that the studied rates of change of the air temperatures are those that can be typically found in buildings during DR events, our results can have implications on the design and control of female-proofed set-point fluctuations, as designing for an average occupant might result in thermally unacceptable conditions for females.

1. Introduction

Future power systems will face an increasing share of intermittent renewable generation and growing electrification of energy demand [1]. To sustain these changes without investing in carbon-intensive traditional power plants and/or expensive network reinforcements, they will need to increase their flexibility through demand response (DR) programs. In buildings, DR-activated smart thermostats can be used to easily and cheaply exploit the flexibility potential of electric thermal systems [2,3]. This can be achieved by time-shifting or -shaving building heating and cooling peak loads through the implementation of dynamic modulations of set-point temperatures [4]. Such temporal thermal variability is useful not only for realising grid-interactive buildings but also for enhancing building occupants' comfort and health [5–14]. Moderately non-steady-state thermal conditions can give occupants more pleasurable thermal experiences than ever achieved by uniform and static states [5–10]. They also reproduce the natural variability found in nature (*"biophilic design"*) which appears to have a beneficial influence on human well-being [11]. Furthermore, they can stimulate the human thermoregulatory system and, therefore, have positive health effects [12–14]. However, the psycho-physiology of thermal perception under transient environmental conditions remains relatively poorly

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Abbreviations: TSV, Thermal Sensation Vote; TPV, Thermal Preference Vote; TCV, Thermal Comfort Vote; PMV, Fanger's Predicted Mean Vote.

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understood and, thus, we are still far from being able to design and control set-point modulations that will be acceptable, let alone comfortable for building occupants [10].

1.1. Thermal overshoot

Under dynamic thermal conditions, thermal sensation anticipates body temperature changes and is not only able to predict the final steady-state sensory response [15] but also to initially exaggerate it [16]. In particular, *"anticipation"* is the ability to forecast the final steady-state sensory response [15] and *"overshoot"* is the initial exaggeration of it [16]. This anticipatory and overshooting behaviour, hereafter simply referred to as *"thermal overshoot"*, depends primarily on the ability of sensory neurons to detect the rate of change of the skin temperature and to send this information to the brain through spiking of their firing rate [17,18]. Hence, the dynamic sensory response has been hitherto related to the magnitude and direction of the rate of change of skin temperature, with cooling predominant over warming in eliciting thermal sensation overshoots [10]. However, it is still not known whether this dynamic response depends on other variables, such as the mean skin temperature. For example, the detection of the warming rate has been found to be related to the inhibition of the firing rate of cold sensory receptors and, therefore, to be inherently linked with cold detection [19]. Hence, the warming-induced thermal sensation overshoot might be stronger under cool compared to warm conditions [10]. For a more comprehensive review of experimental research conducted on the phenomenon of thermal overshoot, the reader is referred to our previous review [10].

1.2. Thermal habituation

Thermal habituation is a short-term (*i.e.*, of the order of minutes or hours) adaptive process that modifies the body's sensory response after non-neutral thermal exposures that are sustained over time [10]. For example, the mean skin temperature has been observed to stabilize at a higher-than-neutral value after prolonged warm exposure, and at a lower-than-neutral value after prolonged cool exposure [20,21]. The corresponding thermal sensation is shifted in the opposite direction to the preceding thermal sensation *i.e.*, nudged towards slightly warm when coming from cool conditions, and slightly cool when coming from warm conditions [20,21]. This phenomenon appears to occur entirely at a central level, rather than being related to the dynamic activity of sensory neurons as the thermal overshoot [22]. However, it is still unknown how habituation influences dynamic thermal perception, especially, whether this phenomenon differs in intensity after cool and warm discomfort exposures and for how long this effect is sustained [10]. For a more comprehensive review of experimental research conducted on the phenomenon of thermal habituation, the reader is referred to our previous review [10].

1.3. Sex differences

Human thermal comfort research investigating sex differences has been mostly conducted under steady-state conditions and near neutrality. Under such conditions, sex differences in thermal comfort are considered to be small and not statistically significant [23–25]. As a consequence, current indoor climate regulations do not take into account any sex-specific requirements [26,27]. However, when exposed to stationary conditions far from neutrality, females have been observed to be more sensitive to temperature deviations and less sensitive to humidity deviations from the optimum conditions, and more thermally dissatisfied than males [28]. In particular, females have been found to perceive the indoor temperature as cooler on the cool side and warmer on the warm side [29–34]. Little is known about sex-related differences in physiological and thermal comfort responses under dynamic conditions, especially when rapidly moving away from neutrality. In this regard, Hashiguchi et al. [35] have exposed the lower part of the body of 8 males and 8 females to different temperature step-change transients and observed that the decrease of the thigh skin temperature is statistically greater in females than males at 16 °C. Correspondingly, the level of thermal comfort at 16 °C is significantly lower for females than males. Xiong et al. [36] have investigated sex differences in response to various whole-body temperature step-changes in 12 males and 12 females. The amplitude of skin temperature change was found to be larger in females than males after both up-steps and down-steps. Furthermore, females felt the lower temperature cooler and the higher temperature warmer than males and had significantly lower mean skin temperature at the lowest tested temperature (22 °C) and significantly higher skin temperature at the highest tested temperature (37 °C) than males. The thermal comfort level at 22 °C was significantly lower for females than males. Similarly, in the study of Yang et al. [23], 20 females and 20 males have been exposed to different whole-body step-change transients. The females' mean skin temperatures were found to decrease more rapidly and to be lower than the males' in cool conditions at 14 °C, 16 °C, and 18 °C. Correspondingly, females' mean thermal sensation was found to be significantly lower than males. While in warm conditions at 30 °C, 32 °C, and 34 °C, the females' mean skin temperatures were higher than males', possibly caused by the significantly lower skin wetness observed in females than in males. Finally, few studies have investigated sex differences in localized thermal sensitivity in the non-noxious range of temperatures [37,38]. For example, Schmidt et al. [37] have investigated warmth and cold detection thresholds of the human torso in 42 young individuals by applying a linear temperature increase (at 0.5 °C/s) and decrease (at 0.25 °C/s) to the skin from the initial baseline temperature set at 32 °C. Participants were instructed to indicate when they were first detecting a temperature change. Males were observed to exhibit a lower thermal sensitivity compared to females, especially during cooling transients and in the least sensitive locations of the human torso. Gerrett et al. [38] have used a different method in which they measured thermal sensation 10 s after the application of a fixed warm stimulus at 40 °C to 31 locations across the body of 12 males and 12 females. After the 10 s the skin temperature was observed to have researched steady-state. Females were found to have a significantly warmer thermal sensation than males at all locations.

These results suggest that sex differences exist in dynamic thermal perception and point to differences in skin temperature, rate of change of skin temperature, and thermal perception between female and male participants. However, these studies have investigated rapid step-change variations and conditions very far from neutrality, that are not normally encountered during DR events. Furthermore, the studied population exclusively consists of young students and, thus, is poorly representative of the real population.

1.4. Research aims

In this paper, the results of an experiment exploring physiological (skin temperature) and subjective (thermal sensation, thermal comfort, and thermal preference) human responses under whole-body warm and cool cyclical thermal conditions are reported. Cyclical temperature variations (*i.e.*, repeated increases and decreases in indoor temperature) are the least studied dynamic conditions in the thermal comfort literature to date [10]. Yet they have the greatest potential to outline the sensory phenomena affecting dynamic thermal perception. In particular, this study aims to investigate the phenomena of *"thermal overshoot"* and *"thermal habituation"* whose psycho-physiology is not fully understood and adequately represented in physiological-based thermal perception models that predict thermal sensation and comfort based on body temperature conditions [7–9,39–41]. It also aims to understand whether interindividual and, in particular, sex differences exist in the unfolding of these two phenomena. We set the following a priori null hypotheses:

1. The mean skin temperature does not affect the thermal overshoot.

2. The direction of the rate of change of the mean skin temperature does not affect the thermal overshoot.
3. The shape of the first cycle has no effect on thermal habituation over the subsequent cycles.
4. Dynamic thermal perception does not differ between females and males.

2. Methods

2.1. Experimental procedure

The laboratory experiment consisted in exposing 64 human participants to four different cyclical sequences of whole-body cooling and warming over 180 min. For the first 30 min of the exposure, the thermal conditions were kept constant to allow the occupants to reach steady-state thermal conditions before the start of the air temperature fluctuations. Both environmental, physiological (skin temperature) and subjective (thermal sensation, thermal preference, and thermal comfort) data were collected during each exposure. The four cyclical sequences include two warm conditions (*"1 Warm"* and *"2 Warm"*) and two cool conditions (*"1 Cool"* and *"2 Cool"*) as shown in Fig. 1. The corresponding rates of change of the air temperature (see Fig. 2) are similar in intensity to those typically found during DR events in buildings [42] and are outside the maximum allowable temperature fluctuations set by the standards [26,27]. In particular, the ASHRAE Standard 55 sets to 3.3 °C the maximum operative temperature change over 4 h as long as the variations are within 1.1 °C, 1.7 °C, 2.2 °C, 2.8 °C for each 15 min, 30 min, 1 h, and 2 h respectively [26]. The two warm and cool exposures differ from each other in terms of intensity and duration of the non-neutral excursion of the first cycle but the average PMV during the two excursions is the same. This was explicitly designed to test whether the shape of the first cycle influences thermal perception in the second cycle (third null hypothesis).

The study was conducted for one week of July 2021 (for the warm conditions) and one week of October 2021 (for the cool conditions) over the northern hemisphere summer and autumn, respectively. The experiments commenced at either 09:30 or 14:30 h, in the morning and afternoon respectively. The mean outdoor temperature during the experiments was 25.3 °C in the morning and 31.9 °C in the afternoon in July and 12.8 °C in the morning and 17.2 °C in the afternoon in October. The participants were asked to arrive 30 min before the beginning of the experiment (*i.e.*, at either 09:00 or 14:00 h) and remained standing in a large waiting room before being transferred to the experimental room. During this time, they were briefed verbally about the study's requirements (without detailing the thermal conditions that they were going to experience) and allowed to ask any questions. They were also provided with written instructions and an information sheet. Each participant gave their written informed consent to participate in the study.

Participants were then accompanied to the experimental room where they stayed in groups of 2, 3 or 4 at most. They were randomly assigned to different experimental conditions. Each participant took part in only one test in summer and one test in autumn. Eight participants participated in both sessions, thus experiencing both one warm and one cool condition but at a distance of three months. Given the three-month gap, we considered the study design as "*between-subjects*" and adapted the statistical analysis accordingly (section 2.5). Participants were explicitly asked to not talk about their subjective answers with the other occupants in the room.

The research protocol was approved by the Ethics Committee at the University of Tours and Poitiers in France (Protocol No. CER-TP 2021-06-02).

2.2. Experimental platform

The experimental platform consists of four experimental rooms located at TIPEE's experimental facilities on the outskirts of La Rochelle (France). In particular, for the warm conditions (*"1 Warm"* and *"2 Warm"*), we used the experimental rooms of the *"Façade Test"*, while for the cool conditions (*"1 Cool"* and *"2 Cool"*) those of the *"Maison Eurêka"*.

The *"Façade Test"* is a building equipped with five test rooms mainly conceived for testing buildings' envelopes. The building acts as a thermal guard room surrounding the test cells that each has a *facade* facing

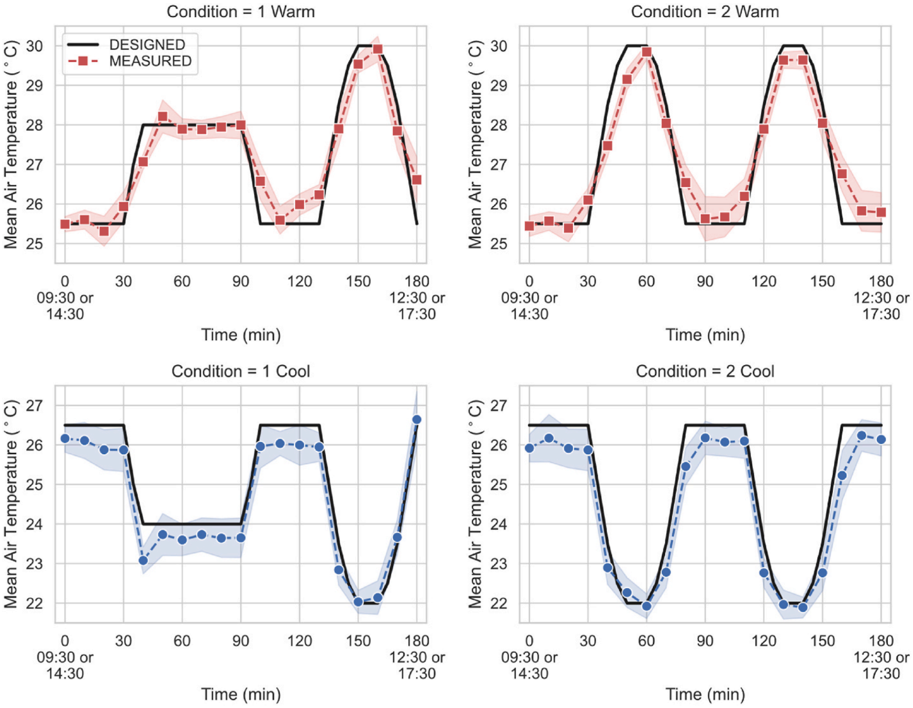

Fig. 1. Designed and measured mean indoor air temperature over the course of the four experimental conditions. Shaded bands represent one standard deviation.

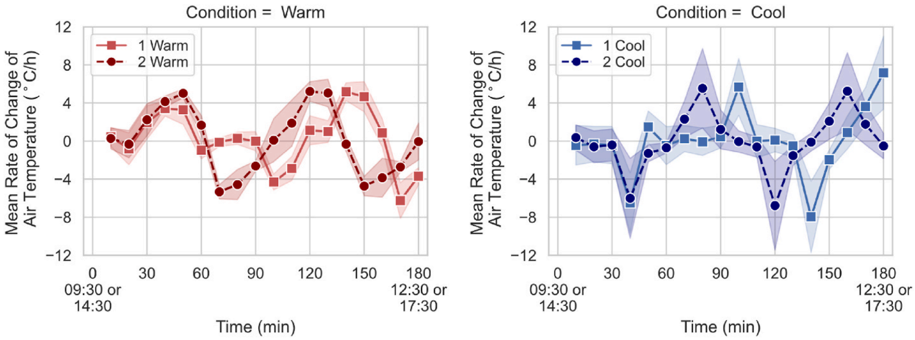

Fig. 2. Measured mean rate of change of air temperature over the course of the four experimental conditions. Shaded bands represent one standard deviation.

the outdoor climate (south-southwest orientation). The internal environment of the test room is separated from the thermal guard environment by 40 cm thick polyurethane foam panels, which are used as insulation. The cells are equipped with an air inlet and an air outlet for ventilation, a fan coil unit for air conditioning and an electric convector unit for heating, see Fig. 3 (left). The internal dimensions of the two test rooms employed are 5.64 m (length) x 3 m (width) x 3 m (height). For a full description of the facility, see Ref. [43]. At the time of the experiments, both test rooms had a 2 m^2 window in the middle of the facade consisting of a PVC frame and double glazing. A low emissivity coating was placed on the inner pane. The test rooms were illuminated by natural lighting; hence the electric lighting was switched off. The ventilation rate was set to approximately 50 m^3/h, *i.e.* about 7 L/s per occupant.

The *"Maison Eurêka"* is a stand-alone test-house or living lab with a surface area of 150 m^2. It consists of two levels with a kitchen/living room, an office room and a WC located on the ground floor and three bedrooms and a bathroom on the first floor. An additional technical room is dedicated to the measurement and control systems and is completely independent of the rest of the house. The test house is characterized by construction materials with low pollutant emissions. Both the envelope airtightness and the mechanical/natural ventilation system can be modulated in terms of supply/extract vents, but also thanks to the automatic control of windows opening/closing. For a full description of the facility, see Ref. [44]. The office room (ground floor) and one of the three bedrooms (first floor) were used for the experiments as test rooms. Both test rooms are equipped with convection heating and cooling units that can be controlled automatically and their windows are oriented southeast, see Fig. 3 (right). Windows were kept closed and sunscreens were used to avoid direct sunlight entering the rooms. The electrical lighting system was switched on. The test rooms were ventilated with 100% outdoor air with a ventilation rate set to approximately 30 m^3/h, *i.e.* about 3 L/s per occupant.

For the experiments, all the test rooms were equipped with desks and chairs. The schematic representation of the configurations of the test rooms is shown in Fig. 3. These configurations implied that the tested thermal environments were not spatially perfectly uniform, but were more similar to what to be expected in real buildings. The weekend before the week of the experiments and the night between the experimental days, all the rooms were ventilated continuously with fresh air. All desks and chairs were cleaned after each test.

2.3. Participants

Sixty-four (29 males and 35 females) adults participated in the experiment. The participants were Western Europeans between 20 and 60 years old recruited by a professional recruiting agency in southwest France. They were asked to wear similar light clothing consisting of short trousers or skirt, a shirt with short sleeves, ankle-length socks and shoes with total clothing insulation estimated to be about 0.6 clo (including the insulation of the chair), based on the tabulated clo values given in ANSI/ASHRAE Standard 55 [26].

During the experiments, they were allowed to drink water (bottled water was provided) and perform office tasks (reading or studying, using their mobile phones, working at the computer or performing other non-physical activities) but were not permitted to move around the room. Their metabolic rate was estimated to be approximately 1 met. For at least 24 h before the experiment, they were requested to:

- avoid heavy exercise,
- avoid alcoholic or stimulating drinks,
- avoid eating large meals,
- maintain a regular sleep schedule (do not stay overnight the night before).

All the participants were paid for their participation. The anthropometric characteristics of the participants are reported in Table 1. The distribution of male and female participants over the four experimental conditions is given in Fig. 4.

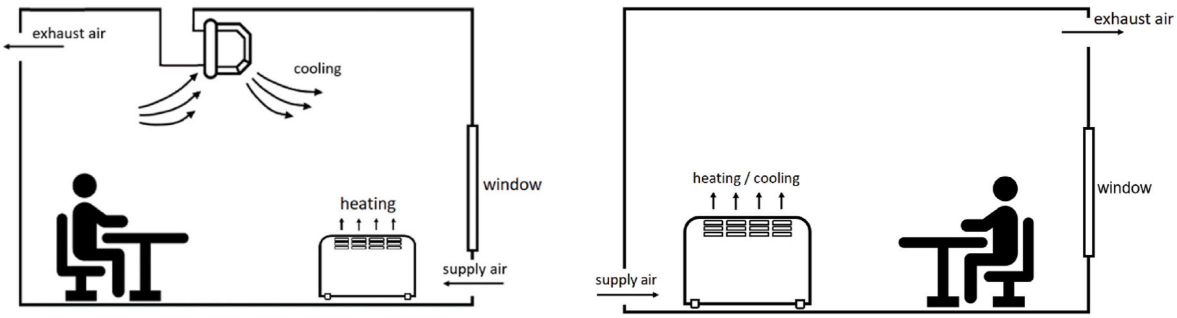

Fig. 3. Schematic representation of the configurations of the test rooms of the "Façade Test" (left) and the "Maison Eurêka" (right).

Table 1
Anthropometric characteristics (mean ± SD) of participants.

	Age (years)				*Height* (cm)				*Weight* (kg)			
	MALE		FEMALE		MALE		FEMALE		MALE		FEMALE	
1 Warm	35.8±	11.5	36.4±	9.6	177.0±	6.2	162.0±	4.7	73.2±	13.4	58.3±	11.1
2 Warm	44.4±	4.90	39.9±	7.0	176.3±	6.9	166.0±	3.4	76.0±	7.50	69.9±	15.0
1 Cool	41.6±	8.90	38.4±	5.6	176.4±	5.8	162.8±	4.2	78.5±	12.4	63.0±	11.5
2 Cool	34.2±	10.3	41.9±	11.3	179.1±	7.0	164.5±	5.3	75.9±	10.2	67.5±	15.1

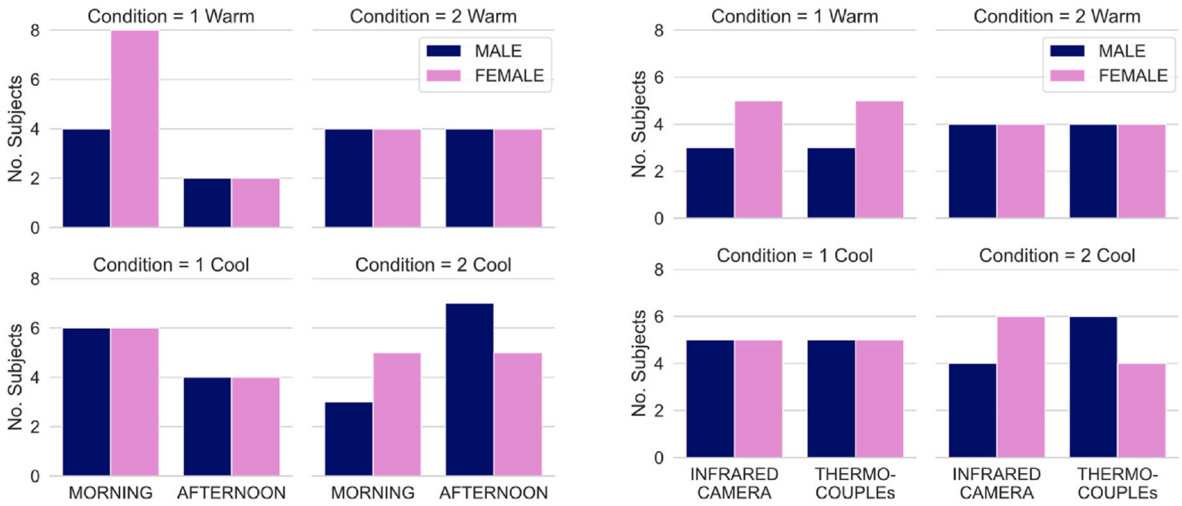

Fig. 4. Distribution of male and female participants over the four experimental conditions according to the time of day (left) and the measurement method for the skin temperature (right).

2.4. Measurements

2.4.1. Environmental

Air temperature T_a, globe temperature T_g, relative humidity *RH*, and air velocity V_a were measured with laboratory-grade equipment according to ISO standard [45]. The characteristics of the equipment used are reported in Table 2. The air temperature was recorded at 0.1, 0.6, 1.1 m height [46] close to the participants (at a distance of a maximum 1 m). In the "*Façade Test*", we had two different sets of air temperature sensors that were used to calculate an average air temperature. Carbon dioxide CO_2 and illuminance *ILL* were also recorded. The mean radiant temperature was computed using the function *psychrometrics.t_mrt* from the *pythermalcomfort* Python package [47]. Fanger's *PMV* index was also computed using the same package. Furthermore, a fully equipped weather station measuring the outdoor conditions was located on the facade and the roof of the building of the *"Façade Test"*. The sampling time step for all the monitoring equipment was set to 60 s.

Table 2
Characteristics of the equipment used for the environmental measurements.

	Façade Test (warm conditions)					*Maison Eurêka* (cool conditions)				
	Model	Manu-facturer	Range	Accuracy	Resolution	Model	Manu-facturer	Range	Accuracy	Resolution
T_a	Pt100 (HD32.3)	DELTA OHM	−40 to 100 °C	±0.2 °C	0.1 °C	–	–	–	–	–
	Pt100+ DAQ Keysight 34980A	TCSA	0–100 °C	±0.15 °C	0.01 °C	Thermo-couples Type T	TCSA	−50 to 400 °C	±0.2 °C	0.01 °C
T_g	Pt100 (HD32.3)	DELTA OHM	−10 to 100 °C	±0.2 °C	0.1 °C	Thermo-couples Type T	TCSA	−50 to 400 °C	±0.2 °C	0.01 °C
RH	HD32.3	DELTA OHM	0–100%	±1.5%	0.1%	HMP155	Vaisala	0–100%	±1%	0.1%
V_a	HD32.3 (omnidirectional)	DELTA OHM	0–5 m/s	±0.05 m/s until 1 m/s ±0.15 m/s beyond	0.01 m/s	8475 (omnidirectional)	TSI	0–2.5 m/s	±(3% of reading +1% of range)	0.07% of range
CO_2	KISTOCK KTH CO2-E	KIMO	0–5000 ppm	±(50 ppm + 3% of reading)	1 ppm	GMP222	Vaisala	0–3000 ppm	±(1.5% of range +2% of reading)	1 ppm
ILL	HD2021T + DAQ Keysight 34972A	DELTA OHM	20 to 2000 lux	±4% of reading	0.1 lux	HD2021T	DeltaOHM	20 to 2000 lux	±4% of reading	0.1 lux

2.4.2. Physiological

Skin temperature measurements were made using both contact and infrared thermometry. It is to be highlighted that, for half of the participants, the skin temperature was measured with contact thermometry and, for the other half, with infrared thermometry as indicated in Fig. 4.

The contact thermometry method consists of temperature sensors positioned in direct contact with the skin surface and, therefore, relies on conductive heat exchange between the skin and the sensor. We used thermocouples of type T (±0.2 °C accuracy, TCSA manufacturer), also known as copper–constantan thermocouples, with a diameter of 0.2 mm. The thermocouples were connected to a multichannel data acquisition system (Campbell CR1000 data logger + AM16/32B multiplexer). Before taking the measurements, the thermocouple system was calibrated for the temperature range of 20–50 °C. These thin thermocouples were fixed onto the skin with a breathable medical tape ensuring good contact and a rapid response time (<10 s), which is necessary for the dynamic conditions being studied. Skin temperatures were measured in 8 areas of the body: neck ($T_{skin,neck}$), chest ($T_{skin,chest}$), arm ($T_{skin,arm}$), forearm ($T_{skin,forearm}$), anterior thigh ($T_{skin,ant\ thigh}$), calf ($T_{skin,calf}$), shin ($T_{skin,shin}$), and hand ($T_{skin,hand}$) as shown in Fig. 5. The temperature probes were attached to the skin by the principal investigator of the study (*i.e.*, the first author) as soon as the participants entered the test room. The sampling time step was set to 30 s.

For infrared thermography, we used a calibrated, cooled digital infrared camera (FLIR SC5200 Model, ±1% of reading accuracy, −20 °C–55 °C range) operating in the 2.5–5.1 μm waveband and able to deliver thermal images of 320 × 256 pixels at a speed of up 170 Hz and with a minimum detectable temperature difference of 0.02 °C. The infrared camera was positioned on a level tripod perpendicular to the seated participant (90°) at a distance of approximately 3 m. The camera was allowed to stabilize for at least 60 min before the start of the experiment. Skin emissivity for the infrared camera was set to 0.98 [48,49]. The sampling time step was set to 1 s. The obtained thermal images were processed using Python by selecting skin areas from the 5 frontal skin measurements points (size of 1 pixel, *i.e.* 30 μm × 30 μm): chest ($T_{skin,chest}$), arm ($T_{skin,arm}$), forearm ($T_{skin,forearm}$), anterior thigh ($T_{skin,ant\ thigh}$), and shin ($T_{skin,shin}$) as shown in the right body of Fig. 5.

Contact and infrared thermometry have different advantages and disadvantages. In particular, a disadvantage of contact thermometry is that the sensor and its attachment modify the immediate environment for the underlying skin [50]. While infrared thermography is influenced by the movements of the participants and by changes in the emissivity of the skin surface due to either sweating or curvature of the skin [51,52]. To correct for errors due to the movement of the participants we applied a filter to the thermal image data that consisted in resampling the time series data to 1 min by always keeping the maximum value of the readings given that the surrounding of the participants was always at a lower temperature than their skin. Outliers were removed with a Gaussian moving average. The Gaussian moving average was also applied to the skin temperature data monitored with the thermocouples as there were some skin temperature peaks due to the participants temporarily covering up the sensors with another part of their body.

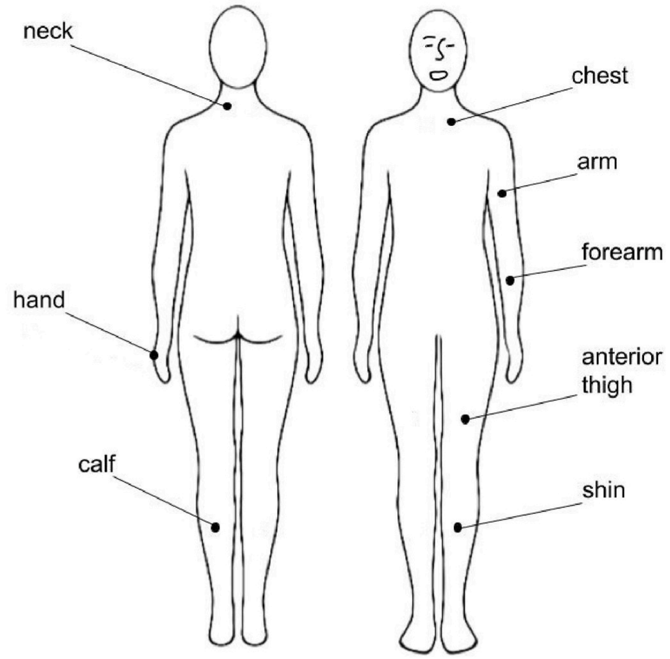

Fig. 5. *Overview of the 8 skin measurement locations. Adjusted from ISO 9886* [55].

Mean skin temperature ($T_{skin\ mean}$) was estimated using the formula proposed by Ramanathan [53] based on four weighted body locations (where the calf was substituted with the shin):

$$T_{skin\ mean} = 0.3 * T_{skin,chest} + 0.3 * T_{skin,arm} + 0.2 * T_{skin,shin} + 0.2 * T_{shin,ant\ thigh} \tag*{1}$$

We decided to use Ramanathan's formula for two reasons: firstly, it is one of the most often used [54] and, secondly, we had a limited number of points measured with the thermal camera so the use of a more complex formula was not possible. We could calculate the mean skin temperature for only 63 subjects as there was a problem with the measurements of the anterior tight, shin, and calf skin temperatures of one participant (female, *"1 Cool"* condition, morning) who, thus, had to be disregarded for the mean skin calculation.

For each skin temperature location and at each minute, we calculated the rate of change of the skin temperature as the first-order derivative with respect to time ($\frac{\partial T_{skin}}{\partial t} = \frac{T_{skin,t} - T_{skin,t-1}}{\partial t}$) and then resampled it to a 10 min average.

2.4.3. Subjective

The participants filled in a questionnaire describing their whole-body thermal perception at 10 min intervals starting either from 09:30 (morning tests) or 14:30 (afternoon tests). The questionnaire was paper-based and translated into French which was the language spoken by all the participants. The participants were provided with a QR code of a browser-based timer to keep the timing of the questions. However, most participants directly used the timer available on their smartphones. The time was also noted on each questionnaire. The questionnaire included three questions. The first question was the Thermal Sensation Vote (TSV) on the classical ASHRAE 7-point scale: *"Hot"* (+3), *"Warm"* (+2), *"Slightly Warm"* (+1), *"Neutral"* (0), *"Slightly Cool"* (−1), *"Cool"* (−2), and *"Cold"* (−3) [26]. The second question was the Thermal Comfort Vote (TCV) on a 6-point scale, including *"Very Comfortable"* (+3), *"Comfortable"* (+2), *"Slightly Comfortable"* (+1), *"Slightly Uncomfortable"* (−1), *"Uncomfortable"* (−2), and "*Very Uncomfortable"* (−3). The third question was the Thermal Preference Vote (TPV) on a 7-point scale, including *"Much Cooler"* (−3), *"Cooler"* (−2), *"Slightly Cooler"* (−1), *"No Change"* (0), *"Slightly Warmer"* (+1), *"Warmer"* (+2), and *"Much warmer"* (+3). The three questions translated into French are reported in the Appendix. To facilitate comparisons with previous works and datasets [56], the French translation of the three questions is based on the French version of EN ISO 10551 [57] except for the thermal comfort question which was slightly modified to include the *"Very Comfortable"* and "*Very Uncomfortable"* votes. We judged that these votes were relevant for the studied dynamic conditions that could have induced thermal alliesthesia [58]. However, a detailed analysis of the thermal comfort and thermal preference votes will be reported in successive works.

2.5. Statistical analysis

Statistical differences between the means of two independent samples (from two scenarios) at each time point are calculated using the *t*-test for the skin temperature data and the non-parametric Kruskal–Wallis test for the subjective votes. The equality of variance of the two populations is tested with *Levene's test*. *Cohen's d*, or standardized mean difference, is used to measure effect size and is interpreted using the following thresholds: 0.2 for small effect size, 0.5 for moderate effect size, and 0.8 for large effect size [59]. The 95% confidence intervals quantifying the accuracy of *Cohen's d* estimate are calculated using *cohen.d.ci* function of the *psych* package in R.

A Mixed-effects Linear Model (MLM) is employed to model the thermal sensation vote as a function of the body temperatures, treating the participants as a random factor. Due to the longitudinal nature of the collected time-series data, the participants represent our particular experimental unit and constitute a deviation from the overall mean. The adopted random-effects structure is a random intercept for each group. The maximum likelihood is the chosen estimation method for the parameters in the MLM model. A *"top-down"* modelling strategy is used, starting with the maximum model followed by a stepwise backward elimination procedure with only significant covariates kept in the model at the end of the procedure. The open-source Python package *scipy.stats* is used for all the statistical analyses (except for calculating the 95% confidence intervals of *Cohen's d*). Differences at $p \leq 0.05$ are considered statistically significant.

3. Results

3.1. Overview

The mean measured environmental conditions during the four experimental exposures are reported in Table 3. While the mean relative humidity was quite uniform (nearly 50%) across the different conditions, there was a marked difference in the air velocity and level of illuminance between the warm and the cool tests. These differences were due to the different experimental facilities and configurations used for the warm (*"Façade Test"*) and the cool (*"Maison Eurêka"*) exposures. In particular, the air velocity was higher during the tested cool conditions (around 0.3 m/s) and the illuminance was lower during the warm conditions (around 100–200 lux). The air quality in terms of CO_2 was better controlled in the *"Façade Test"* than in the *"Maison Eurêka"* due to the higher employed ventilation rate per occupant. Furthermore, the difference between the mean air and radiant temperature was about 1 °C in the *"Maison Eurêka"*, while in the *"Façade Test"* the air temperature closely followed the mean radiant temperature thanks to well-insulated wall panels. To account for all the environmental variables, Fig. 6 gives an overview of the four tested conditions in terms of Fanger's Predicted Mean Vote (PMV) which is compared to the measured thermal sensation vote (TSV). The difference between the mean predicted and measured thermal sensation vote was always kept within half vote, while the standard deviation of the measured thermal sensation was observed to be always larger than one vote. In the following section (section 3.2), some of the causes of such interindividual variation are investigated.

In Fig. 7, the mean skin temperature and its rate of change are compared between the two different methods used for measuring skin temperature, *i.e.* thermocouples and the infrared camera. The comparison is only shown for male participants under condition *"1 Cool"* since for this condition there was a balance concerning the time of day in which the tests were done. The two methods gave comparable results and the *t*-test did not reveal any statistically significant difference. Thus, in the rest of the analysis, we do not further distinguish between the skin temperature data collected with the thermocouples and the infrared camera.

3.2. Time of day and sex effects

In this section, we analyse both physiological and subjective data considering the effect of the time of day and sex. To derive Fig. 8, we first group the data based on the time of day (morning and afternoon), the sex (female and male), and the tested condition (*"1 Warm"*, *"2 Warm"*, *"1 Cool",* and *"2 Cool"*). For each group, we then calculate the difference between the afternoon and morning mean values. The mean difference calculated over all the groups is shown in Fig. 8. Apart from the chest skin temperature, all the other skin temperatures were slightly higher in the afternoon than in the morning. This was particularly evident during the first 30 min of exposure, and especially for the anterior thigh and shin skin temperatures. The mean thermal sensation vote was correspondingly slightly higher in the afternoon, while the mean thermal preference vote was shifted slightly towards cooler preference. Concerning sex differences, from the time series of Fig. 9, we can notice that females had lower mean skin temperatures and corresponding lower mean thermal sensation votes than males throughout the cool conditions (*"1 Cool"* and *"2 Cool"*).

To quantitatively compare the physiological and subjective data both in terms of the time of day and sex, we consider their values after 30 min from the start of the exposure, when the bodies reached a quasi-steady-state thermal condition (Figs. 10 and 11). It can first be observed that there was a vertical gradient in the skin temperature distribution, with higher skin temperatures observed in the chest and then progressively lower values in the shin and anterior thigh. The skin temperatures in the afternoon were generally higher for both female and male participants. However, these differences were statistically significant only in the warm tests for the males' anterior thigh and the females' forearm skin temperatures and in the cool tests for the females' anterior thigh and shin skin temperatures (Table 4 and Table 6). Differences in thermal perception votes between afternoon and morning were not statistically significant (Table 8) but the mean thermal sensation was warmer in the afternoon and the mean thermal preference was shifted towards cooler conditions in the afternoon. Also, participants were more comfortable in the afternoon during the cool conditions, and this difference was statistically significant. Female skin temperatures were generally lower than males', and the differences were statistically significant during the warm tests at the shin, arm and anterior thigh and the cool tests at the shin, forearm and anterior thigh (Table 5 and Table 7). Females' mean skin temperature was statistically significantly lower than males' in the afternoon during the warm tests and in the morning during the cool tests. Differences in subjective votes were not statistically significant but males felt warmer than females and the male mean thermal preference was shifted towards cooler conditions (Table 9).

Other than considering the steady-state conditions, we also compare physiological and subjective data during the warming skin temperature transients under warm conditions and cooling skin temperature transients under cool conditions to test the fourth null hypothesis (Figs. 12

Table 3
Measured environmental conditions (mean ± SD).

	T_a (°C)		T_r (°C)		RH (%)		V_a (m/s)		CO_2 (ppm)		ILL (lux)	
1 Warm	27.2±	1.4	27.3±	1.3	50.9±	6.2	0.1±	0.1	718±	93	124±	74
2 Warm	27.1±	1.6	27.4±	1.5	47.4±	5.2	0.1±	0.1	804±	113	164±	98
1 Cool	24.6±	1.6	25.5±	1.0	49.8±	7.4	0.3±	0.1	1041±	274	587±	346
2 Cool	24.5±	1.8	25.4±	1.1	49.1±	6.6	0.3±	0.2	1060±	246	554±	206

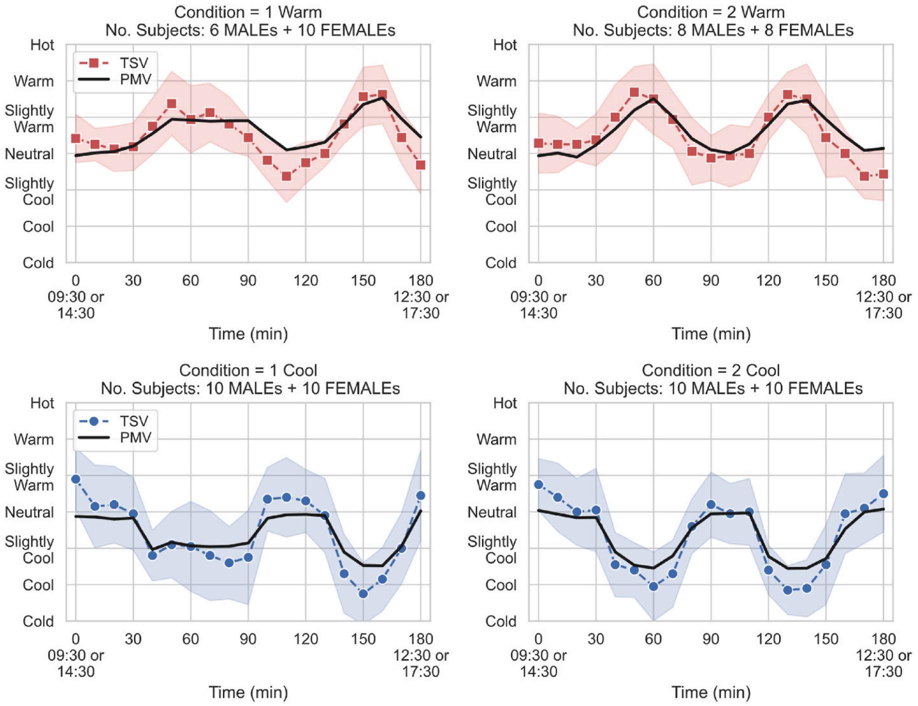

Fig. 6. Mean Fanger's predicted mean vote (PMV) and thermal sensation vote (TSV) over the course of the four experimental conditions. Shaded bands represent one standard deviation.

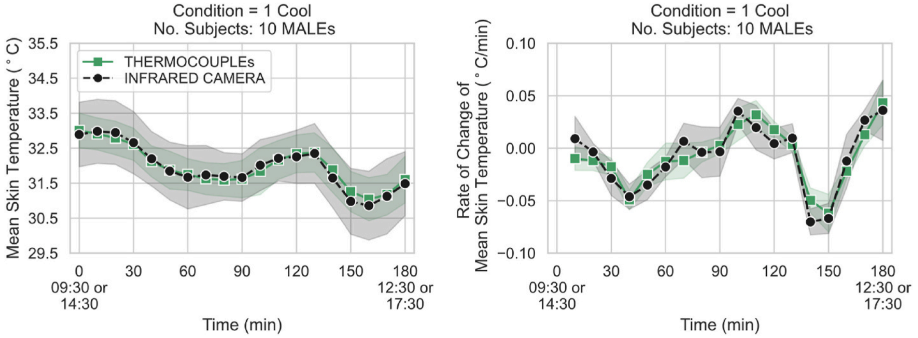

Fig. 7. Males' mean skin temperature (left) and its rate of change (right) over the course of condition "1 Cool" as measured by the infrared camera and the thermocouples. Shaded bands represent one standard deviation.

and 13). We only consider the initial transients that are occurring at times equal to 40 and 50 min, as the following transients are influenced by the thermal habituation phenomenon. Furthermore, we consider morning and afternoon data together as we tested for time-of-day differences in the rate of change of skin temperatures and thermal perception votes after 30 min and found them to not be statistically significant for both females and males under both warm and cool conditions. We found that the rates of change of the shin and mean skin temperature were statistically significantly lower (about 0.01 °C/min lower) for female participants during cooling under cool conditions. While during warming under warm conditions, statistically significant differences were not found (Table 10). Correspondingly, the mean thermal sensation vote was statistically significantly lower for female than male participants during cooling with a mean difference of about 1 vote and a large effect size, equivalent to one standard deviation (Table 11). Furthermore, we can be 95% *confident* that the effect size is not small since it lies within the 0.44 and 1.77 of the estimated interval.

The thermal sensation during the cooling transients gives a direct measure of the thermal overshoot. Thus, we can reject the fourth null hypothesis for the cool conditions but not for the warm ones.

3.3. Thermal overshoot

In the physiological-based thermal perception models that have been developed so far, the thermal sensation vote is modelled as the sum of a steady-state and dynamic component [7–9,39–41]. The steady-state component depends on the mean skin temperature $T_{skin,mean}$, while the dynamic term, that account for the thermal overshoot, depends on its first-order derivative with respect to time $\frac{\partial T_{skin,mean}}{\partial t}$. Thus, we have decided to follow the same approach to study the thermal overshoot. See Fig. 14 for an overview of $T_{skin,mean}$ and $\frac{\partial T_{skin,mean}}{\partial t}$ throughout the four experimental conditions. However, TSV does not depend linearly on $T_{skin,mean}$ and $\frac{\partial T_{skin,mean}}{\partial t}$ but rather reaches a positive and negative asymptote at $+3$ and -3 as we move away from the neutral condition on the warm and cool side, respectively. To model this asymptotic behaviour we use the hyperbolic tangent function ($Y = tanh(x)$) as already done in Ref. [39] and, thus, $arctanh(TSV/3)$ becomes our dependent variable, instead of TSV. As an example in Fig. 15 we show the relationship between the TSV and $T_{skin,mean}$ modelled with the hyperbolic tangent function ($TSV = tanh(T_{skin,mean})$). In this section, we aim to verify whether the

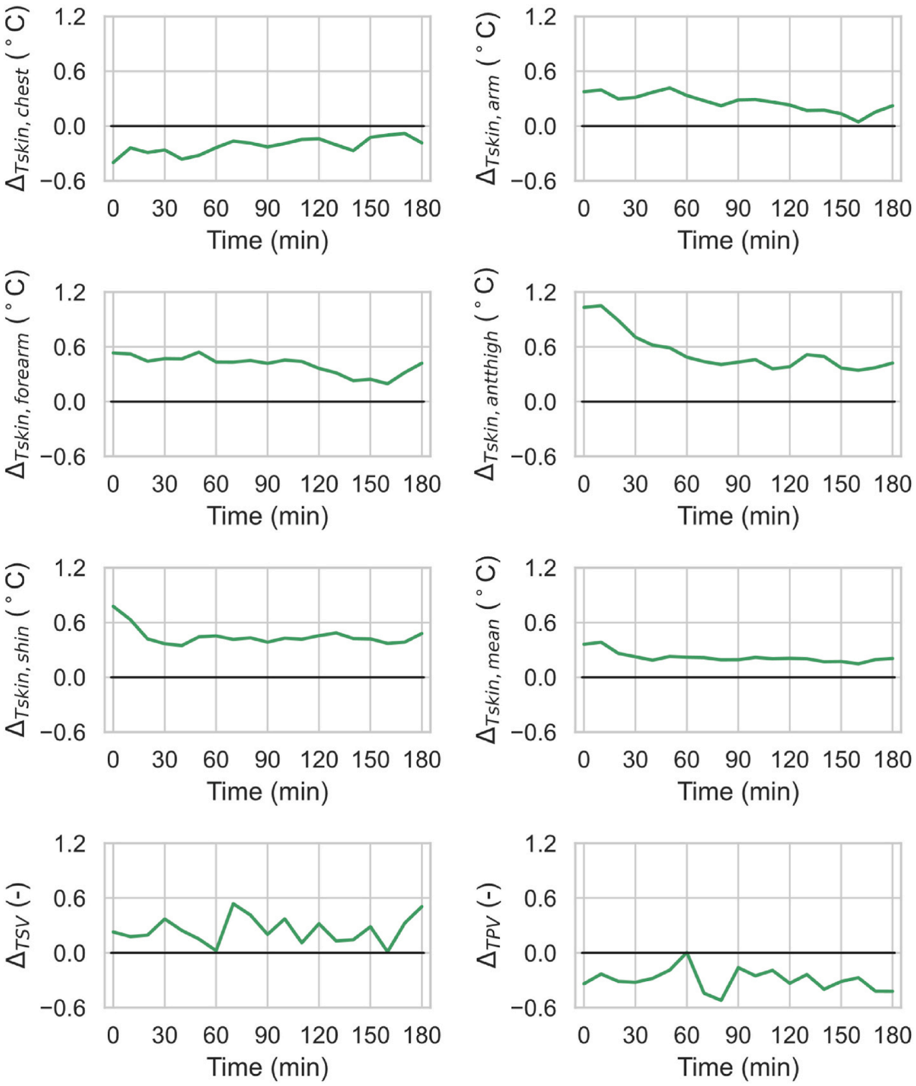

Fig. 8. Mean difference (Δ) between the afternoon and morning values of the different variables.

phenomenon of thermal overshoot depends on the mean skin temperature and the direction of its rate of change (the first two a priori null hypotheses). We employ MLM with possible two-way interactions, where $T_{skin,mean}$ and $\frac{\partial T_{skin,mean}}{\partial t}$ are included as fixed effects. We further include the categorical variable (*DIR*) to distinguish the direction of the skin transients, *i.e.* between *"cooling"* ($\frac{\partial T_{skin,mean}}{\partial t} < 0$) and *"warming"* ($\frac{\partial T_{skin,mean}}{\partial t} > 0$). An overview of the independent variables is given in Table 12. We use the Z score standardization to normalize data by rescaling each variable to have a mean of zero and a standard deviation of one. A *"top-down"* modelling strategy is adopted and the regression coefficients of the resulting linear models are shown in Table 13. The key assumptions of MLM (normality, homoscedasticity and no autocorrelation of the residual errors, no multicollinearity of the independent variables) have been checked and met. From the MLM we found that both $T_{skin\ mean}$ and $\frac{\partial T_{skin\ \ mean}}{\partial t}$ affect the thermal sensation vote (Fig. 16) but the interaction term between these two predictors is not significant so the effect of the rate of change is not found to depend on the value of the mean skin temperature. We further observed that the effect of $\frac{\partial T_{skin\ \ mean}}{\partial t}$ does not depend on the direction of the rate of change (*DIR*) which means that cooling skin temperature transients elicit the same responses that warming skin temperature transients. Thus, we failed to reject the first two null hypotheses.

3.4. Thermal habituation

In this section, we analyse the phenomenon of thermal habituation to understand what happens when humans are exposed to repeated warm and cool thermal exposures. From Fig. 17 we can observe that after the first cycle of warm exposure the skin temperature returns to its initial steady-state value (represented by the continuous black line), while after the cool exposure, the skin temperature stabilizes at a lower value than that associated with the initial steady-state exposure, whereas the thermal sensation vote returns and stabilizes to its initial value. This can be also observed in Fig. 18 which shows that, except for the chest, all the other skin temperatures decrease throughout the cool exposure on average by 1 °C. On the contrary, the thermal sensation vote slightly increases at the end of the cool exposure. The two warm (*"1 Warm"* and *"2 Warm"*) and cool (*"1 Cool"* and *"2 Cool"*) exposures differ from each other in terms of intensity and duration of the non-neutral excursion of the first cycle but the average PMV during the excursions is the same. The thermal sensation in the second cycle does not statistically differ between conditions 1 and 2 implying that the shape of the first cycle does not influence thermal perception in the second cycle as long as the average thermal discomfort level is the same. Thus, we failed to reject the third null hypothesis.

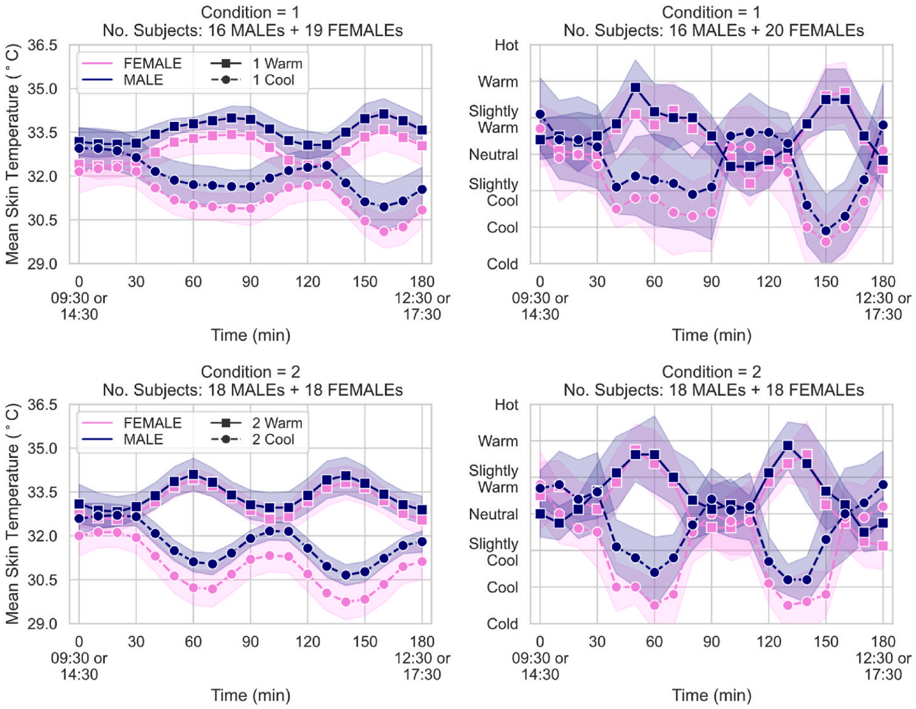

Fig. 9. Mean skin temperature (left) and thermal sensation vote (right) over the course of the four experimental conditions for females and males. Shaded bands represent one standard deviation.

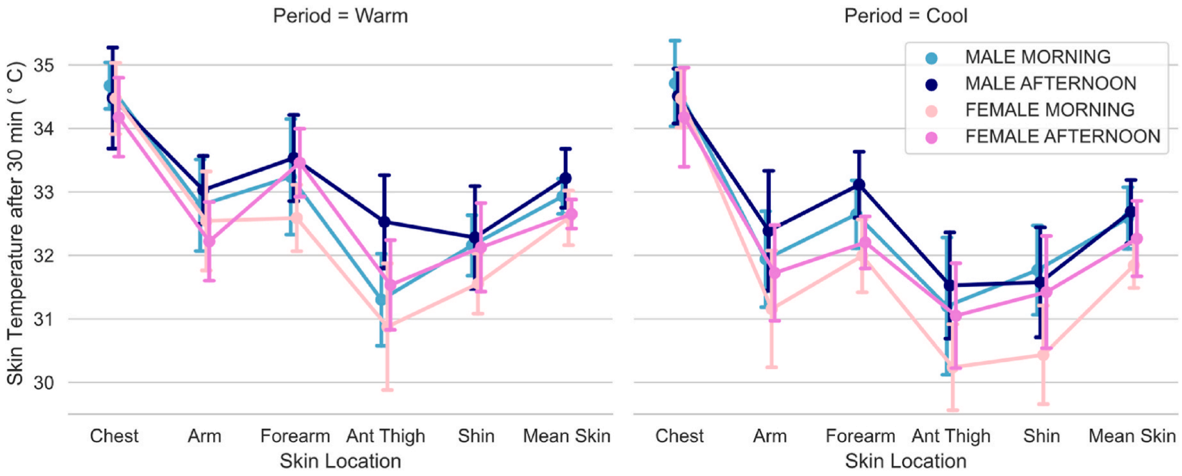

Fig. 10. Mean skin temperatures at different skin locations during steady-state conditions (time = 30 min) of the warm (left) and cool (right) tests for male and female participants in the morning and afternoon. Error bars represent one standard deviation.

3.5. Relationship between thermal sensation and body temperatures

So far, we have separately analysed differences in physiological and subjective data due to time of day and sex effects, but we did not test whether these factors also affect the relationship between body temperatures and thermal perception. We now want to understand whether the observed differences in thermal perception are only due to differences in skin temperature (as suggested by the data shown above). We employ MLM with possible two-way interactions to model the thermal sensation vote as a function of the skin temperature and its rate of change as already done in section 3.3, but we further include the following independent variables as fixed effects of our model: sex and time of day as categorical variables (female/male and morning/afternoon), the body mass index (BMI) and age as continuous variables. BMI is calculated by dividing participants' weight in kilograms by the square of their height in metres. The participants are treated as a random factor. Since the test rooms have different environmental conditions in terms of air velocity and illuminance, we additionally include a categorical variable to test whether the type of employed test room, i.e. either *"Maison Eurêka" or "Façade Test",* influences the relationship between the skin temperature and the thermal sensation. An overview of the independent variables is given in Table 14. A *"top-down"* modelling strategy is used. The key assumptions of MLM (normality, homoscedasticity and no autocorrelation of the residual errors, no multicollinearity of the independent variables) have been checked and met (see Fig. 19 for the correlation matrix).

Regression coefficients of the resulting linear model are shown in Table 15. Sex, time of day and room type were not found to affect the relationship between skin temperature and thermal sensation. Interestingly, we found that BMI and age of the participants influence the

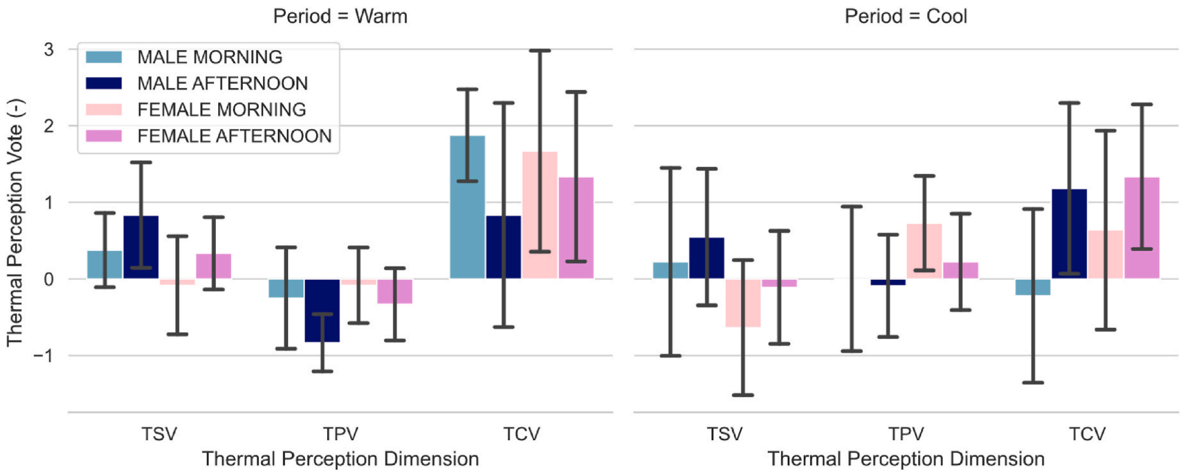

Fig. 11. Mean thermal perception vote during steady-state conditions (time = 30 min) of the warm (left) and cool (right) tests for male and female participants in the morning and afternoon. Error bars represent one standard deviation.

Table 4
Time of day differences in skin temperature at different locations during steady-state conditions (time = 30 min) of the warm tests.

	MALE				FEMALE			
	MOR(8) (mean ± SD)	AFT(6) (mean ± SD)	p-value (*t*-test)	Cohen's d +(CI)	MOR(12) (mean ± SD)	AFT(6) (mean ± SD)	p-value (*t*-test)	Cohen's d +(CI)
$T_{skin,chest}$	34.7± 0.4	34.5± 0.8	0.58	−0.31 (-1.37 0.76)	34.5± 0.6	34.2± 0.6	0.35	−0.48 (-1.47 0.52)
$T_{skin,arm}$	32.8± 0.7	33.0± 0.5	0.54	0.34 (-0.73 1.40)	32.5± 0.8	32.2± 0.6	0.42	−0.42 (-1.40 0.58)
$T_{skin,forearm}$	33.2± 0.9	33.5± 0.7	0.55	0.33 (-0.74 1.39)	32.6± 0.5	33.5± 0.5	≤0.01 *	1.56 (0.42 2.66)
$T_{skin,antthigh}$	31.3± 0.7	32.5± 0.7	≤0.01 *	1.56 (0.31 2.76)	30.9± 1.0	31.5± 0.7	0.19	0.68 (-0.34 1.68)
$T_{skin,shin}$	32.2± 0.5	32.3± 0.8	0.74	0.18 (-0.88 1.24)	31.6± 0.5	32.1± 0.7	0.07	0.96 (-0.09 1.98)
$T_{skin,mean}$	32.9± 0.3	33.2± 0.5	0.21	0.72 (-0.39 1.80)	32.6± 0.4	32.7± 0.2	0.76	0.15 (-0.83 1.13)

* statistically significant.

Table 5
Sex differences in skin temperature at different locations during steady-state conditions (time = 30 min) of the warm tests.

	MORNING				AFTERNOON			
	FEMALE(12) (mean ± SD)	MALE(8) (mean ± SD)	p-value (*t*-test)	Cohen's d +(CI)	FEMALE(6) (mean ± SD)	MALE(6) (mean ± SD)	p-value (*t*-test)	Cohen's d +(CI)
$T_{skin,chest}$	34.5± 0.6	34.7± 0.4	0.41	0.39 (-0.52 1.29)	34.2± 0.6	34.5± 0.8	0.52	0.39 (-0.76 1.52)
$T_{skin,arm}$	32.5± 0.8	32.8± 0.7	0.51	0.31 (-0.59 1.21)	32.2± 0.6	33.0± 0.5	0.05 *	1.28 (0.00 2.51)
$T_{skin,forearm}$	32.6± 0.5	33.2± 0.9	0.07	0.87 (-0.08 1.80)	33.5± 0.5	33.5± 0.7	0.85	0.11 (-1.03 1.24)
$T_{skin,antthigh}$	30.9± 1.0	31.3± 0.7	0.34	0.45 (-0.46 1.35)	31.5± 0.7	32.5± 0.7	0.05 *	1.26 (-0.02 2.49)
$T_{skin,shin}$	31.6± 0.5	32.2± 0.5	0.02 *	1.2 (0.21 2.16)	32.1± 0.7	32.3± 0.8	0.75	0.19 (-0.95 1.32)
$T_{skin,mean}$	32.6± 0.4	32.9± 0.3	0.08	0.86 (-0.09 1.79)	32.7± 0.2	33.2± 0.5	0.03 *	1.41 (0.10 2.67)

* statistically significant.

relationship between the rate of change of skin temperature and thermal sensation. In particular, as the BMI increases, the sensory dynamic response to skin temperature transients gets weaker, while as age increases the sensory dynamic response to skin temperature transients gets stronger.

4. Discussion

The discussion is organized around five issues. We first discuss the differences in thermal sensory responses that were observed between the morning and afternoon (section 4.1). Then, we examine sex differences in skin temperatures and thermal perception votes (section 4.2). Section 4.3 is dedicated to the relationship between skin temperature and thermal sensation. The phenomena of thermal overshoot and thermal

Table 6

Time of day differences in skin temperature at different locations during steady-state conditions (time = 30 min) of the cool tests.

	MALE				FEMALE			
	MOR(9) (mean ± SD)	AFT(11) (mean ± SD)	p-value (*t*-test)	Cohen’s d +(CI)	MOR(11) (mean ± SD)	AFT(9) (mean ± SD)	p-value (*t*-test)	Cohen’s d +(CI)
$T_{skin,chest}$	34.7± 0.7	34.5± 0.4	0.46	−0.34 (-1.22 0.55)	34.5± 0.5	34.2± 0.8	0.33	−0.45 (-1.34 0.45)
$T_{skin,arm}$	31.9± 0.8	32.4± 0.9	0.29	0.49 (-0.41 1.38)	31.2± 0.9	31.7± 0.8	0.18	0.63 (-0.28 1.53)
$T_{skin,forearm}$	32.6± 0.5	33.1± 0.5	0.08	0.84 (-0.09 1.75)	32.0± 0.6	32.2± 0.4	0.39	0.40 (-0.50 1.29)
$T_{skin,antthigh}$	31.2± 1.1	31.5± 0.8	0.48	0.32 (-0.57 1.20)	30.2± 0.7	31.1± 0.8	0.04 *	1.02 (0.07 1.95)
$T_{skin,shin}$	31.8± 0.7	31.6± 0.9	0.62	−0.23 (-1.11 0.66)	30.4± 0.8	31.4± 0.9	0.03 *	1.13 (0.16 2.07)
$T_{skin,mean}$	32.6± 0.5	32.7± 0.5	0.67	0.20 (-0.69 1.08)	31.8± 0.4	32.3± 0.6	0.09	0.83 (-0.10 1.74)

* statistically significant.

Table 7

Sex differences in skin temperature at different locations during steady-state conditions (time = 30 min) of the cool tests.

	MORNING				AFTERNOON			
	FEMALE(11) (mean ± SD)	MALE(9) (mean ± SD)	p-value (*t*-test)	Cohen’s d +(CI)	FEMALE(9) (mean ± SD)	MALE(11) (mean ± SD)	p-value (*t*-test)	Cohen’s d +(CI)
$T_{skin,chest}$	34.5± 0.5	34.7± 0.7	0.38	0.40 (-0.50 1.29)	34.2± 0.8	34.5± 0.4	0.27	0.51 (-0.39 1.40)
$T_{skin,arm}$	31.2± 0.9	31.9± 0.8	0.07	0.87 (-0.07 1.78)	31.7± 0.8	32.4± 0.9	0.12	0.73 (-0.19 1.63)
$T_{skin,forearm}$	32.0± 0.6	32.6± 0.5	0.02 *	1.11 (0.15 2.05)	32.2± 0.4	33.1± 0.5	≤0.01 *	1.82 (0.74 2.86)
$T_{skin,antthigh}$	30.2± 0.7	31.2± 1.1	0.04 *	1.02 (0.07 1.95)	31.1± 0.8	31.5± 0.8	0.24	0.54 (-0.37 1.43)
$T_{skin,shin}$	30.4± 0.8	31.8± 0.7	≤0.01 *	1.7 (0.64 2.72)	31.4± 0.9	31.6± 0.9	0.71	0.17 (-0.72 1.05)
$T_{skin,mean}$	31.8± 0.4	32.6± 0.5	≤0.01 *	1.67 (0.62 2.69)	32.3± 0.6	32.7± 0.5	0.12	0.74 (-0.18 1.64)

* statistically significant.

Table 8

Time of day differences in thermal perception during steady-state conditions (time = 30 min) of the warm and cool tests.

	MALE				FEMALE			
	MOR(8) (mean ± SD)	AFT(6) (mean ± SD)	p-value (Kruskal)	Cohen’s d +(CI)	MOR(12) (mean ± SD)	AFT(6) (mean ± SD)	p-value (Kruskal)	Cohen’s d +(CI)
TSV (Warm)	0.4± 0.5	0.8± 0.7	0.22	0.73 (-0.38 1.81)	−0.1± 0.6	0.3± 0.5	0.20	0.67 (-0.35 1.67)
TPV (Warm)	−0.2± 0.7	−0.8± 0.4	0.09	−0.97 (-2.08 0.17)	−0.1± 0.5	−0.3± 0.5	0.34	−0.49 (-1.48 0.51)
TCV (Warm)	1.9± 0.6	0.8± 1.5	0.17	−0.91 (-2.01 0.22)	1.7± 1.3	1.3± 1.1	0.38	−0.25 (-1.23 0.74)
	MOR(9) (mean ± SD)	AFT(11) (mean ± SD)	p-value (Kruskal)	Cohen’s d +(CI)	MOR(11) (mean ± SD)	AFT(9) (mean ± SD)	p-value (Kruskal)	Cohen’s d +(CI)
TSV (Cool)	0.2± 1.2	0.5± 0.9	0.55	0.29 (-0.60 1.17)	−0.6± 0.9	−0.1± 0.7	0.14	0.61 (-0.30 1.50)
TPV (Cool)	0.0± 0.9	−0.1± 0.7	0.84	−0.11 (-0.99 0.77)	0.7± 0.6	0.2± 0.6	0.12	−0.77 (-1.68 0.16)
TCV (Cool)	−0.2± 1.1	1.2± 1.1	0.02*	1.19 (0.21 2.14)	0.6± 1.3	1.3± 0.9	0.18	0.57 (-0.34 1.46)

* statistically significant.

habituation are finally discussed in sections 4.5 and 4.4, respectively.

4.1. Time of the day

Participants’ skin temperatures were observed to be slightly higher in the afternoon than in the morning, even after the 30 min of adaptation. The mean thermal sensation vote was correspondingly higher and found to be more comfortable in the afternoon. These results could be explained by the higher outdoor temperatures to which the occupants were exposed before the experiments in the afternoon as compared to the morning. This fact suggests that the widely-used adaptation time of 30 min might not be sufficient for homogenizing the participants’ initial thermal state. Making the participants perform a light exercise (e.g., stepping on a small platform) to obtain skin vasodilatation and, thus, homogenize the initial thermal state might be necessary even when the initial experimental conditions are neutral. Another possible

Table 9
Sex differences in thermal perception during steady-state conditions (time = 30 min) of the warm and cool tests.

	MORNING						AFTERNOON					
	FEMALE(12) (mean ± SD)		MALE(8) (mean ± SD)		p-value (Kruskal)	Cohen's d +(CI)	FEMALE(6) (mean ± SD)		MALE(6) (mean ± SD)		p-value (Kruskal)	Cohen's d +(CI)
TSV (Warm)	−0.1±	0.6	0.4±	0.5	0.12	0.75 (-0.19 1.67)	0.3±	0.5	0.8±	0.7	0.21	0.77 (-0.43 1.93)
TPV (Warm)	−0.1±	0.5	−0.2±	0.7	0.49	−0.28 (-1.18 0.62)	−0.3±	0.5	−0.8±	0.4	0.09	−1.07 (-2.27 0.18)
TCV (Warm)	1.7±	1.3	1.9±	0.6	0.83	0.18 (-0.72 1.07)	1.3±	1.1	0.8±	1.5	0.50	−0.35 (-1.48 0.80)
	FEMALE(11) (mean ± SD)		MALE(9) (mean ± SD)		p-value (Kruskal)	Cohen's d +(CI)	FEMALE(9) (mean ± SD)		MALE(11) (mean ± SD)		p-value (Kruskal)	Cohen's d +(CI)
TSV (Cool)	−0.6±	0.9	0.2±	1.2	0.11	0.77 (-0.16 1.68)	−0.1±	0.7	0.5±	0.9	0.10	0.75 (-0.17 1.65)
TPV (Cool)	0.7±	0.6	0.0±	0.9	0.11	−0.88 (-1.80 0.06)	0.2±	0.6	−0.1±	0.7	0.31	−0.46 (-1.35 0.44)
TCV (Cool)	0.6±	1.3	−0.2±	1.1	0.17	−0.66 (-1.56 0.26)	1.3±	0.9	1.2±	1.1	0.87	−0.14 (-1.02 0.74)

*statistically significant.

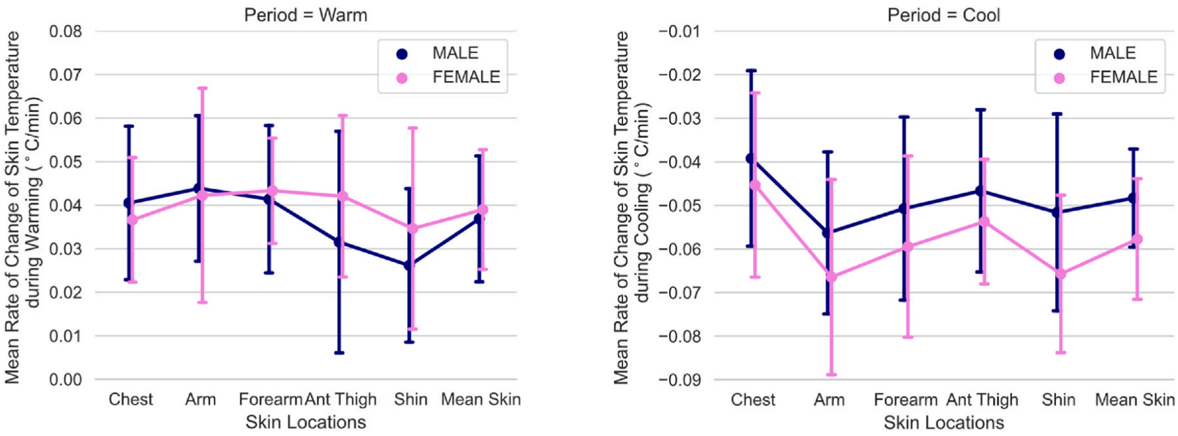

Fig. 12. Mean rate of change of skin temperature during warming time steps under warm conditions (left) and cooling time steps under cool conditions (right) for male and female participants. Error bars represent one standard deviation.

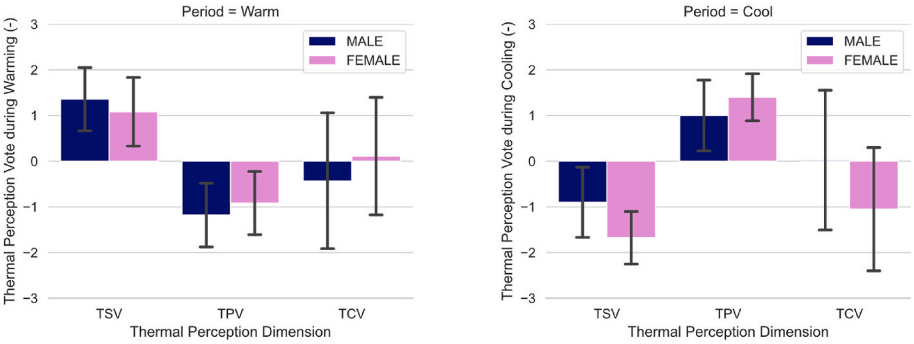

Fig. 13. Mean thermal perception during warming time steps under warm conditions (left) and cooling time steps under cool conditions (right) for male and female participants. Error bars represent one standard deviation.

explanation might be related to the diurnal fluctuations of body temperatures, and in particular, to the core temperature lowering down at night and raising during the afternoon [60]. By regulating the temperature thresholds that control autonomic thermoregulatory responses, the central circadian clock in humans is responsible for these diurnal body temperature fluctuations. Thus, similar daily variations could also characterize human thermal perception, the ultimate role of which is to drive thermoregulatory behaviours [61]. Vellei et al. [61] reviewed thermal comfort studies investigating the effect of the time of day and found contradictory results. Hence, future research will need to be dedicated to this topic.

4.2. *Sex*

Sex differences in thermal comfort have been explained in terms of a variety of physiological, psychological, and behavioural factors.

Table 10
Sex differences in mean rate of change of skin temperatures during warming time steps under warm conditions (left) and cooling time steps under cool conditions (right).

	Warm (Warming)				Cool (Cooling)			
	FEMALE(18) (mean ± SD)	MALE(14) (mean ± SD)	p-value (*t*-test)	Cohen's d +(CI)	FEMALE(20) (mean ± SD)	MALE(20) (mean ± SD)	p-value (*t*-test)	Cohen's d +(CI)
$\partial T_{skin,chest}/\ \partial t$	0.04± 0.01	0.04± 0.02	0.51	0.24 (-0.46 0.94)	−0.05± 0.02	−0.04± 0.02	0.37	0.29 (-0.34 0.91)
$\partial T_{skin,arm}/\ \partial t$	0.04± 0.02	0.04± 0.02	0.84	0.07 (-0.63 0.77)	−0.07± 0.02	−0.06± 0.02	0.14	0.48 (-0.15 1.11)
$\partial T_{skin,forearm}/\ \partial t$	0.04± 0.01	0.04± 0.02	0.72	−0.13 (-0.83 0.57)	−0.06± 0.02	−0.05± 0.02	0.21	0.41 (-0.22 1.03)
$\partial T_{skin,antthigh}/\ \partial t$	0.04± 0.02	0.03± 0.03	0.20	−0.47 (-1.17 0.24)	−0.05± 0.01	−0.05± 0.02	0.21	0.41 (-0.22 1.03)
$\partial T_{skin,shin}/\ \partial t$	0.03± 0.02	0.03± 0.02	0.28	−0.39 (-1.09 0.32)	−0.07± 0.02	−0.05± 0.02	0.04 *	0.67 (0.03 1.30)
$\partial T_{skin,mean}/\ \partial t$	0.04± 0.01	0.04± 0.01	0.68	−0.15 (-0.85 0.55)	−0.06± 0.01	−0.05± 0.01	0.03 *	0.73 (0.08 1.37)

* statistically significant.

Table 11
Sex differences in thermal perception during warming time steps under warm conditions (left) and cooling time steps under cool conditions (right).

	Warm (Warming)				Cool (Cooling)			
	FEMALE(18) (mean ± SD)	MALE(14) (mean ± SD)	p-value (*t*-test)	Cohen's d +(CI)	FEMALE(20) (mean ± SD)	MALE(20) (mean ± SD)	p-value (*t*-test)	Cohen's d +(CI)
TSV	1.1± 0.8	1.4± 0.7	0.43	0.37 (-0.34 1.07)	−1.7± 0.6	−0.9± 0.8	≤0.01 *	1.11 (0.44 1.77)
TPV	−0.9± 0.7	−1.2± 0.7	0.34	−0.37 (-1.07 0.34)	1.4± 0.5	1.0± 0.8	0.10	−0.59 (-1.22 0.05)
TCV	0.1± 1.3	−0.4± 1.5	0.38	−0.38 (-1.08 0.33)	−1.0± 1.4	0.0± 1.5	0.02	0.73 (0.08 1.37)

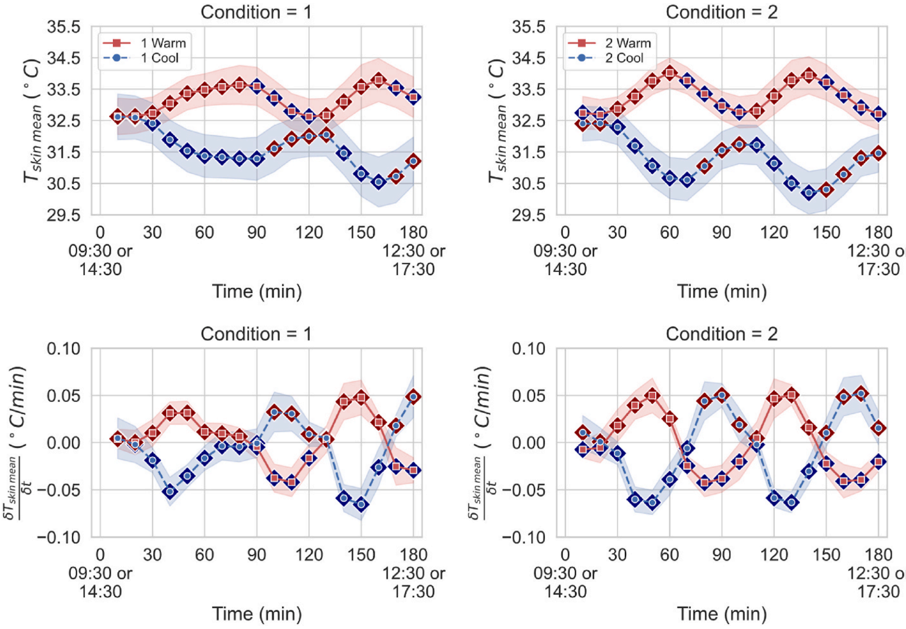

Fig. 14. Mean skin temperature ($T_{skin\ mean}$) and its first-order derivative with respect to time ($\frac{\partial T_{skin\_mean}}{\partial t}$) over the four experimental conditions. Diamonds serve to identify cooling (blue) and warming (red) skin temperature transients. Shaded bands represent one standard deviation.

Observational studies in the field have mostly justified the observed thermal comfort discrepancies between males and females based on sex-specific behaviour, in particular clothing insulation, and cultural factors [25]. Only a minority of studies have been dedicated to studying sex differences in thermal perception under dynamic thermal conditions by considering human physiology [23,35,36]. We observed that females responded to cooling transients with a higher rate of cooling of the skin temperature (about 0.01 °C/min lower). This led to a correspondingly lower mean thermal sensation vote for females than males under cooling temperature transients (about 1 vote lower). Sex differences in thermal perception under step-change transient conditions were already observed in Refs. [23,35,36] but here we confirm these findings for rates of change of the air temperatures that are less extreme and could be typically found during DR events.

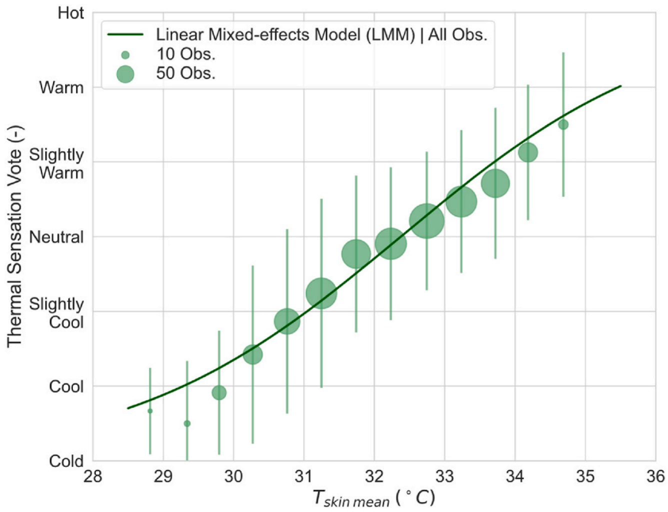

Fig. 15. Mean thermal sensation vote as a hyperbolic tangent function of the mean skin temperature. Observations are binned according to the mean skin temperature. Error bars represent one standard deviation.

Table 12
Independent variables in the MLM.

Independent variables	Levels
$T_{skin\ mean}$	Continuous
$\frac{\partial T_{skin\ \ mean}}{\partial t}$	Continuous
DIR	*Cooling/Warming*

From a physiological perspective, there are several morphological and functional sex differences affecting thermoregulation and body temperature distribution. Females have on average a higher surface-to-volume ratio, higher fat mass, less muscle mass, lower body surface area, lower metabolic rate, lower stroke volume, and blood flow rate to the body extremities than males. In particular, the lower metabolic rate of females means they have lower metabolic heat-production capacity during cold exposures and, thus, a poorer ability to thermoregulate compared to males which makes them more vulnerable to cold conditions. Hence, females must be more responsive to cooling transients through vasoconstriction which explains the observed higher cooling rates of the skin temperature. For example, Cankar et al. [62] showed that the decrease in blood flow in the hand during local cooling at 15°C is larger for females than for males. In warm conditions, males have a larger sweating response than females, which explains why females rely upon convective heat loss through cutaneous vasodilation more than evaporative heat loss [63], and why higher temperatures are usually found in females compared to males [23]. However, in our study, the warm conditions did not induce much sweating (sweating was not generally observed). This is probably the reason why we did not observe higher skin temperatures in females during warm conditions.

From these observations, we can conclude that the primary mechanism of thermoregulation for females appeared to be through skin blood flow adjustments [62,64]. This enhanced vascular response and the related greater skin temperature variations induce behavioural temperature regulation responses earlier in females than males which has great relevance for the design and control of temperature fluctuations during DR events.

4.3. Relationship between skin temperature and thermal sensation

Physiological-based thermal perception models predict thermal sensation and comfort based on body temperature conditions and are to be coupled with thermophysiological models that are mathematical descriptions of the *passive* and *active autonomic* systems of the human body and can predict high-resolution skin and core body temperature responses [65]. Thermophysiological models can address physiological differences between individuals by adjusting model inputs, for example by adapting the basal metabolic heat production for body weight and body type, the thermal capacitance and conductance of fat, the blood flow volume for the body type, and the solar absorptivity for skin colour [66]. Hence, the observed sex-related thermal response variance can be controlled by adjusting the inputs in thermophysiological models and, thus, by predicting the correct skin and core body temperature responses. However, we do not know whether the relationship between skin/core body temperature and thermal sensation also differs for different individual characteristics. Thus, it is important to investigate such a relationship to better understand the causes of interindividual variability in thermal comfort and to better account for these differences in physiological-based thermal perception models. In this study, we confirmed that the relationship between the thermal sensation vote and skin temperature is independent of sex under steady-state exposures, as already observed in Refs. [23,34]. We also observed that this is true under dynamic exposures.

However, we found that the BMI and the age of the participants influence the relationship between the rate of change of skin temperature and the thermal sensations so these variables should be accounted for in

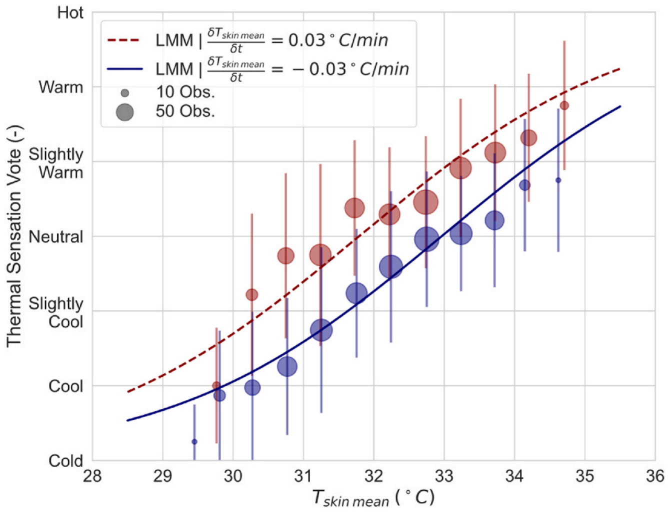

Fig. 16. Mean thermal sensation vote as a hyperbolic tangent function of the mean skin temperature. Observations are binned according to the mean skin temperature for cooling (blue) and warming (red) skin temperature transients. Error bars represent one standard deviation.

Table 13
Normal and standardized regression coefficients for the significant predictors of the thermal sensation vote in the MLM (1278 observations and 71 groups).

	Coef.	Standardized Coef.	Std.Err.	z	P>|z|	[0.025	0.975]
Intercept	−8.43		0.40	−21.05	0.00	−9.22	−7.65
$T_{skin\ mean}$	0.26	0.25	0.01	21.01	0.00	0.24	0.29
$\frac{\partial T_{skin\ \ mean}}{\partial t}$	5.10	0.14	0.23	22.46	0.00	4.65	5.54
Subject Var	0.04	0.03	0.03				

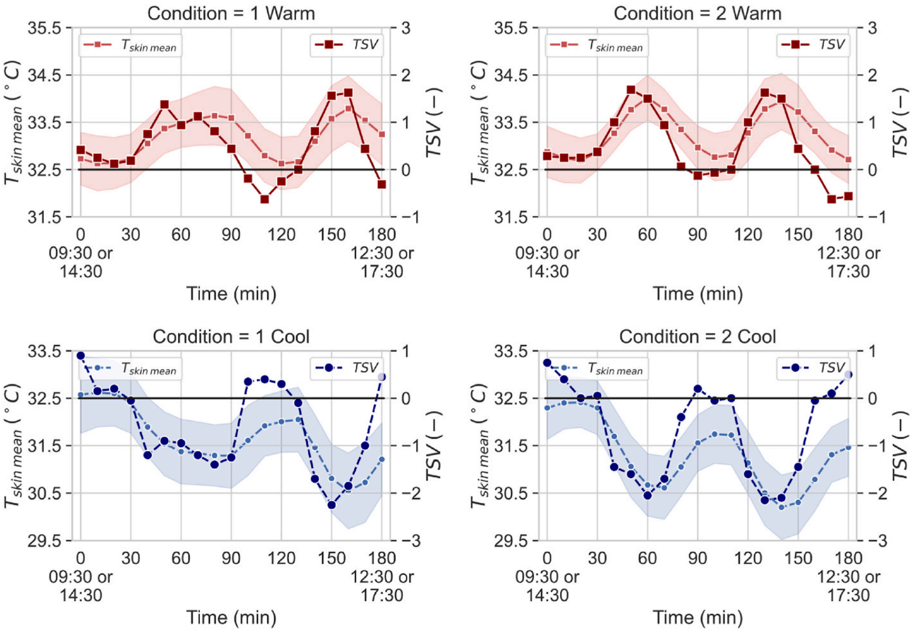

Fig. 17. Mean skin temperature (left y-axis) and thermal sensation vote (right y-axis) over the course of the four experimental conditions. Shaded bands represent one standard deviation.

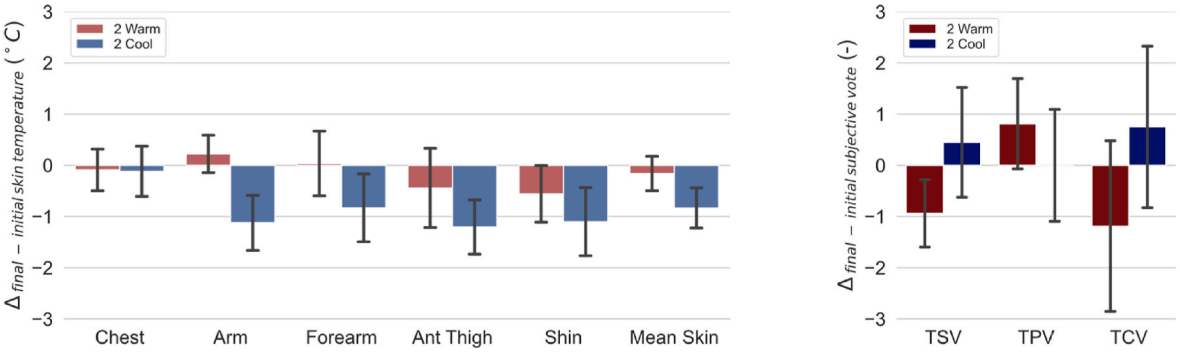

Fig. 18. Mean difference (Δ) between the steady-state final (time = 180 min) and initial (time = 30 min) values of the skin temperatures (left) and thermal perception votes (right) over the course of conditions no. 2. Error bars represent one standard deviation.

Table 14
Independent variables in the MLM.

Independent variables	Levels
$T_{skin\ mean}$	Continuous
$\frac{\partial T_{skin\ \ mean}}{\partial t}$	Continuous
Sex	*Female/Male*
Age	Continuous
BMI	Continuous
Test room	*Maison Eurèka/Façade Test*

physiological-based thermal perception models. In particular, as the BMI increases, the sensory dynamic response to cutaneous thermal transients diminishes. This could be due to a higher thickness of subcutaneous fat associated with a higher BMI. Previous studies on localized thermal sensitivity in the non-noxious range of temperatures have highlighted that thermal sensitivity decreases with an increasing amount of excess fat [67,68] and, in particular, this phenomenon is site-specific with body areas having more excess subcutaneous fat, such as the abdomen, being more impacted by the loss of thermal sensitivity [67]. This phenomenon has been explained by mechanical factors, such as the decreased density of sensory fibres due to skin stretching

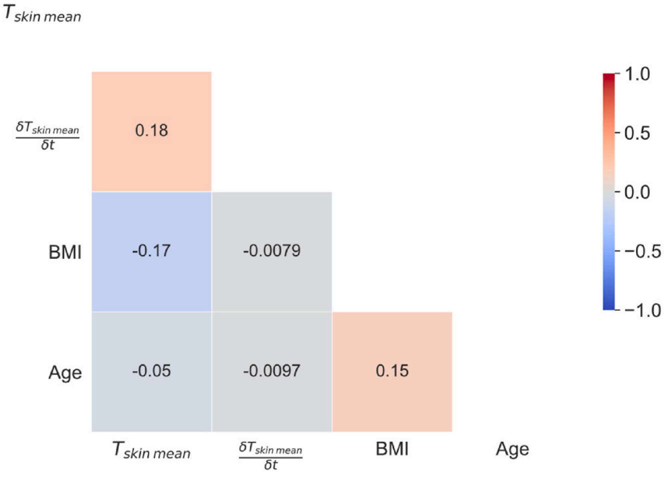

Fig. 19. Correlation matrix for the selected predictors. Each cell shows the Pearson coefficient, colour coded according to the strength of positive (red) and negative (blue) correlation.

Table 15

Normal and standardized regression coefficients for the significant predictors of the thermal sensation vote in the MLM (1278 observations and 71 groups).

	Coef.	Standardized Coef.	Std.Err.	z	P>|z|	[0.025	0.975]
Intercept	−8.80		0.45	−19.61	0.00	−9.68	−7.92
$T_{skin,mean}$	0.26	0.25	0.01	21.46	0.00	0.24	0.29
$\partial T_{skin,mean}/\partial t$	8.89	0.14	1.51	5.88	0.00	5.93	11.85
BMI	0.01	0.03	0.01	1.82	0.07	−0.00	0.02
Age	−0.00	−0.01	0.01	−0.12	0.91	−0.01	0.01
$\partial T_{skin,mean}/\partial t$* *BMI*	−0.26	−0.03	0.05	−5.04	0.00	−0.36	−0.16
$\partial T_{skin,mean}/\partial t$* Age	0.07	0.02	0.02	2.86	0.00	0.02	0.12
Subject Var	0.04	0.02	0.03				

associated with excess fat, but also by chemical factors, such as the higher levels of anti-compared with pro-inflammatory cytokines found in adipose tissue.

Finally, we observed that, with increasing age, the sensory dynamic response to skin temperature transients increases. This contradicts a vast body of literature showing that thermal sensitivity, especially during warm conditions, decreases in the elderly compared to young individuals [69,70]. However, in these studies elderly people are usually older than 65 years, while we only recruited participants between 20 and 60 years old with a mean age of 39 years old and a standard deviation of 9 years. Hence, the majority (about 68%) of our participants are between 30 and 48 years old. So, it could be that thermal sensitivity increases with age up to 50–60 years old and then decreases when people get older. Indeed, a recent field study [71] highlights that women in the perimenopausal age range have an increased perception of warmth due to dysregulation of the thermoregulatory system. Thus, menopausal hormonal changes could be one of the factors contributing to the increased observed thermal sensitivity with age up to 50–60 years old. However, this needs to be confirmed by future dedicated research.

4.4. Drivers of thermal overshoot

The dynamic sensory response has been hitherto related to the magnitude and direction of the rate of change of skin temperature, with cooling predominant over warming in eliciting thermal sensation overshoots [10]. In this study, we tested whether this dynamic response depends on the mean skin temperature and did not find that the mean skin temperature interacts with its rate of change. Thus, the warming and cooling thermal overshoot are equal under cool and warm conditions. Surprisingly, we found that the effect of the rate of change of the skin temperature is comparable under cooling and warming transients. These findings are in contradiction with the current literature where cooling has been shown to elicit stronger responses than warming [10]. This difference could be due to the studied rates of change of the air temperatures that are less extreme than those experienced during step-change conditions. It could be that the differences between cooling and warming transients are evident only at higher rates of change of skin temperature.

4.5. Relevance of thermal habituation

In past thermal comfort studies of step-change dynamic conditions, mean skin temperature was observed to stabilize at a higher-than-neutral value after a warm exposure, and at a lower-than-neutral value after a cool exposure [20,21]. The corresponding thermal sensation has been observed to shift in the opposite direction to the preceding thermal sensation, *i.e.* nudged towards slightly warm when coming from cool conditions, and slightly cool when coming from warm conditions [20,21]. We call this phenomenon thermal habituation to distinguish it from the long-term adaptive processes recognized and characterized thanks to adaptive thermal comfort research [72,73]. In this study, we observe that after the first cycle of warm exposure the skin temperature returns to the initial steady-state value, but when exposed to the cool condition, the skin temperature returns and stabilizes at a lower value than where it started. So, the habituation phenomenon appears to be more relevant after cool thermal exposures. Our tested conditions were always within *"warm"* and *"cool"* thermal sensation votes as in the experiments of Ji et al. [20] and Zhang et al. [21]. When exposed to conditions more displaced from neutrality, *i.e.* in the range of *"cold"* and *"hot"*, the phenomenon of thermal habituation might be even more pronounced but this needs to be confirmed in future experiments.

5. Limitations

As the main limitation of this study, the test rooms used for the warm and cool exposures were different, especially in terms of illuminance and air velocity. While we found that the type of test room did not affect the relationship between skin temperature and thermal sensation, we could not directly test for the effect of the illuminance and air velocity as these variables were correlated with the mean skin temperature given that we conducted the warm experiments in the test rooms characterized by high air velocity and illuminance and the cool experiments in the test rooms characterized by low air velocity and illuminance.

Another limitation of this work is the potential influence of the noise levels caused by decentral thermal systems employed. While we qualitatively check that the systems were not particularly noisy, we did not quantitatively measure noise levels. At the end of the tests, we informally asked the participants if there was something that was annoying them other than the thermal conditions and nobody mentioned the noise as a problem. Indeed, nobody mentioned any non-thermal-related problem.

As a further limitation, we did not check the menopause status of older female participants. Unfortunately, we did not anticipate that this could be a piece of important information as, until very recently, there were little or no thermal comfort studies on the topic.

Finally, we did not conduct any prospective power analysis to determine the required sample size for the desired level of statistical power, so there is a risk of incurring a false negative result. The generalisability of the results is also limited by the sample constitution, which is made of only Western Europeans between 20 and 60 years old exclusively recruited in southwest France.

6. Conclusions

This study aimed to investigate the phenomena of *"thermal overshoot"* and *"thermal habituation"* under whole-body warm and cool cyclical thermal conditions. It also aimed to quantify the impact of interindividual and, in particular, sex differences in the unfolding of these two phenomena. We found that females have greater skin temperature variations during cooling than males and, correspondingly, experience stronger thermal overshoot responses. These differences in perceptual responses could be fully explained in terms of skin temperature differences since the relationship between the thermal sensation vote and the skin temperature was found to be independent of sex. We tested whether other factors influence the interindividual variability of the sensory response and found that the participant's BMI and age affect the thermal sensation overshoot response to cutaneous thermal transients by diminishing it as the BMI increases and the age decreases. We hypothesize that the decrease in thermal sensitivity is due to a higher thickness of subcutaneous fat associated with a higher BMI. The decrease of thermal sensitivity associated with excess subcutaneous fat has been explained by both mechanical and chemical factors, such as the higher levels of anti-compared with pro-inflammatory cytokines found in adipose tissue. The observed increase of thermal sensitivity with age contradicts a vast body of literature showing that thermal sensitivity decreases in the elderly compared to young individuals. However, in these studies, elderly participants are usually older than 65 years, while the majority of our participants are between 30 and 48 years old. Thus, it could be that thermal sensitivity increases with age up to 50–60 years old and then decreases once people get older. Menopausal hormonal changes could be one of the factors contributing to the increased thermal sensitivity with age. These results suggest that we need to account for interindividual differences not only in thermophysiological models but also in physiological-based thermal perception models. Furthermore, these models should also better consider the phenomenon of thermal habituation that was observed to occur after cool exposures, with the skin temperature returning and stabilizing at a lower value than where it started. Given that the studied rates of change of air temperatures are those that can be typically found in buildings during DR events, our results can contribute to the design and control of comfortable temperature fluctuations during these events. In particular, since we now see that females are more sensitive to discomfort arising from cooling transients, the design of DR events should be informed by their dynamic set-point acceptability limits rather than by the *"average"* building occupant. These results also point to the importance of using Personal Comfort Systems (PCS) as a further means of accommodating individuals' thermal needs, in particular females' ones, while at the same time being able to operate on batteries and, therefore, independently of the grid during DR events.

CRediT authorship contribution statement

Marika Vellei: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Richard de Dear:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Jérôme Le Dreau:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Jérôme Nicolle:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Manon Rendu:** Writing – review & editing, Methodology, Data curation. **Marc Abadie:** Writing – review & editing, Methodology, Funding acquisition. **Ghislain Michaux:** Writing – review & editing, Methodology, Data curation. **Maxime Doya:** Writing – review & editing, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

The 3 thermal perception questions translated into French are reported below:

1. Comment vous sentez-vous en ce moment précis?

☐ Très Froid ☐ Froid ☐ Légèrement Froid ☐ Ni Chaud Ni Froid.
☐ Légèrement Chaud ☐ Chaud ☐ Très Chaud.

2. Trouvez-vous cela … ?

☐ Très Confortable ☐ Confortable ☐ Légèrement Confortable.
☐ Légèrement Inconfortable ☐ Inconfortable ☐ Très Inconfortable.

3. En ce moment, préféreriez-vous avoir … ?

☐ Beaucoup Plus Froid ☐ Plus Froid ☐ Un Peu Plus Froid ☐ Sans Changement.
☐ Un Peu Plus Chaud ☐ Plus Chaud ☐ Beaucoup Plus Chaud.

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