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Implications of lower indoor temperatures – Not cool for cold susceptible individuals across both sexes

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ABSTRACT

Wider temperature ranges in buildings can reduce building energy use and prevent shortage of energy availability. However, humans do not perceive temperature equally and a general lowering of indoor temperature may in particular impact susceptible individuals. The discrepancy between individuals has been ascribed to sex differences, but is not well understood and could relate to heterogeneity in endogenous heat production or other personal parameters. We, therefore, evaluated individual thermal responses including physiological measurements of metabolic heat production in both men and women, identified, and via experiments, verified as cold sensitive or cold resilient. On average, the cold sensitive group had an 18 % lower resting metabolic rate compared to the cold resilient group when controlling for clothing and other important parameters for heat exchange. We observed a 0.9 °C difference in neutral temperature between sexes, but no difference in thermal perception or skin temperature. We concluded that cold susceptibility is not simply a matter of perception, but relates to a measurable difference in endogenous heat production. Currently mandated temperature setpoints at workplaces or recommended household temperatures do therefore not seem to discriminate between sexes as a result of sex-related differences in physiology, but they might have negative implications for cold sensitive individuals.

1. Introduction

Lower energy expenditure in residential and commercial buildings is urgently needed, both in the context of climate change and the rapidly emerging energy shortage. In cold dominated climates, an obvious strategy to lower energy use is to lower indoor temperatures in the heating season and in hot climates to raise temperatures in the cooling season. Each degree Celsius change of setpoint temperature has been estimated to save about 10 % of energy in buildings [1]. In dwellings where energy billing is divided among individual households, increasing energy costs may take up significantly larger shares of the available income, which will affect even stronger selected temperature settings. In public and commercial buildings, relaxed temperature setpoints are foreseen and are in some countries, including Denmark, already a fact.

Humans are not alike and perceive temperatures differently due to personal and contextual factors, which are far less understood than the thermal factors related to heat transfer from the body [2–5]. It has been suggested that females typically feel colder than males under identical thermal exposure [5–8], may be more dissatisfied than males when sharing the same space [5,9], and may respond stronger than males to temperatures deviating from the optimal [10]. Some studies have argued that sex differences in thermal perception are largely driven by clothing behaviours [11,12]. Others have reasoned about physiological aspects, for instance, that females are smaller in size, have a larger body surface area-to-mass ratio, and have a lower endogenous heat production than males. These differences may compromise thermal comfort for women as indoor climate standards [13,14] intrinsically misrepresent thermal demands for females [6] (see Appendix A for a review of experimental studies on human metabolic rate [6,15–22]). However, the latter assumption is driven by data from the field or is model-based and therefore lacks solid experimental backup [6]. Thus, are differences in thermal sensitivity a true sex issue?

The psychological pathway has also been suggested to potentially influence thermal perception, but little is known about it [23–28]. One mechanism is thermal disposition[1] that can be

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[1] This psychological factor was originally called “perceived coldnaturedness” by Howell and Kennedy (1979) [23] and Howell and Stramler (1981) [24]. Later, Healey and Webster-Mannison (2012) [25] and Rupp et al. (2020, 2022) [27,28,43] referred to it as “thermal disposition”.

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described as a person's assessment of own thermal sensitivity, i.e. being more sensitive to heat, cold, both or neither, in relation to their perception of the thermal sensitivity of their peers.

To understand better how thermal sensitivity depends on sex and thermal disposition, we recruited participants that were either sensitive to cold or sensitive to heat (hereinafter referred to as resilient to cold) with equal representation of females and males in each group. Under controlled conditions, they were then exposed to low, comfortable and high temperatures, while a range of physiological and subjective parameters were recorded as explanatory factors. We hypothesised that: a) people resilient to cold would express a higher thermal sensation and those sensitive to cold would express a lower thermal sensation than their counterparts under comparable thermal exposure (null hypothesis being that thermal disposition would not affect thermal perception), b) females would express lower thermal sensation than males under comparable thermal exposure (null hypothesis being that sex would not affect thermal perception), c) thermal disposition affects thermal perception, but not sex (null hypothesis being that neither people's thermal disposition or sex affect their thermal perception).

2. Method

In short, we exposed 24 participants to three temperature levels 20 °C (cool condition), 25 °C (neutral condition), and 30 °C (warm condition) in a controlled environmental chamber. Participants were selected based on their self-expressed thermal disposition as being distinctively sensitive or resilient to cold. Data collection included measurements of the environmental conditions and physiological parameters, as well as subjective evaluation of the perceived thermal conditions.

The present study was carried out in two stages. First, effects on thermal perception of thermal disposition and sex were studied and subsequently, the same participants had their metabolic rate measured in a secondary experimental session.

2.1. Infrastructure and materials

The main experimental campaign was conducted in a climate chamber at the International Centre for Indoor Environment and Energy (Technical University of Denmark, DTU) [29]. Six workstations including table, chair and computer were distributed in the space, where during the experiments, the participants' work simulated a typical office situation.

The climate chamber was equipped with laboratory-grade instruments to measure environmental parameters (air temperature, globe temperature, air velocity, relative humidity). Wireless sensors (*iButtons*) were used to measure skin temperature and *fitbit* smartwatches were used to track the participants' heart rates. Body height was measured using a measuring tape, and body weight and fat percentage were measured with a bioelectrical impedance scale (Tanita RD-545, Japan).

For the metabolic rate measurements, we used another climate chamber at the Department of Nutrition, Exercise and Sports at the University of Copenhagen (KU). The metabolic rate was measured through indirect calorimetry following ISO 8996 (2021), Level 4 method [30], obtaining breath-by-breath recordings of VO_2 and VCO_2 (Oxycon CPX, Carefusion, CA, USA). The climate chamber was equipped with the same instruments that were used to measure the thermal environment in the initial experiments (air temperature, globe temperature, air velocity, relative humidity).

2.2. Recruitment and criteria for participation

We aimed to recruit 24 participants (12 females) to participate in the studies based on a *priori* power analysis using data from earlier series of experiments [31].

Participants were recruited through posters, social media and group e-mails of DTU students and student accommodations between September and October 2021.

The criteria for participation took into account the participant's demographics and anthropometrics, health condition, thermal history and thermal disposition. Specifically, the criteria for participation included that participants:

- were between 20 and 35 years old;
- had a body mass index between 18.5 and 24.9 kg/m^2 (i.e. normal range);
- were non-smokers and generally healthy without any thyroid gland problem or personal history of metabolic disorder, nutritional deficiency or other endocrine disorders;
- did not have any electronic medical implant (e.g. heart pacemaker or implantable cardioverter defibrillator) since body composition measurements were performed by bioelectrical impedance analysis;
- must be living in Denmark for the past 12 months or more;
- should not be taking any medication (with the exception of contraceptives for females);
- could be categorised as being sensitive to cold or sensitive to heat (cold resilient);
- only female participants already taking oral contraceptives were selected to reduce the difference in body temperature between phases of the menstrual cycle [32]. Also, female participants could not be pregnant.

As we were interested in investigating only two categories of thermal disposition, we asked potential participants about their thermal disposition during the recruitment (background) survey applied weeks before the start of the experimental campaign. This also had the advantage of avoiding potential risk of recall bias when participants later responded to thermal comfort surveys during the experimental sessions [28]. The thermal disposition question was as follows.

Thermal disposition

Thinking about your daily life and compared to the people around you (for example, your colleagues at the university), **you consider yourself** a person:

() more **sensitive to heat** (for example, I normally complain about feeling warm while others around me are not feeling warm)

() more **sensitive to cold** (for example, I normally complain about feeling cold while others around me are not feeling cold)

() **sensitive to both** cold and heat (for example, I normally complain about feeling warm or cold while others around me are not feeling warm or cold, respectively)

() **not too sensitive to both** cold and heat (for example, I normally do not complain or complain very little about feeling warm or cold while others around me are complaining about feeling warm or cold).

2.3. Research ethics and data protection

The International Centre for Indoor Environment and Energy (ICIEE, DTU) holds a statement from the regional ethics review board confirming that studies of this nature are not encompassed within the Danish law of ethics in science, as the exposure does not cause strain that is worse than in buildings in practice (KA 04741). The Department of Nutrition, Exercise and Sports at KU holds an ethics approval for the metabolic rate measurements, National Committee on Health Research Ethics (protocol number: 55907_v3_02012017).

Participation in the study was entirely voluntary. An information sheet was distributed among all participants and informed written consent was required from each participant before the experiments. Participants were paid to participate in the studies.

As personal information was recorded, special attention was dedicated to GDPR (General Data Protection Regulation) rules. For instance, all personal data was pseudonymised.

2.4. Experimental conditions

For the main experimental campaign at DTU, the thermal conditions inside the climate chamber were controlled to provide either a cool, neutral or warm sensation as predicted by the PMV model [10]. Participants wore clothes with an insulation level of 0.61 clo and they performed office-like tasks (reading/typing) corresponding to 1.1 met. The clothing ensemble consisted of a long-sleeve shirt, trousers, ankle-high socks, shoes and underwear. Air temperatures were controlled at 20 °C, 25 °C and 30 °C. All other environmental parameters were held constant. Relative humidity was kept between 30 and 45 % and the air speed below 0.1 m/s. The ventilation rate of the chamber was kept at 1,100 m^3/h. The illumination at desktop height was 550 lx and the lighting had a correlated colour temperature (CCT) of 3200 K.

During the metabolic rate measurements at KU, participants wore the same ensemble as at DTU (i.e. clothing insulation of 0.61 clo) and indoor air temperatures were controlled at 25 °C (neutral sensation for sedentary activity).

2.5. Experimental protocol

The 24 participants were divided into four groups/blocks according to their personal characteristics, i.e. thermal disposition and sex. Each block consisted of six participants. Each participant was submitted to the three thermal conditions (20 °C, 25 °C and 30 °C) on different days, always at the same time slot (9–11, 12–14 or 15–17). In order to counterbalance the order of exposure to the different temperatures, participants were randomly assigned to the different sequences of temperature exposition within each group/block.

After the end of the three experimental sessions at DTU, participants participated in a separate session at KU to measure their metabolic rate.

The main experimental campaign was completed in three weeks starting in the middle of October, followed by two weeks of metabolic rate measurements, i.e. experiments started on 18 October 2021 and were finished by 19 November 2021.

2.5.1. Instruction to participants before the sessions

On the day preceding an experimental session, participants were asked to have a good nights sleep and to avoid the consumption of alcohol and caffeine from 6 pm.

On the day of the session, participants were instructed to avoid performing strenuous activity or vigorous exercise, and to have a normal meal avoiding eating too much at breakfast or lunch before the session. They were also informed that during the session in the chamber, they would only have access to bottled water, i.e. no food or other beverage would be allowed. During the metabolic rate measurements, participants were not allowed ingestion of food or liquids.

At the time of the experiments, the use of facemasks was no longer mandatory in Denmark and people were expected to have at least two shots of COVID-19 vaccine. Nonetheless, participants were instructed to not show up if not feeling well (for example, with flu/cold symptoms) prior to an experimental session.

2.5.2. Experimental sessions to assess thermal perception

The total duration of each experimental session was 120 min. During the first 30 min participants prepared and acclimatized to the thermal conditions in the chamber. In this period, their metabolism approached the experimental activity level to minimize unwanted effects of residual heat in the body. Also during the first 30 min, participants were instructed on the experiment procedures, had their body height, weight and fat percentage measured, were asked to install skin temperature sensors in seven body parts (upper chest, upper arm, forearm, hand back, 4th finger of the hand, thigh, and calf - all in the left side of the body) and to wear a smartwatch to measure heart rate.

In each of the three sessions, after the preparation and acclimatization, participants remained seated until the end of the session (90 min more) and were asked to answer five rounds of thermal perception questionnaires (Q1 to Q5, Fig. 1) at regular intervals through their computers. Participants had five minutes to answer each round of questionnaires.

Standard scales were used to record participants' perceptions of the thermal exposure [33]. Thermal sensation was assessed with a 7-point thermal sensation scale ranging from −3 "Cold" to +3 "Hot", with a "Neutral" midpoint of 0 (zero). Thermal preference was evaluated on a 3-point scale (−1 "Cooler", 0 "Neither cooler nor warmer" and +1 "Warmer"). For thermal comfort, a 4-point scale was adopted: 0 "Comfortable", +1 "Slightly comfortable", +2 "Slightly uncomfortable" and +3 "Uncomfortable". Participants were not restricted to marking only at integer values, but could mark anywhere on the scale that best represented their perception. For thermal acceptability, a binary scale (0 "Unacceptable", +1 "Acceptable") was used.

When participants completed the online questionnaire, data was saved on a secure server at DTU. During the intervals between experimental sessions, all surfaces were disinfected to minimize the risk of COVID-19 spread.

2.5.3. Experimental session to measure the metabolic rate

The duration of each session to measure metabolic rate was approximately 50 min. Measurements were performed with one participant at a time. Upon arrival, a participant was seated in a chair and asked to wear a rubber facemask that covered his/her nose and mouth. The facemask was connected to an indirect calorimetry system to measure gas exchange by the breath-by-breath method. Then, the participant was asked to remain in a relaxed position for about 30 min, in order to measure both his/her oxygen consumption rate (VO_2, ml/min) and carbon dioxide production rate (VCO_2, ml/min) for later calculation of his/her resting metabolic rate.

2.6. Data analysis

We used R software [34] for data processing and analysis. Survey data was pseudonymised and merged with environmental and personal measurements. Thereafter, descriptive statistics were generated and inferential analyses were made with mixed-effects models with between-group (thermal disposition and sex) and

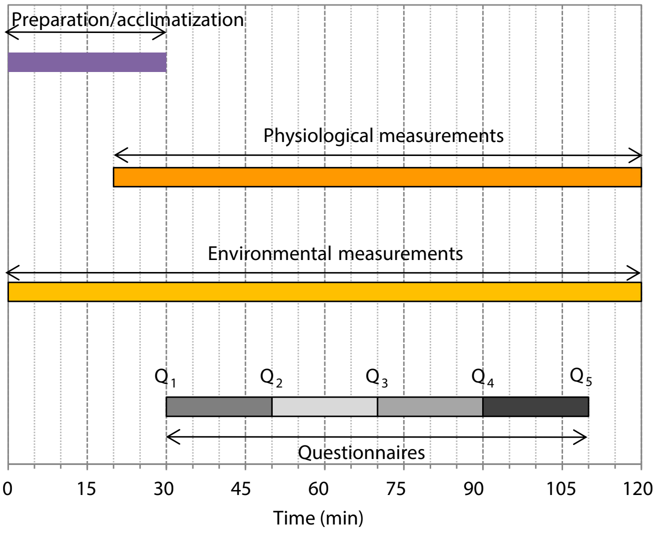

Fig. 1. Timeline of each experimental session showing the different procedures.

within-subjects (i.e. repeated measures) factors (temperature, hereinafter referred to as the thermal condition) as predictors. The models were defined to test the effects of thermal disposition and sex on participants' thermal responses as the outcome. Analyses were controlled for metabolic rate, heart rate, skin temperature, and body composition.

The non-parametric, two-sample Wilcoxon rank-sum test was used to compare physiological outcomes between contrasting groups, such as e.g. heart rate or endogenous heat production between sexes and thermal disposition categories. The same test was used to explore the influence of the normalised endogenous heat production on the participants' neutral temperature.

Mean skin temperature was calculated using Ramanathan's equation [35,36] based on skin temperatures of four body parts (weighting coefficients of 30 % for the upper chest and forearm, and 20 % for the thigh and calf).

The metabolic rate (in W) for each participant was determined based on the measured rates of oxygen consumption and carbon dioxide production, according to equations 1–3 presented in ISO 8996 (2021), subsection "9.1.2 Evaluation of metabolic rate from oxygen consumption rate" [30]. The average of the last 10 min of the 30 min measurements was used to calculate the resting metabolic rate (RMR). Thereafter, we calculated the body surface area based on body weight and height using DuBois' formula (Equation (4)), as shown in ISO 8996 (2004) [37]. Then, we divided the metabolic rate (in W) by the body surface area (m^2) to get the metabolic rate in W/m^2, following the procedures of ISO 8996 (2004) [37]. Finally, we adopted the convention 1 MET = 58.2 W/m^2 (ASHRAE 55 [13]) to convert the metabolic rate in W/m^2 to the metabolic equivalent of task (MET) units.

$$RQ = \frac{V_{CO_2}}{V_{O_2}} \tag{1}$$

$$EE = (0.23 \times RQ + 0.77) \times 5.88 \tag{2}$$

$$M = EE \times V_{O_2} \tag{3}$$

where RQ is the respiratory quotient (adm); V_{O_2} is the oxygen consumption rate ($L.O_2/h$); V_{CO_2} is the carbon dioxide production rate ($L.CO_2/h$); EE is the energetic equivalent ($W.h/L.O_2$); M is the metabolic rate (W).

$$A_{du} = 0.202 \times BW^{0.425} \times BH^{0.725} \tag{4}$$

where A_{du} is the body surface area (m^2); BW is the body weight (kg); BH is the body height (m).

3. Results

In this section we present the main results of our study in two subsections. An overview of the characteristics of the participants, the measured environmental conditions and subjective responses may be found in Supplementary Information, as well as supporting material for the data analysis.

3.1. The effect on thermal perception of sex and thermal disposition

Fig. 2 presents the mean thermal sensation vote (TSV) and the interaction between thermal disposition and experimental condition (Supplementary Table S4.1). As hypothesised, we observed that people resilient to cold felt significantly warmer than those sensitive to cold under all three experimental conditions (hypothesis *a* – rejecting the null hypothesis). The interaction between the thermal disposition and the experimental condition was not significant, meaning that the difference in TSV between participant groups with different thermal disposition was the same regardless of the temperature. The neutral temperature was 24.9 °C for participants sensitive to cold and 23.2 °C for those resilient to cold and it thus differed by 1.7 °C between participants with different thermal dispositions.

Females felt cooler than males under all three experimental conditions, but this finding was not significant (Fig. 3 and Supplementary Table S4.2) (hypothesis *b* – accepting the null hypothesis). The neutral temperature of females was 24.7 °C and of males it was 23.8 °C, a difference of 0.9 °C. Although females voted lower TSV than males, in particular at 20 °C, none of the possible interactions between exposure condition, thermal disposition or sex significantly affected the TSV (Supplementary Section 4 provides details on statistical analysis). Only thermal disposition significantly affected the TSV when analysing thermal disposition and sex in the same model (hypothesis *c* – rejecting the null hypothesis). Table 1 summarizes statistics of the thermal sensation vote for each experimental condition, thermal disposition category and sex.

3.2. Physiological responses

Table 2 presents the mean heart rate and the mean skin temperature of different body parts and overall for the body. Table 2 also shows the difference between the forearm and finger temperatures, which is commonly used to assess vasomotor tone [38–40]. Overall, no significant differences in the mean heart rate or skin temperature were observed between females and males or with different thermal disposition categories, with two exceptions under the cool condition: 1) a slightly higher heart rate was observed for females, 2) the hand skin temperature of participants sensitive to cold was significantly lower than in their counterparts. This may indicate a stronger physiological response for these groups under the cool condition.

A temperature difference between the forearm and finger that is higher than 2 to 4 °C may indicate that the blood vessels are constricted [38–40]. Under the cool experimental condition, participants sensitive to cold had a mean difference of 6.4 °C against 5.3 °C for participants resilient to cold, i.e. a 1.1 °C higher difference for those sensitive to cold, indicating an increased degree of vasoconstriction. Similarly, participants sensitive to cold had approximately 1 °C lower hand and finger skin temperatures. However, the difference between thermal disposition categories was signifi-

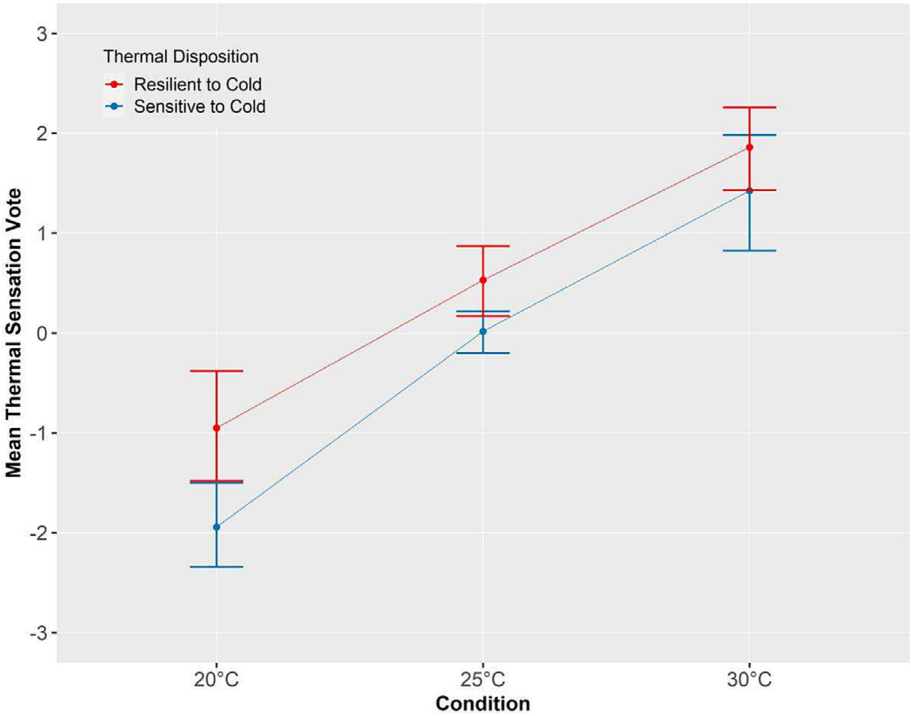

Fig. 2. Mean Thermal Sensation Vote for each experimental condition and thermal disposition category. Error bars indicate the standard error of the mean.

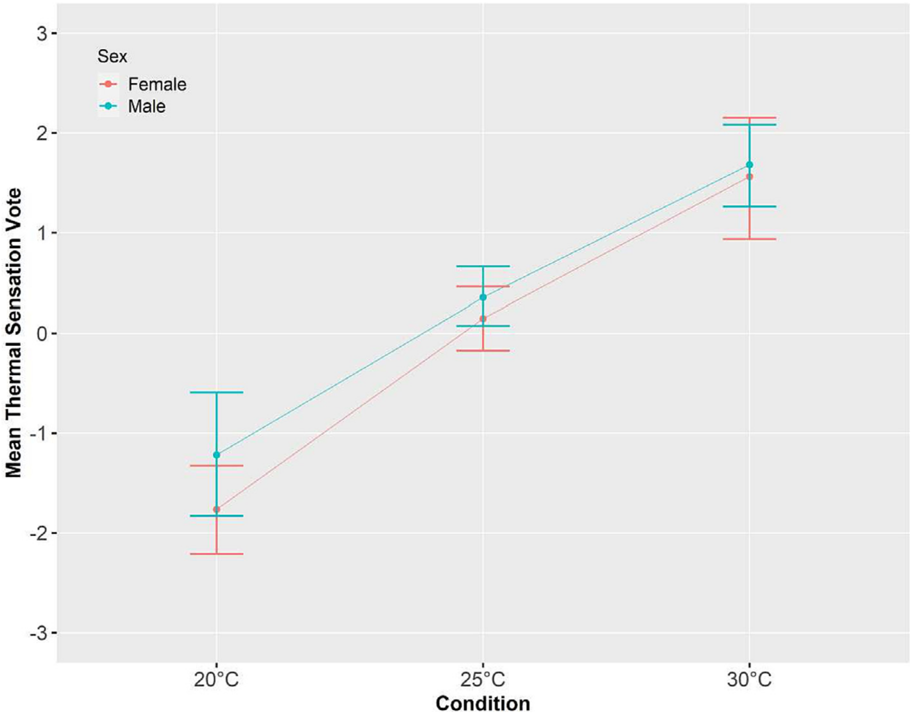

Fig. 3. Mean Thermal Sensation Vote for each experimental condition and sex category. Error bars indicate the standard error of the mean.

cant only for the hand skin temperature. Under the warmer experimental conditions, the forearm-finger temperature difference was considerably smaller.

Table 3 shows the results from the indirect calorimetry measurement at resting activity (seated) for 22 of the participants. Two participants were excluded from this stage of the study due to technical issues with the indirect calorimetry device.

Overall, participants sensitive to cold had lower resting metabolic rates than those resilient to cold (Table 3). Also, females had significantly lower resting metabolic rates (RMR) than males, although it was not sufficient to cause significantly different thermal sensations. The differences in mean RMR for participants sensitive to cold (86.7 W) and those resilient to cold (105.2 W) and for females (83.3 W) and males (106.9 W) were significant (rank-sum

Table 1
Summary statistics of the thermal sensation vote according to the experimental condition, thermal disposition category and sex (♀ and ♂).

Condition	Sex	Thermal Disposition	N	Mean	SD
20 °C	Female ♀	Sensitive to cold	6	−2.18	0.69
		Resilient to cold	5	−1.26	0.86
	Male ♂	Sensitive to cold	6	−1.70	0.93
		Resilient to cold	5	−0.64	1.09
25 °C	Female ♀	Sensitive to cold	6	−0.22	0.34
		Resilient to cold	5	0.58	0.56
	Male ♂	Sensitive to cold	6	0.25	0.35
		Resilient to cold	5	0.48	0.73
30 °C	Female ♀	Sensitive to cold	6	1.18	1.32
		Resilient to cold	5	2.02	0.74
	Male ♂	Sensitive to cold	6	1.67	0.84
		Resilient to cold	5	1.70	0.77

Table 2
Summary of mean skin temperature and heart rates according to sex and thermal disposition category for each experimental condition (5-min average prior to the last subjective vote of the participants under each condition).

Condition	Category	N	Heart Rate (bpm)	Skin temperature (°C)			
				Body overall	Difference forearm-finger	Hand	Finger
20 °C	Sensitive to Cold	12	62	32.0	6.4	27.2[*]	25.3
	Resilient to Cold	10	62	31.6	5.3	28.4[*]	26.1
	Females	11	66[#]	31.6	5.9	27.5	25.5
	Males	11	59[#]	32.0	5.9	27.9	25.8
25 °C	Sensitive to Cold	12	66	33.4	3.2	31.7	30.4
	Resilient to Cold	10	64	33.5	2.4	32.0	31.2
	Females	11	68	33.4	3.1	31.7	30.3
	Males	11	64	33.5	2.6	31.9	31.3
30 °C	Sensitive to Cold	12	72	34.9	0.7	34.7	34.5
	Resilient to Cold	10	70	34.9	0.7	34.7	34.6
	Females	11	72	34.9	0.4	34.9	34.7
	Males	11	70	34.9	1.0	34.5	34.4

[*] Indicates a significant difference between thermal disposition categories (rank-sum test, $p < 0.05$).
[#] indicates a significant difference between sexes (rank-sum test, $p < 0.05$).

Table 3
Anthropometric data and metabolic rate (RMR) from indirect calorimetry measurement at resting (seated) activity.

Sex	Thermal disposition	N	A_{du} (m^2)	Body weight (kg)	A_{du}/Body weight (m^2x10^2/kg)	Fat-free body mass (kg)	RMR (W)	RMR (W/m^2)	RMR (W/kg)
Females	Sensitive to cold	6	1.64 ± 0.12[#]	59.2 ± 6.5	2.78 ± 0.14	41.5 ± 2.5[*,#]	75.9 ± 6.1[*,#]	46.5 ± 5.5	1.83 ± 0.17
	Resilient to cold	5	1.78 ± 0.12[#]	68.9 ± 9.4	2.61 ± 0.19	47.6 ± 2.8[*#]	92.2 ± 6.0[*,#]	51.9 ± 5.4	1.95 ± 0.20
Males	Sensitive to cold	6	1.86 ± 0.15[#]	65.7 ± 8.9[*]	2.85 ± 0.17[*]	56.0 ± 7.2[#]	97.5 ± 14.5[#]	52.8 ± 9.6	1.77 ± 0.39
	Resilient to cold	5	1.98 ± 0.05[#]	77.0 ± 5.1[*]	2.58 ± 0.12[*]	60.6 ± 2.6[#]	118.1 ± 19.9[#]	59.6 ± 9.7	1.95 ± 0.37

[*] Indicates a significant difference (rank-sum test, $p < 0.05$) between thermal disposition categories.
[#] Indicates a significant difference (rank-sum test, $p < 0.05$) between sexes.

test, $p < 0.05$). Sex differences in RMR (W) when analysed by matching thermal disposition were statistically significant. However, females sensitive to cold had a lower RMR than females resilient to cold, but the same difference was not observed between males sensitive to cold and resilient to cold (Table 3).

A similar trend was observed when adjusting the metabolic rate for differences in body surface area and the fat-free body mass calculated by correcting the body weight for the measured percentage of body fat (Table 3). Significantly lower mean RMRs were observed for the cold sensitive participants (49.6 W/m^2) in contrast to those resilient to cold (55.7 W/m^2) (rank-sum test, $p < 0.05$). Likewise, females had a lower RMR (48.9 W/m^2) as compared with males (55.9 W/m^2) (rank-sum test, $p < 0.05$). However, females and males resilient to cold had the same RMR (W/m^2) and likewise for those sensitive to cold (rank-sum test, $p > 0.05$, Table 3). Also, females sensitive to cold had the same RMR (W/m^2) as females resilient to cold and likewise for males. The fat-free body mass, which represents the mass of the heat-producing tissue, differed significantly between sexes (rank-sum test, $p < 0.05$), but the RMR adjusted for fat-free body mass (W/kg) did not. The neutral temperature was not significantly associated with the adjusted RMR (W/kg).

4. Discussion

The present study showed that participants sensitive to cold felt cooler than those resilient to cold with the same thermal exposure. This is in accordance with findings from previous field studies [23–28], with the novelty in the present study that the finding is supported by evaluation of physiological characteristics including the surface-area to body mass and metabolic rate. In contrast to commonly suggested differences in thermal perception caused by sex *per se,* they were not observed in the present study. Facing an imminent energy crisis where both higher and lower indoor temperatures are expected, this result is encouraging, as shared indoor temperatures do not seem to discriminate between sexes as a result of sex-related differences in physiology.

The association between the participants' thermal disposition and their physiological responses may better contribute to explaining inter-individual differences in thermal perception. Cold sensitive participants had an 18 % lower mean resting metabolic rate than those resilient to cold (86.7 W *vs* 105.2 W), corresponding with 11 % lower when considering the values in W/m^2 and 14 % when adjusting the mean resting metabolic for the fat-free body mass. Furthermore, during the cool experimental condition, the hand skin temperature was significantly lower for participants sensitive to cold and the temperature gradient between the forearm and finger was 1.1 °C higher for this group compared to cold resilient participants. This implies that participants sensitive to cold had a stronger physiological response to the cooler environment, including a higher degree of vasoconstriction [38–40]. This was also reflected in their psychological response, where participants sensitive to cold had an, on average, one unit lower response on the applied seven-point thermal sensation scale for the cool condition as compared with their counterparts. The mean TSV differences between thermal disposition categories are substantial for application/engineering purposes, as well as, to a lesser extent, the differences in mean TSV between sexes (Supplementary Table S4.1).

Even though males had significantly higher mean RMR than females it was not reflected in different thermal sensations. Notably, the RMR did not differ between sexes when adjusting for the surface area or the fat-free body mass. Based on predictions made with the PMV model, the difference in RMR corresponded to a 1.3 °C higher neutral temperature for females than males [10]. The observed (experimental) difference in neutral temperature between sexes was only 0.9 °C indicating that the PMV model, despite being sex neutral, overestimated the influence on thermal sensation of the metabolic rate. Both the observed and predicted differences in thermal sensation were considerably larger than the 0.3 °C reported by Fanger [10].

Participants sensitive to cold had a 1.7 °C higher mean neutral temperature than those resilient to cold (24.9 °C *vs* 23.2 °C). Mean neutral temperatures ranged between 22.9 °C for males resilient to cold up to 25.6 °C for females sensitive to cold. In a shared space, such differences in neutral temperature up to 2.7 °C will be highly challenging when aiming to provide comfortable thermal conditions for all. Moreover, neutral temperatures were 23.4 °C for females resilient to cold and 24.4 °C for males sensitive to cold. This shows that when people from these two groups share a space, there will be a 1 °C difference in their neutral temperature, which may cause thermal dissatisfaction adding to the (already considerable) risk of thermostat battles. It is important to highlight that in our experiments we controlled for several confounding factors, including personal and contextual ones such as age, body mass index, health status, thermal history, activity level and clothing insulation. In practice, group differences in neutral temperatures may therefore be even larger than the ones determined under such controlled conditions. For instance, a 3.6 °C higher mean neutral temperature was measured for occupants sensitive to cold in comparison to those resilient to cold in actual office buildings in a subtropical climate [27,28].

The measured metabolic rates were higher than those observed in several previous studies (Table A.1, Appendix A), but lower than specified by international standards [13,37,41]. The mean metabolic rate estimated for females based on the literature review was 45.3 W/m^2 against 55.0 W/m^2 as suggested in ISO standard 8996-2021 [30], differences of −7% and 12 % when compared to the values measured in the present study. For males, the differences were −9% and 7 % when comparing our measured values with those in the literature (mean of 51.2 W/m^2) and ISO standard 8996-2021 (60.0 W/m^2), respectively.

4.1. Perspectives

Although it currently affects mostly Europe, the current energy crisis has caused several countries to mandate lower heating setpoints in public buildings. Obviously, these will affect cold sensitive people the most, i.e. those with inherently low metabolic rates. On the other hand, people resilient to cold will be more affected by climate change projections pointing to a warming world with higher indoor and outdoor temperatures. Practical implications of these findings and solutions to address individual differences in thermal comfort include relaxing strict dress codes at workplaces and making buildings climate change resilient. Preferably, this should be through carbon–neutral solutions, such as improving envelopes and implementing passive cooling strategies (e.g. using the thermal mass of constructions to accumulate heat) [27,28].

Another complementary innovative solution is the adoption of personalised conditioning systems, also known as personal comfort systems or personalised environmental control systems [11,42]. They may improve the local microenvironment surrounding an occupant by providing the person with control over heating, cooling and ventilation, according to the occupant's preferences. Categorising occupants by their thermal disposition, in addition to improving thermal comfort predictions by accounting for thermal disposition, may be a key factor for improving the design of personalised conditioning systems. Such personal systems, when implemented in combination with the overall conditioning system of a space, have the potential to also save energy in buildings.

4.2. Conclusions

We concluded that thermal disposition affects thermal perception, but not sex. People sensitive to cold felt cooler than those resilient to cold when exposed to equivalent thermal conditions. Cold susceptibility is not simply a matter of perception, but relates to a measurable difference in endogenous heat production affecting vulnerable individuals across both sexes.

Data availability

Data will be made available on request.

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.

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Appendix A

Table A.1 presents the findings of a range of experimental studies that used indirect calorimetry to measure human metabolic rate at sedentary activity. Most of the listed studies found lower metabolic rates for females than males, but not all differences were statistically significant, and some studies did not detect any sex difference in the metabolic rate. Usually, differences were expressed in relative terms as the percent difference between the measured metabolic rate for the different sexes and/or compared to standardised values in ISO 7730 (2005) [41], ISO 8996 (2004)[2] [37] and/or ASHRAE 55 (2020) [13]. Also, the metabolic rate was expressed in Watts (W) equivalent to heat production with no physical work. Other studies used Watts per body surface area (W/m^2) or MET (adm), and sometimes other units (e.g. kJ/day). Using available data from the publications presented in Table A.1, we tried to estimate the metabolic rate in W, W/m^2 and MET units and have summarized these in Table A.2. The mean of the sex differences indicated that on average, females had 18% lower metabolic rate (i.e. heat production, W) than males – similar to the 22% lower metabolic rate for females found in our measurements in this study. The differences were considerably smaller when adjusting the metabolic rate for differences in body surface area. When doing so, females on average had a 7% lower metabolic rate than males – in our study the sex difference was 13%.

The reviewed publications shown in Table A.1 presented the mean metabolic rate for sedentary activity in different units (kcal or kJ per day or min, W, W/m^2 or MET), which makes it difficult to compare differences among different studies. We tried to convert the units for W, W/m^2 and MET, where applicable, by performing the following steps (not necessarily in sequence since sometimes we needed to convert back from MET to W/m^2 and W): a) we converted the units in kcal or kJ to W (metabolic rate = heat production), i.e. 1 kcal = 4.184 kJ; 1 W = 1 J/s, b) to get the metabolic rate in W/m^2, we divided the metabolic rate in W by the body surface area (A_{du}), calculated using the DuBois formula, as shown in ISO 8996 (2004) [37], c) we converted the metabolic rate in W/m^2 to MET units adopting the convention 1 MET = 58.2 W/m^2. Results are presented in Table A.2.

Table A.1
Findings from studies measuring metabolic rate by indirect calorimetry at sedentary activity.

Source	Sample	Subjects	Experimental conditions	Findings
Arciero et al. (1993) [15]	194 females; 328 males	Probably American subjects with diverse characteristics (age, height, weight, body composition).	Thermal conditions and clothing were not described.	Females had a lower resting metabolic rate than males, even after controlling for fat-free mass, fat mass and peak $VO_{2.}$
Byrne et al. (2005) [16]	593 females; 78 males	Probably Swiss subjects with diverse characteristics (age, height, weight, body composition).	Thermal conditions and clothing were not described.	Females had a lower resting metabolic rate than males.
Kingma & van Marken Lichtenbelt (2015) [6]	16 females	Young adult females. Probably Dutch.	Indoor temperatures around 24-26 °C (near-neutral conditions). Clothing insulation: 0.68 clo.	Females had a 20% or 32% lower metabolic rate than ASHRAE standard values (based on an adult male) for resting seated ($60W/m^2$) and seated filling ($70W/m^2$), respectively.
Luo et al. (2016) [17]	30 males	Young adult Chinese males with similar BMI.	Indoor temperatures ranged between 16 and 31 °C. RH: 50%. V_a: 0.1 m/s. Two clothing insulation levels: 0.42 and 0.91 clo.	Metabolic rate (MET) was similar to ASHRAE standard value (based on an adult male) for seated, quiet. Metabolic rate was similar in temperatures from 24 to 31°C and increased with lower temperatures. Also, it was observed significant differences in metabolic rates due to clothing levels in temperatures $\leq$ 21°C.
Zhai et al. (2018) [18]	30 females; 30 males	Young adult Chinese subjects with similar BMI.	Indoor temperature: 26 °C, RH: 50%, V_a: < 0.1 m/s (neutral condition). Clothing insulation: 0.6 clo.	No significant sex difference in the metabolic rate. Measured metabolic rates (W/m^2 or MET) were $\approx$10% lower than ISO and ASHRAE standard values.
Yang et al. (2021) [19]	20 females; 20 males	Young adult Chinese subjects with similar BMI.	Indoor temperatures ranged between 14 and 34 °C. RH $\approx$ 50%. V_a < 0.1 m/s Clothing insulation: 0.6 clo.	Overall, the metabolic rate was lower for females than for males, but differences were only significant for temperatures $\leq$ 18 °C.
Nomoto et al. (2021) [20]	22 females; 23 males	Young adult Japanese subjects with similar BMI.	Indoor temperature: 26 °C, RH: 50%, V_a: 0.1 m/s (neutral condition). Clothing insulation: 0.6 clo.	Females had significantly lower metabolic rates than males. Compared with ISO and ASHRAE standards, measured metabolic rates (MET) for females and males were respectively 15 and 22% lower for seated quiet, and 26 and 32% lower for sitting and typing.
Anand et al. (2022) [21]	24 females; 24 males	Indian subjects with diverse characteristics (age, ethnicity, BMI).	Indoor temperatures: 16, 26 (neutral condition) and 36 °C, RH: 40 and 60%. V_a: 0.5 and 2 m/s. Clothing not described.	Females had a significantly lower metabolic rate than males.
Khovalyg & Ravussin (2022) [22]	3 females; 3 males	Probably Swiss subjects with diverse characteristics (age, BMI).	Indoor temperature: 24 °C (neutral condition). Clothing insulation: 0.8 clo.	Females had a lower resting metabolic rate than males.

Note: RH: relative humidity; V_a: air velocity; BMI: body mass index.

Table A.2
Sex differences in mean metabolic rate for sedentary activities measured by indirect calorimetry. Positive differences indicate that males have a higher metabolic rate than females.

Source	Sex (activity)	N	Metabolic rate (W)	Sex differences (W)	A_{du} (m^2)	Metabolic rate (W/m^2)	Metabolic rate (MET)	Sex differences (W/m^2 or MET)
Arciero et al. (1993) [15]	Female (resting)	194	65.3	23%	1.67	39.1	0.67	10%
	Male (resting)	328	84.3		1.94	43.4	0.75	
	Female adjusted* (resting)	194	75.7	3%	-	-	-	-
	Male adjusted* (resting)	328	78.1		-	-	-	
Byrne et al. (2005) [16]	Female (resting)	593	74.9	21%	1.86	40.3	0.69	9%
	Male (resting)	78	94.8		2.15	44.1	0.76	
Kingma et al. (2015) [6]	Female (light office work)	16	90.2	-	1.88	48.0	0.82	-
Luo et al. (2016) [17]	Male (seated)	30	109.8	-	1.80	61.0	1.05	-
Zhai et al. (2018) [18]	Female (seated)	30	83.5	16%	1.60	52.2	0.90	6%
	Male (seated)	30	99.5		1.80	55.3	0.95	
	Female (seated typing)	30	96.5	10%	1.60	60.3	1.04	-1%
	Male (seated typing)	30	107.1		1.80	59.5	1.02	
	Female (seated filing)	30	110.9	11%	1.60	69.3	1.19	0%
	Male (seated filing)	30	124.9		1.80	69.4	1.19	
Yang et al. (2021) [19]	Female (seated)	20	87.4	13%	1.58	55.3	0.95	6%
	Male (seated)	20	100.5		1.71	58.8	1.01	
Nomoto et al. (2021) [20]	Female (seated)	22	67.8	23%	1.50	45.2	0.78	9%
	Male (seated)	23	88.0		1.77	49.7	0.85	
	Female (seated typing)	22	71.4	22%	1.50	47.6	0.82	8%
	Male (seated typing)	23	91.3		1.77	51.6	0.89	
Anand et al. (2022) [21]	Female (seated)	24	76.2	21%	1.69	45.1	0.77	16%
	Male (seated)	24	96.9		1.81	53.6	0.92	
Khovalyg et al. (2022) [22]	Female (seated)	3	62.4	24%	1.56	40.0	0.69	9%
	Male (seated)	3	82.1		1.87	43.9	0.75	

Note: * adjusted for fat-free mass, fat mass and peak VO_2.

Overall for sedentary activities, the metabolic rate in W ranged between 62.4 and 110.9 W for females (mean 80.6 W) and between 82.1 and 124.9 W for males (mean 98.1 W). The metabolic rate in W/m^2 ranged between 39.1 and 69.3 W/m^2 for females (mean 49.3 W/m^2) and between 43.4 and 69.4 W/m^2 for males (mean 53.7 W/m^2). The metabolic rate in MET ranged between 0.67 and 1.19 MET for females (mean 0.85) and between 0.75 and 1.19 MET for males (mean 0.92).

For seated activity, the metabolic rate in W ranged between 62.4 and 87.4 W for females (mean 73.9 W) and between 82.1 and 109.8 W for males (mean 94.5 W). The metabolic rate in W/m^2 ranged between 39.1 and 55.3 W/m^2 for females (mean 45.3 W/m^2) and between 43.4 and 61.0 W/m^2 for males (mean 51.2 W/m^2). The metabolic rate in MET ranged between 0.67 and 0.95 MET for females (mean 0.78 MET) and between 0.75 and 1.05 MET for males (mean 0.88 MET).

For seated typing activity, the metabolic rate in W ranged between 71.4 and 96.5 W for females (mean 86.0 W) and between 91.3 and 107.1 W for males (mean 99.2 W). The metabolic rate in W/m^2 ranged between 47.6 and 60.3 W/m^2 for females (mean 52.0 W/m^2) and between 51.6 and 59.5 W/m^2 for males (mean 55.6 W/m^2). The metabolic rate in MET ranged between 0.82 and 1.03 MET for females (mean 0.89 MET) and between 0.89 and 1.02 MET for males (mean 0.95 MET).

Only one study reported the metabolic rate for seated filing activity, which showed similar results between sexes, i.e. 110.9 W or 69.3 W/m^2 or 1.19 MET for females and 124.9 W or 69.4 W/m^2 or 1.19 MET for males.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2023.112829.

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