Energy & Buildings 220 (2020) 110085

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

Predicted percentage dissatisfied with vertical temperature gradient

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ARTICLE INFO

Article history:
Received 19 October 2019
Revised 14 April 2020
Accepted 22 April 2020
Available online 29 April 2020

Keywords:
Vertical temperature gradient
Local thermal discomfort
Thermal comfort
Displacement ventilation
Whole body thermal sensation

ABSTRACT

A vertical thermally stratified environment provides opportunities for improved ventilation effectiveness and energy efficiency, but vertical temperature gradient can also cause local thermal discomfort. ASHRAE 55 and ISO 7730 prescribe a 3 °C/m limit between head and feet for seated persons. However, an increasing amount of evidence suggests that this limit is too restrictive. To revisit how vertical temperature gradient affects local thermal comfort, we conducted laboratory tests with four nominal vertical temperature gradients (0.4, 2.9, 5.9, and 8.4 °C/m). Ninety-eight seated college-age students participated in a blind within-subject experiment. Cold-feet discomfort is more frequently rated than warm-head discomfort with increasing temperature gradients. By using logistic regression modeling, we show that the whole-body dissatisfaction increases only slightly (<10%) with vertical temperature gradient, even up to 8.4 °C/m. Sex does not significantly affect the results except at 8.4 °C/m. Acceptable vertical temperature gradient changes with thermal sensation votes. The results suggest that the vertical temperature gradient could be increased to 5 °C/m between head and feet when the subject is thermally neutral.

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1. Introduction

Displacement ventilation (DV) and underfloor air distribution systems (UFAD) are based on vertical temperature gradient to provide comfort in the occupied zone, therefore, they have the potential to be energy-efficient compared to mixing air distribution strategies. Energy-saving can be achieved by providing less airflow rate, resulting in a higher vertical temperature difference in a space and between feet and head levels. An excessive vertical temperature gradient may cause local thermal discomfort as specified by ASHRAE Standard 55 [1] and ISO 7730 [2]. The limit of 3 °C/m between head and feet is stipulated in ASHRAE 55 and ISO 7730 (Category C buildings), based on the work of Olesen et al. [3]. However, numerous laboratory and building field studies have reported that the limit could be higher without causing significant occupant discomfort: 4 °C/m by Wyon and Sandberg [4], 5 °C/m by Tanaka et al. [5] and Yu et al. [6]., and 8 °C/m by Liu et al. [7] and Möhlenkamp et al. [8]. The considerable inconsistency indicates that there might be other influencing variables, beyond differences in experiment size and setup, that have not been considered in previous studies. Thus, we first summarize prior key studies on this topic and attempt to identify possible reasons for the diverse vertical temperature gradient limits that are reported in the literature. Note that in this study we refer to temperature differences between head and feet as vertical air temperature gradients in which the temperature at the head is higher than that at the feet.

1.1. Literature review

In the study upon which ASHRAE 55 and ISO 7730 specifications are based, Olesen et al. [3] exposed 16 seated subjects (8 males, 8 females) with light clothing (0.6 clo) in a tiny chamber (length: 2.0 m; width: 1.4 m; height: 2.0 m) at four vertical temperature gradients (0.4, 2.5, 5.0, and 7.5 °C/m) for 3 h. Cooling panels in lower walls/floors and heating panels in upper walls/ceilings created the vertical temperature gradient, while the influence of radiant asymmetry was not controlled or investigated [8,9]. The mean indoor temperature was adjusted according to the subjects' preference in an initial test without a vertical temperature gradient. In the experiment, only one of the sixteen participants (6.3%) reported discomfort at 2.5 °C/m and two (12.5%) reported discomfort at 5 °C/m; these votes underlie the 3 °C/m air temperature limit specified in the standards (aiming at 5% or less of the population dissatisfied). Regardless of the design of questionnaires, such

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[1] The first two authors made the same contribution to this paper.

https://doi.org/10.1016/j.enbuild.2020.110085
0378-7788/Published by Elsevier B.V.

a small number of sample size is not acceptable from a statistical power perspective. Additionally, the effect of radiation on thermal discomfort was not excluded or isolated.

In the experiment conducted by Wyon and Sandberg [4], 100 male and 107 female subjects aged from 18 to 65 were kept seated for 1 h in a chamber (length: 4.2 m; width: 3.6 m; height: 2.5 m) with an office layout. Subjects were allowed to adjust clothing according to their preferences. The vertical temperature gradient was produced by adjusting the supply air temperature of a displacement ventilation system, the heating capacity of a convective heater (up to 900 W) and the surface temperature of a cooling panel (3.0 by 4.0 m) attached to the ceiling. Nine conditions were tested with a full factorial matrix consisting of three vertical temperature gradients (nominally, 0, 2, and 4 °C/m) and three equivalent homogeneous temperatures (22.6, 24.0, 25.4 °C). The authors did not test conditions above 4 °C/m. They found that vertical temperature gradient up to at least 4 °C/m is likely to be acceptable if the air quality is satisfactory and the operative temperature is controlled to be comfortable. Nevertheless, the increase of vertical temperature gradient might be a problem when the occupants are sensitive to indoor air quality, such as dryness - subjects reported their eyes to be significantly drier at 4 °C/m than 2 °C/m. This latter result is unique in the literature so far. Yu et al. [10]. did not find any significant impact on perceived air quality or Sick Building Syndrome with vertical temperature gradient up to 5 °C/m.

Experiments conducted by Yu et al. [10] and Cheong et al. [11] had 60 college-aged subjects (30 males and 30 females) seated in an environmental chamber (length: 11.1 m; width: 7.5 m; height: 2.6 m). The chamber was served by displacement ventilation with air velocity kept below 0.2 m/s. Subjects were exposed to nine experiment conditions, three vertical temperature gradients (nominally 1, 3, and 5 °C/m between 0.1 and 1.1 m heights) times three air temperatures at 0.6 m height (nominally 20, 23 and 26 °C). The experimental conditions were controlled by adjusting the supply airflow rate and temperature. Half the subjects were free to adjust their clothing and stayed in the chamber for 2 h, while the other half were not allowed adjustment but stayed for only 1 h They found that when the whole-body thermal neutrality was maintained between −0.60 and 0.13 on a scale ranging from −3 (much too cold) to 3 (much too hot), a vertical temperature gradient up to 5 °C/m was acceptable. They found also that the percentage dissatisfied with the overall body thermal state was not significantly affected by vertical temperature gradient even when whole-body thermal neutrality was not maintained.

Kawahara et al. [12] exposed 16 seated subjects in a climatic chamber to different equivalent temperatures at 1.1 m and 0.2 m from the floor. They used equivalent temperature as $0.55T_a + 0.45T_r (0.2–0.75V^{0.5})/(1 + I_{clo})$, where T_a, T_r, V, and I_{clo} are air temperature, mean radiant temperature, air velocity, and clothing insulation, respectively. The results showed that 80% or more of the subjects were overall comfortable with 3 °C or 6 °C difference between the head and feet when the equivalent temperature was 26 °C or 29 °C at 1.1 m, respectively.

A study by Möhlenkamp et al. [8] evaluated the percentage dissatisfied with five vertical temperature gradients (1, 4.5, 6, 8, and 12 °C/m) between head and feet for seated subjects (sample size between 42 and 96 for each condition). The experiments were conducted in the Aachen comfort cube (length: 2 m; width: 2 m; height: 2.5 m) to simulate vehicles or meeting rooms with high thermal loads. Subjects wore preferred clothing with insulation about 0.7 clo on average (0.4–1.6 clo), including the clothing insulation of the chair. The air movement was not measured in their study. The results showed that a vertical temperature gradient up to 8 °C/m was likely to be acceptable. They found that room air temperature was an important factor, and when subjects were permitted to adjust their preferred mean room temperature, a higher vertical temperature gradient was accepted. The importance of room air temperature was also reported by Wyon and Sandberg [4].

The effects of vertical temperature gradients on occupants' comfort have also been studied using thermal comfort modeling. By applying the CBE multi-segmented thermal comfort model [13,14], Zhang et al. [15] found that the acceptable stratification depends on room operative temperature. The closer the average operative temperature is to the center of the comfort zone, the higher the acceptable vertical temperature gradient (up to 7 °C/m in the simulation). No stratification was acceptable at the cool and warm limits of the comfort zone because either the feet or head would become uncomfortable.

1.2. Research gaps

These studies of the effect of vertical temperature gradient on thermal discomfort allow no consistent conclusions for the following possible reasons. Wyon and Sandberg [4], Zhang [15], Yu [10], and Möhlenkamp [8] all observed that the mean room air temperature or operative temperature affects dissatisfaction with vertical temperature gradient. The overall room thermal environment that affects whole-body thermal sensation is a dominant stimulus for overall and local thermal discomfort. When the whole-body thermal sensation is on the cooler side, occupants are more dissatisfied with vertical temperature gradient [15]. By contrast, [6] found that the effect of temperature gradient became insignificant at cold and slightly warm whole-body thermal sensation. Our prior research on ankle draft risk also found that whole-body thermal sensation is an indicating factor for local discomfort [7]. However, in none of the above work is the whole-body thermal sensation included as an input parameter in the prediction models and this could be one of the reasons of the discrepancy. We hypothesize that adding whole-body thermal sensation may generate more consistent results and higher prediction accuracy.

A second possible reason might be the metrics employed to indicate the dissatisfaction with vertical temperature gradient. Previous studies used different thermal indicators (such as comfort, satisfaction, and acceptability) that limited their comparability. For example, Kawahara et al. [12] determined whether a specific degree of vertical temperature gradient was acceptable or not with the criterion of comfort rating being more than 80%. In contrast, Olesen et al. [3] utilized a stricter criterion "the discomfort rating should not exceed 10%" to conclude that the vertical temperature gradient should be less than 3.7 °C/m. The suggested limits in the reviewed studies were based on either whole-body discomfort or local discomfort (e.g., head, feet or any segments), and sometimes not clearly specified. Table 1 summarizes the limits on vertical temperature gradient identified with different criteria. Human subjects in all the studies in Table 1 were at the sitting condition.

1.3. Objectives

The acceptable vertical temperature gradient between head and feet identified in previous research ranges from 3 °C/m [3] to 8 °C/m [15] for seated occupants. Such substantial differences demand further evidence given the importance of vertical temperature gradient in the energy use, indoor air quality, and design and operation of HVAC systems. Strict regulation of vertical temperature gradient impedes the application of thermally stratified systems, such as displacement ventilation and underfloor air distribution systems, which may provide improved air quality, and energy efficiency [19–21]. Therefore, we need a vertical temperature gradient limit as accurate as possible to avoid suboptimal solutions for thermal comfort, indoor air quality, and energy efficiency.

Table 1
Allowed maximum vertical temperature gradient between head and feet in the literature with different setups and metrics based on sitting subjects.

Studies	Sample size	Exposure time	Vertical temperature gradient (°C/m)	Temperature range (°C)	Acceptable range (°C/m†)	Evaluation metrics	Statistical tests
[16]	48	1 h	0.0, 1.3, 2.7, 4.0	–	<4	Overall thermal sensation	–
[17]	15		Up–8	–	−8–6	Overall thermal comfort	–
[3]	16	3 h	~0, 2.5, 5.0, 7.5	–	3–4	5–10% uncomfortable rating for head and feet	–
[5]	6	1.5 h	−10, −5, 0, 5, 10	Head: 15–35; Feet: 25	<5	Average overall thermal discomfort based on the scale:1 = comfort; 2 = slight discomfort; 3 = discomfort	No
[4]	207	1 h	0, 2, 4	Equivalent homogeneous temperature: 22.5, 24, 25.5	<4	7 point scale of average local and whole-body thermal comfort	Yes
[12]	16	1.5 h	−6, −3, 0, 3, 6	Head: 23–26; Feet: 17–26	<6	80% overall thermal comfort rating	Yes
[6]	24	2 h	1, 5	At the height of 0.6 m: 22	<5	Average overall thermal acceptability	Yes
[11]	60	2 h, and 1 h	1, 3, 5	At the height of 0.6 m: 20, 23, 26	<5	Average overall thermal comfort; percentage dissatisfied for the overall body and any body segments	Yes
[18]	40	25 min	1.2–5.8	Overall: 22.6, 23.7	<5.8	Average overall thermal satisfaction based on the Likert scale from 1 = very dissatisfied to 5 = very satisfied.	Yes
[7]	110	20 min	Up to 8	Head: 25–26; Feet: 17–22	<=8	Average whole-body thermal acceptability	Yes
[8]	42 –96	>20 min	1, 4.5, 6, 8, 12	At the height of 0.6 m: 23	<=8	7% dissatisfied for overall thermal comfort	Yes

† The metric of temperature difference (°C) used in some studies was converted to vertical temperature gradient (°C/m).

Other objectives are 1) to develop a statistical model for the estimation of the predicted percentage dissatisfied with vertical temperature gradient ($PPD_{\nabla T}$) between the head (1.1 m) and feet (0.1 m) level above the floor, this model may use as input the whole-body thermal sensation and vertical temperature gradient; 2) to develop new stratification recommendations.

2. Methodology

We performed human subject tests in a laboratory room and collected data on environmental conditions and self-reported thermal comfort. All the obtained data are publicly available at https://doi.org/10.15146/tavf-rm36.

2.1. Chamber and protocol

The experiment was conducted in a climate-controlled room at the University of California, Berkeley in the winter. The chamber settings resembled a real working environment as much as possible with windows in two sides, as shown in Fig. 1. Details of the chamber can be found in [22]. Participants would feel less spatially confined than in a tiny cube that might trigger psychological dissatisfaction with the environment [23,24]. Three temperature sensor trees were placed in three locations, measuring the air temperature at 0.1 (feet), 0.6, 1.1 (head), and 1.7 m above the floor. The measuring heights followed the specification of ASHRAE 55 [1] and ISO 7726 [25]. The test room has six workstations (~0.7 m high) located in the center capable of hosting six seated subjects per test session.

An underfloor air distribution (UFAD) system was used to condition the chamber and to create vertical temperature gradients. We monitored indoor CO_2 concentration (HOBO MX 1102, Onset Computer Corporation, USA) with an accuracy of 50 ppm and dry-bulb temperature (TJHY HQZY-1,Tianjinhuayi,Ltd., China) with an accuracy of 0.3 °C. The provided airflow to the room was fresh outdoor air that maintained indoor CO_2 concentration at 540 ± 66 ppm (mean ± standard deviation). The total supply airflow rate was approximately 900 m^3/h, corresponding to a UFAD-diffuser face air-speed of nearly 0.55 m/s. We created four vertical temperature gradients by deploying portable fan heaters and flat-panel heaters at different heights that varied with experimental conditions, when the UFAD system alone cannot create high temperature gradients. The location and power level of each heater were determined during the system tune-up. Special effort was taken to ensure that participants were not affected by direct airflow from UFAD vents or fan heaters, or possible radiation from panel heaters. For instance, we covered all surfaces of the panel heaters with aluminum foil of <0.05 emissivity. Since the total surface area of these heaters was much smaller than the walls, the view factors between heaters and subjects were minimal. In order to minimize any ankle draft that could have added to temperature gradient discomfort [26–28], work stations were located in the interior of the room while all ventilation outlets and heaters were positioned around the perimeter. The distance between a subject and a fan heater or ventilation outlet was at least 0.8–1 m. To determine any effects of fan heaters on the subjects, we measured the mid-plane air speeds in front of a heater at the maximum fan settings. Fig. A1 in the appendix shows that the warm jet from a heater rises up and has negligible impact on the subjects 0.8–1 m away. The measured air speeds in the figure exceed what subjects experienced in the real experiments since subjects were off centerline where air speed is less, and the fan settings in the experiment were mostly lower than the maximum. Therefore, the environmental air speed in the vicinity of subjects is estimated to have been lower than 0.2 m/s.

We considered four vertical temperature gradients that had vertical temperature gradients, 0.4 ± 0.3, 2.9 ± 0.5, 5.9 ± 0.5 and 8.4 ± 0.5 °C/m (mean ± standard deviation), respectively. Fig. 2a shows the temperature distribution at the four heights measured at three locations as illustrated in Fig. 1. The average temperature

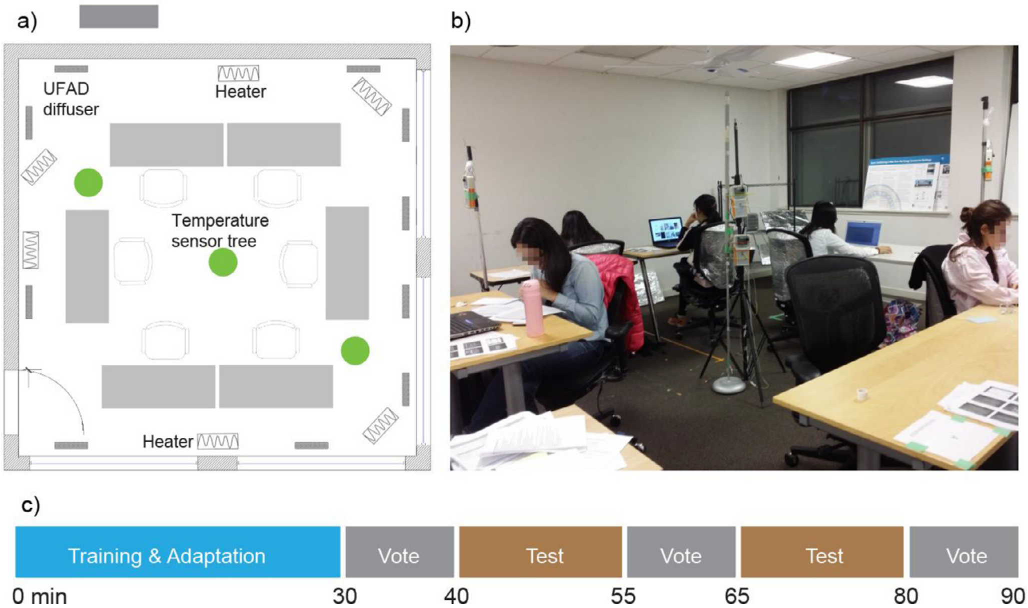

Fig. 1. Experimental setup for human subject tests in a controlled climate room; (a) floor plan; (b) subjects in a test session (photo taken in the late afternoon); (c) experimental protocol.

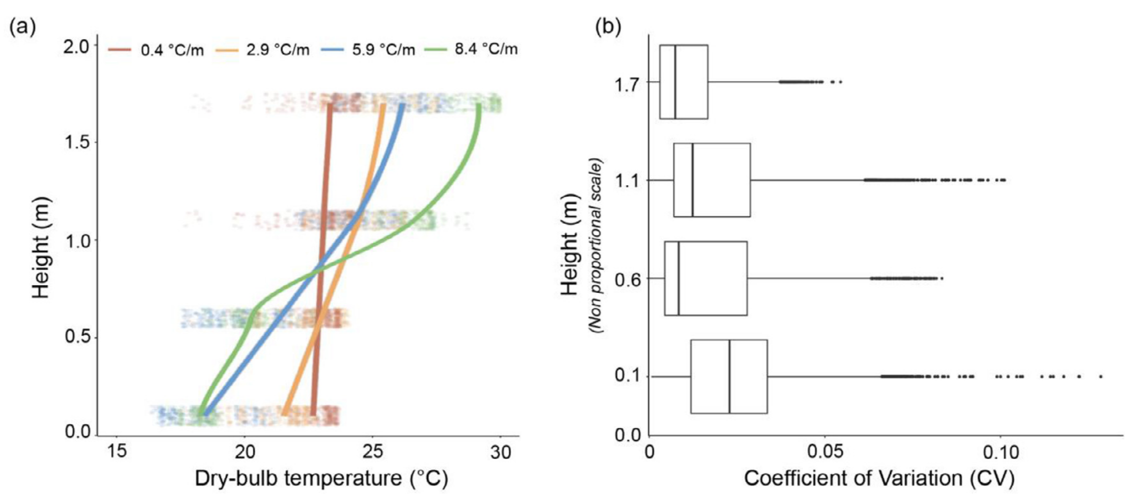

Fig. 2. Air temperatures and measurement variations at 0.1, 0.6, 1.1, and 1.7 m; (a) dry-bulb temperature. A curve is the local polynomial regression (LOESS) fit of the raw data points (scattered in the plot) at each corresponding vertical temperature gradient; (b) coefficient of variation (standard deviation divided by mean) of temperatures measured at three locations in Fig. 1.

over three heights (0.1, 0.6, and 1.1 m) was 22.4 ± 1.2 °C. Since no radiant HVAC systems were used and the chamber is well insulated, we can assume that the air temperature was approximately equal to the radiant temperature and operative temperature. Besides, the inner glass panel of the double-glazed windows, and all exterior walls, had their temperature controlled by a separate HVAC loop, eliminating potential effects of radiant asymmetry. The abrupt increase of air temperature at 0.6 m for the condition of 8.4 °C/m was possibly caused by the extra perimeter heaters added at the height to create the strongest gradient. The measurement variation over the three locations was determined by the coefficient of variation (standard deviation divided by mean). Fig. 2b shows that the median coefficient of variations is smaller than 0.03 (3%) for all the four heights, which indicated that vertical temperature gradient was well created near the subjects.

Fig. 1c illustrates the experimental protocol of the study. Each test session lasted for 1.5 h consisting of two phases, Training & Adaptation (0.5 h), and Test & Vote (1 h). During the Training & Adaption, one of the authors who stayed in the room during the whole session briefly introduced the test procedure and showed the survey platform to the participants. The process was also used to acclimate participants to the controlled environment before the formal test. We asked participants to take the survey three times with an interval of 20 min. While not taking surveys, they had the freedom to read, type, or browse the internet to simulate school or office work at the desk.

2.2. Subjects and survey

We recruited 98 college-age subjects (66 females and 32 males) in this test. Most participants were students on campus. The UC Berkeley Committee for Protection of Human Subjects approved the research protocol, CPHS #2010-04-1312. After signing an informed consent form, each subject participated in four test sessions, one for each vertical temperature gradient. Table 2 describes the anthropometric data of the subjects. The clothing insulation

Table 2
Anthropometric data (average ± standard deviation) of the participants.

	Age (years)	Heights (m)	Weight (Kg)	BMI (kg/m^2)	Number of subjects
Female	23.4 ± 6.2	1.63 ± 0.06	55.9 ± 8.8	20.9 ± 2.9	66
Male	25.7 ± 8.0	1.75 ± 0.06	71.6 ± 9.7	23.4 ± 3.4	32
Total	24.1 ± 6.9	1.67 ± 0.08	61.1 ± 11.7	21.7 ± 3.3	98

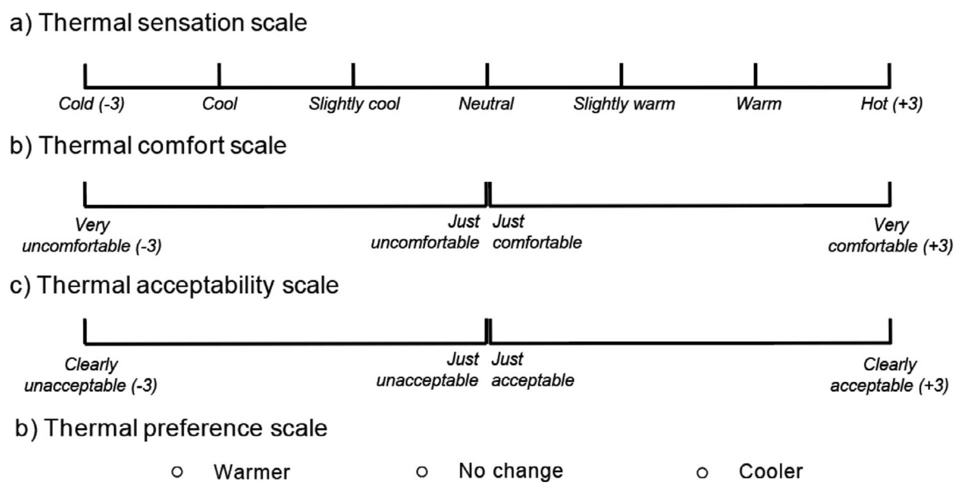

Fig. 3. Questionnaires in the study; (a) thermal sensation surveyed for the whole body, head, and feet; (b) thermal comfort surveyed for the whole body, head, and feet; (c) thermal acceptability surveyed for the whole body; (d) thermal preference surveyed for the whole body.

was not controlled but observed in the range of 0.5–0.7 clo including the insulation effect a mesh office chair. The experiment was completed in November 2017 with the average daily outdoor air temperature 13.2 °C (average high 16.5 °C, average low 10.7 °C).

The survey, developed in Qualtrics (Qualtrics International Inc.), displayed questions regarding the thermal comfort of the whole body and body segments (head, hands, and feet). A participant can indicate their thermal condition by answering the questions of thermal sensation (slider scale from −3 to 3), thermal comfort (−3 to 3, truncated at 0), thermal acceptability (−3 to 3, truncated at 0), and thermal preference (3 points, discrete). Fig. 3 shows the scale of each question type based on ASHRAE 55[1]. The questions are resolved to one decimal precision.

2.3. Statistical analysis

The statistical analysis together with plotting were conducted with R version (3.4.3) using Rstudio (RStudio, Inc. Version 1.2.1335). The procedure was similar to our previous study [7]. Our initial data analysis using the Shapiro–Wilk normality test found that the dataset and subsets of it were non-normally distributed [29]. We therefore assessed the difference of the median with the paired Wilcoxon signed-rank test [30]. Also, the effect size of the difference was calculated in terms of Cohen's d [31]. The thresholds of the Cohen's d were $|d| < 0.147$ *"negligible"*, $|d| < 0.33$ *"small"*, $|d| < 0.474$ *"medium"*, otherwise *"large"* [32]. The statistical significance was based on $p < 0.05$ (*), $p < 0.01$(**), and $p < 0.001$ (***).

2.4. Linear and logistic regression

We employed logistic regression with the format described in Eq. (1) to develop the percentage dissatisfied.

$$\ln\left(\frac{P}{1-P}\right) = \alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n \quad (1)$$

where α, β_i $(i = 1,n)$ are coefficients, and X_i $(i = 1,n)$ are the independent variables of P that could be the percentage dissatisfied with the overall thermal environment or local discomfort.

Selection of input variables and dependent parameters

We applied 10-fold cross-validation to ensure that the variable selection was adequate for a logistic regression model by comparing the mean square error, since R^2 cannot be directly calculated. Though some researchers have used pseudo-R^2 indices [33,34], we did not consider them in this present analysis.

Local head (or feet) comfort was determined using subjects' local thermal comfort vote. Dissatisfaction with the entire thermal environment was assessed using the negative votes on the scale for whole-body thermal acceptability with the environment ($TA_{wholebody} < 0$). Instead, dissatisfaction caused by local discomfort coming from the vertical temperature gradient was determined by negative thermal comfort at head or feet ($TC_{head} < 0$ or $TC_{feet} < 0$), under the condition that the head was warmer than feet ($TS_{head} > TS_{feet}$). In other words, the conditional logic for the dissatisfied with vertical temperature gradient was "($TC_{head} < 0$ **OR** $TC_{feet} < 0$) **AND** $TS_{head} > TS_{feet}$ ".

3. Results and discussion

3.1. Statistics of thermal sensation and comfort

Since whole-body sensation contributes to local discomfort, we controlled it to be at the same level for all four temperature gradients. The experiment in this study was designed to maintain a thermally neutral environment for the majority of subjects during testing, with temperature gradients being the only variable. The median (Q1, Q3) whole-body thermal sensation obtained for each stratification was at −0.2 (−0.7, 0.4), −0.1 (−0.5, 0.4), −0.5 (−1, 0.2) and 0.2 (−0.6, 0.8) (Fig. 4).

We tested the statistical significance of the differences of thermal sensation and thermal comfort for different vertical temperature gradients. Though the differences between one and another (except TS at 0.4 °C/m and 2.9 °C/m) are statistically significant, the effect size of such difference is small or negligible according to Cohen's d. When considering feet (or head), the medium or higher effect size (*stars in red*) occurs when the vertical temperature

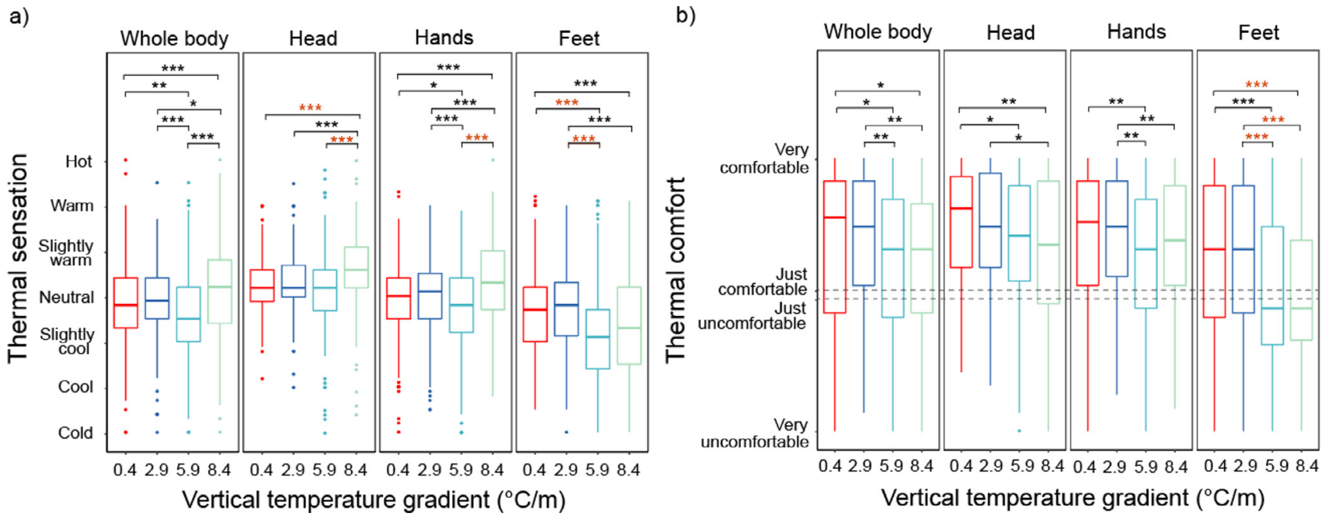

Fig. 4. Thermal sensation and thermal comfort varying with vertical temperature gradient; (a) whole-body and local thermal sensation; (b) whole-body and local thermal comfort. (Statistical significance: * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$; stars in red refer to medium or higher effect sizes based on Cohen's d; |d | < 0.147 "negligible", |d| < 0.33 "small", |d| < 0.474 "medium", otherwise "large"). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

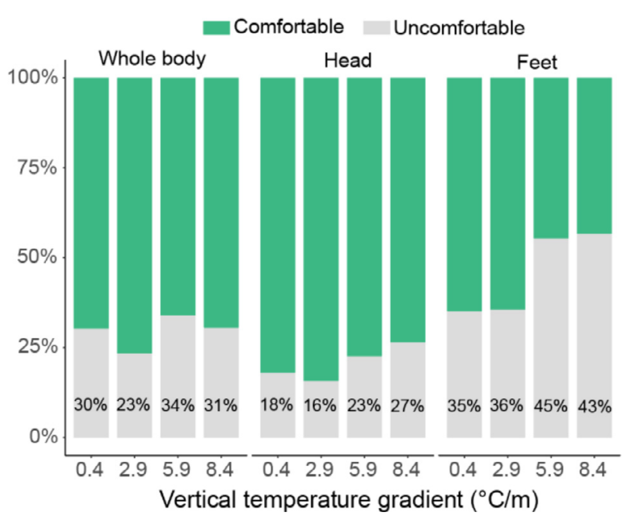

Fig. 5. Binary distribution of thermal comfort votes (n = 1177).

gradient increases to 5.9 °C/m (or 8.4 °C/m). On the other hand, median thermal comfort values for the whole body and local body parts are between 'just comfortable' and 'very comfortable' except for the feet at 5.9 °C/m and 8.4 °C/m. The thermal comfort statistics imply that local thermal comfort at the feet changes more dramatically than that at the head for low (0.4 or 2.9 °C/m) to high gradients (5.9 or 8.4 °C/m), while at whole-body thermal neutrality.

The percentage of votes for discomfort on the whole body, head, and feet in Fig. 5 shows that the discomfort rating for a certain value of vertical temperature gradient is highest at the feet and the lowest at the head. Increasing vertical temperature gradient from 0.4 °C/m to 8.4 °C/m results in small changes in discomfort rating for the whole body and the head but a large difference for the feet. The statistics of thermal sensation and comfort suggests that the whole body and head are less likely influenced by vertical temperature gradient than feet when temperature gradient increased from low levels (0.4 or 2.9 °C/m) to high levels (5.9 or 8.4 °C/m). The dissatisfaction with vertical temperature gradient is more related to feet discomfort. Further confirmation of this can be supported by logistic regression models.

The whole-body discomfort rating is 30%, even for the homogeneous thermal environment (0.4 °C/m) in which some people may feel uncomfortably warm or cold as described in Fig. 4a. As pointed out in other studies [4,8], the high discomfort rating may be caused by subjects' lack of access to room temperature adjustment.

3.2. Whole-body thermal acceptability and dissatisfaction with the thermal environment

Fig. 6a displays the whole-body thermal acceptability varying with vertical temperature gradient. The thermal environments are, for the large part, acceptable, and acceptability tends to decline slightly when vertical temperature gradient rises above 3 °C/m.

The percentage of dissatisfaction with the overall environment changes more rapidly with vertical temperature gradient when the thermal sensation is on the cool side ($TS = -1$) than on the neutral ($TS = 0$) or warm side ($TS = 1$), as shown in Fig. 6b, and the dissatisfaction is higher at a cold sensation. This supports Wyon and Sandberg's conclusion [4] that whole-body discomfort is affected more by operative temperature than by vertical temperature gradient. Similar conclusions had also been reported by [8,10] and [11]. The percentage of dissatisfaction with the thermal environment increases by only roughly 10% even at the cool side ($TS = -1$) when vertical temperature gradient rises from the uniform condition 0.4–8.4 °C/m. In [8] the increase in dissatisfaction was 7% between 0 and 8 °C/m, and in [4] it was 2% between 0 and 4 °C/m. Synthesis of the available evidence supports that vertical temperature gradient contributes little (<10%) to whole-body thermal acceptability.

3.3. Comparison of local discomfort of head and feet

The changes in discomfort rating due to temperature gradient are not equivalent for head and feet. Fig. 7 shows that feet are more sensitive than head to air temperature variations. It is therefore more challenging to achieve thermal comfort in lower body segments than in the upper body [11]. On average, participants felt comfortable at the head for an air temperature from 22 to 28 °C but uncomfortable at the feet when the air temperature near the floor dropped below 18 °C.

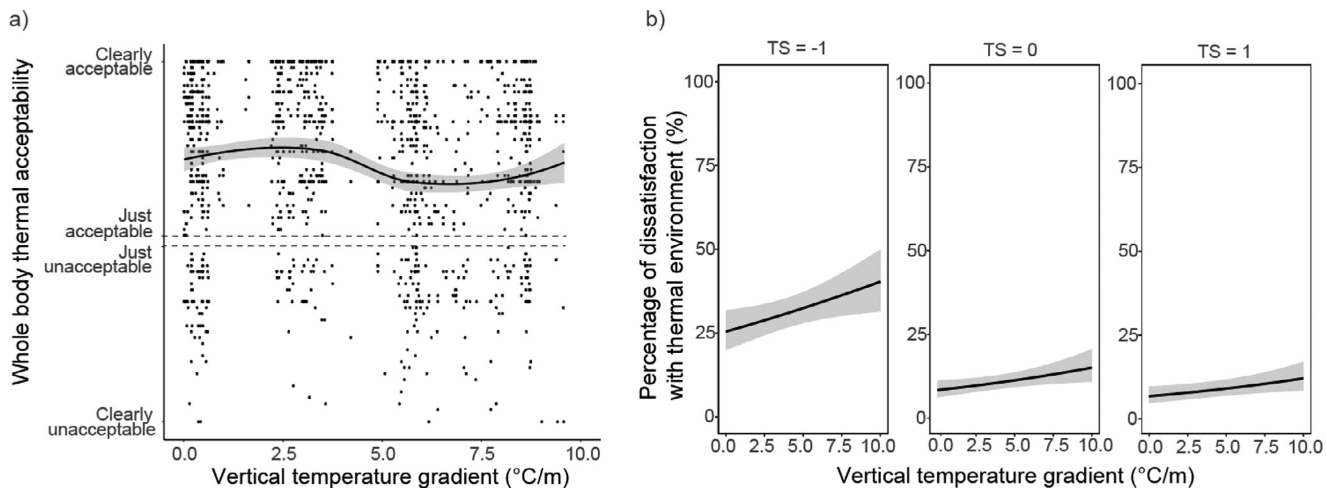

Fig. 6. Whole-body thermal acceptability and the percentage dissatisfied with the thermal environment at different vertical temperature gradients between head and feet. (a) Whole-body thermal acceptability ($n = 1177$); (b) The predicted percentage of dissatisfaction with the thermal environment at three thermal sensations (TS = −1, 0, 1) using logistic regression, Eq. (1) (The gray shades represent pointwise 95% confidence interval for the fitted values).

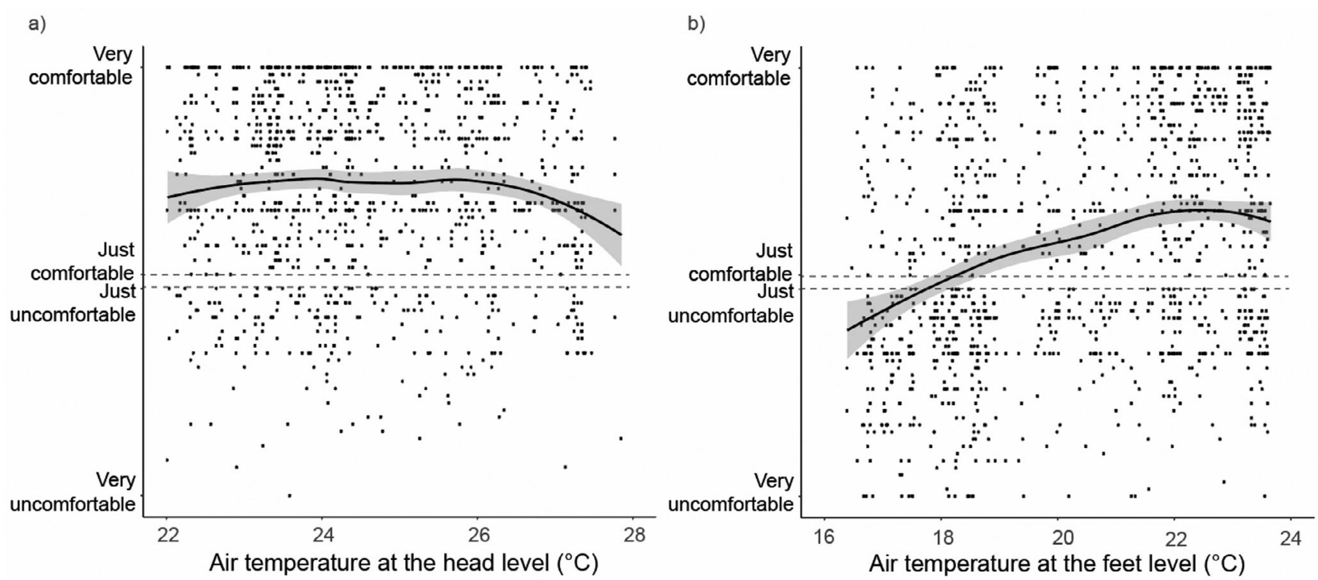

Fig. 7. Local segmental thermal comfort level ($n = 1177$). (a) head; (b) feet; the gray shades represent pointwise 95% confidence interval for the fitted values with local polynomial regression (LOESS).

3.4. Predicted percentage dissatisfied with vertical temperature gradient ($PPD_{\nabla T}$) *for local discomfort*

We related the dissatisfaction with vertical temperature gradient defined in Section 2.4 as negative thermal comfort at head or feet ($TC_{head} < 0$ *or* $TC_{feet} < 0$) and the condition that the head was warmer than feet ($TS_{head} > TS_{feet}$). The independent variable selection analysis shows that the dissatisfaction is affected by both vertical temperature gradient and whole-body thermal sensation. The prediction model based on sitting occupants is shown in Eq. (2):

$$PPD_{\nabla T} = \frac{e^{0.13(TS-1.91)^2+0.15\nabla T-1.6}}{1+e^{0.13(TS-1.91)^2+0.15\nabla T-1.6}} \tag{2}$$

where

$PPD_{\nabla T}$: Predicted percentage dissatisfied with vertical temperature gradient for local discomfort,%

TS: Whole-body thermal sensation, from −3 to 3 (*significantly important in the regression, p < 0.000*).

∇T: Vertical temperature gradient, °C/m (*significantly important in the regression, p < 0.000*)

The average mean-squared error (MSE) for Eq. (2) was 0.22 based on 10-fold cross-validation [35].

Fig. 8a depicts the binary data of local discomfort caused by vertical temperature gradient. Unlike whole-body thermal dissatisfaction (Fig. 6a), the percentage of dissatisfaction due to local discomfort is significantly enhanced with vertical temperature gradient, from 35% at 0 °C/m to 52% at 9 °C/m. [8] reported that the percentage dissatisfied at the feet increased by approximately 30% at 9 °C/m difference compared to the baseline 1 °C/m, this can be seen from the reproduced Fig. 8b. The curve in Fig. 8a, based on the local polynomial regression, shows that the dissatisfaction is almost constant below 3 °C/m.

Table 3 shows that local feet cold-related discomfort is the most frequent discomfort related to the dissatisfaction with the vertical temperature gradient. Uncomfortable cold feet but comfortable head comprise 28.3% of the votes, much larger than uncomfortable warm feet or uncomfortable warm head. Approximately 50% of the votes in the dataset *(n = 1177)* are comfortable head and feet.

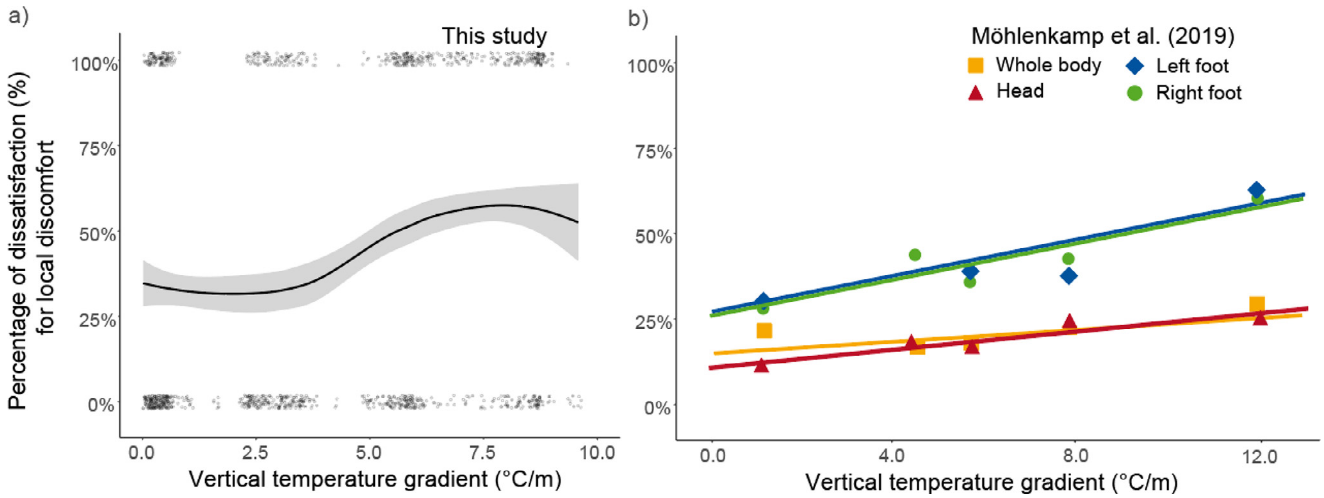

Fig. 8. Percentage dissatisfied with vertical temperature gradient ($n = 1711$) for local discomfort. (a) This study. Binary raw data points (comfort and discomfort) with local polynomial regression (LOESS) fit; the gray shade represents pointwise 95% confidence interval. Note: dissatisfaction is determined when ($TC_{head} < 0$ or $TC_{feet} < 0$) and $TS_{head} > TS_{feet}$; (b) Results reprinted from [8].

Table 3
Decomposition of local discomfort with vertical temperature gradient ($n = 1711$).

		Head Uncomfortable cold	Comfortable	Uncomfortable warm
Feet	Uncomfortable cold	8.9%	**28.3%**	4.1
	Comfortable	1.4%	49.4%	4%
	Uncomfortable warm	0.2%	1.8%	1.9

3.5. The maximum acceptable vertical temperature gradient

Fig. 8a shows that the dissatisfaction for local discomfort at the head or feet level is 34.5%, even when there is no stratification. The high discomfort level (30%) at feet was also observed by [8] as presented in Fig. 8b. The high ratio of local discomfort may be related to the whole-body discomfort in the uniform environment discussed in Section 3.1, which can be observed in Figs. 5 and 8b that the discomfort rating for the whole body is 30% and 25% respectively. Both this study and papers [4,6,8] found that the percentage dissatisfied with head or feet exceeds 10% or more in environments with no stratification, which suggests that other factors (e.g., whole body thermal sensation) have more significant impact than vertical temperature gradient. However, the original study [3] underlying ASHRAE 55′s specification found no participants dissatisfied with local discomfort when vertical temperature gradient was 0.4 °C/m.

In this study, we use the percentage dissatisfied at 0 °C/m as the baseline and calculate the corresponding vertical temperature gradient using the $PPD_{\nabla T}$ model (Eq. (2)) when the percentage dissatisfied rises 5% and 10% above the baseline. The baseline, 34.5%, is the average $PPD_{\nabla T}$ over whole-body thermal sensation from −3 to 3 calculated using Eq. (2). Therefore, the percentage dissatisfied, $PPD_{\nabla T}$, can be rewritten as Eq. (3):

$$PPD_{\nabla T} = max\left\{\left(\frac{e^{0.13(TS-1.91)^2+0.15\nabla T-1.6}}{1+e^{0.13(TS-1.91)^2+0.15\nabla T-1.6}} - PPD_{\nabla T\_base}\right), 0\right\} \tag{3}$$

where

$PPD_{\nabla T}$: Predicted percentage dissatisfied with vertical temperature gradient for local discomfort (head or feet),%

TS: Whole-body thermal sensation, from −3 to 3 (*significantly important in the regression, p < 0.000*)

∇T: Vertical temperature gradient, °C/m (*significantly important in the regression, p < 0.000*)

$PPD_{\nabla T\_base}$: baseline 34.5%, the average percentage dissatisfied at 0 °C/m over the whole-body thermal sensation from −3 to 3.

Fig. 9 displays the allowed maximum vertical temperature gradient at various whole-body thermal sensations. For thermal environments at thermal neutrality (*TS = 0*), vertical temperature gradient should not exceed 4.7 °C/m and 6.0 °C/m for 5% and 10% $PPD_{\nabla T}$ above the baseline, respectively.

Table 4 summarizes the acceptable vertical temperature gradient interpolated from various studies. Large discrepancies exist due to the experimental setup, sample size, and/or metrics used to determine dissatisfaction. For instance, the 95% confidence interval of the percentage dissatisfied for either left foot or right foot was roughly 30% in [8]. In the present study, the 95% confidence interval is 13% (the width of the shaded area in Fig. 8). The size of these variations exceed Fig. 9's predicted increases in percentage dissatisfied caused by vertical temperature gradient. Individual differences in thermal requirements might be a reason for the variation. Large individual differences among occupants in local discomfort were also revealed in a field study of displacement ventilation [28]. Thus, we conclude that a vertical temperature gradient under 5 °C/m would be unlikely to produce significant local discomfort, given the large variation of dissatisfaction even without vertical temperature gradient.

ASHRAE 55 (2017) [1] imposes a limit of 3 °C between the head and feet of a seated occupant (equivalent to 3 °C/m) as the maximum vertical temperature gradient to keep the percentage dissatisfied below 5%. This is also the limit for Category B buildings in ISO 7730 [2]. However, Table 4 shows that a higher limit is possible. Studies of local discomfort under different vertical temperature gradients have provided extensive evidence that significant differences in the percentages dissatisfied due to vertical temperature gradient are unlikely for the whole body up to 8 °C/m and for body segments up to 5 °C/m for seated occupants.

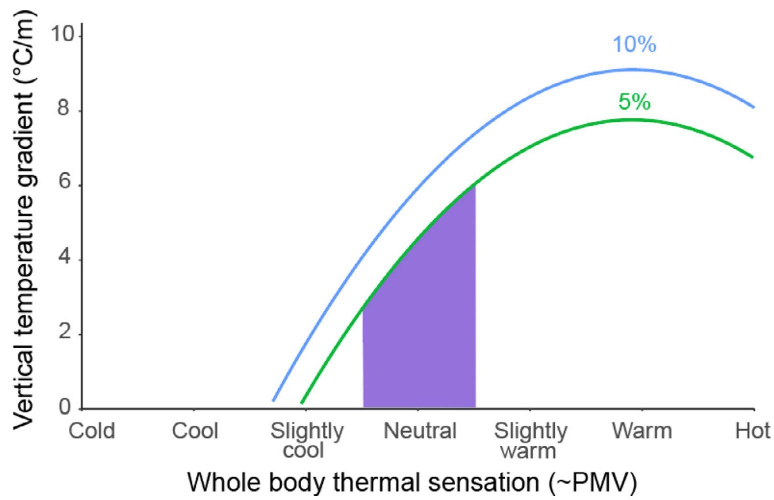

Fig. 9. Allowed vertical temperature gradient between head (1.1 m) and feet (0.1 m) for local discomfort. The shaded area denotes the allowed vertical temperature gradient for 5% dissatisfied when thermal sensation is designed from −0.5 to 0.5.

Table 4
Allowed vertical temperature gradient between head and feet for 5% and 10% $PPD_{\nabla T}$.

	5%	10%	Comments
[1–3]	3.0 °C/m	3.7 °C/m	Interpolation from ASHRAE 55 instead of the equation in ISO 7730[2]; whole-body thermal sensation not considered; discomfort for head or feet or both
[4]	2 °C/m	3 °C/m	Interpolation based on discomfort for any segmental parts after 1 h exposure. Insignificant effects of the vertical temperature gradient up to 4 °C
[6]	>5 °C/m	>5 °C/m	Neutral whole-body thermal sensation at the room air temperature, 23 °C; based on discomfort for any segmental parts; almost constant percentage dissatisfied up to 5 °C/m.
[8]	2.5 °C/m	4.5 °C/m	Based on the average percentage of dissatisfaction for left and right foot; whole-body thermal sensation not considered
This study	4.6 °C/m	6.0 °C/m	Neutral whole-body thermal sensation (TS = 0); discomfort for head or feet or both; calculated from Eq. (3).

3.6. Effect of sex

Research on draft risk revealed that sex is not an essential factor influencing perceived draft [7,36,37]. However, little previous research has reported the influence of sex in environments with different vertical temperature gradients. Hashiguchi et al. [23] studied the difference between males and females in thermal comfort under various vertical temperature gradients. The study utilized a climatic box that was originally adopted by Tanaka et al. [24] to create four vertical temperature gradients (upper body at 25 °C, lower body at 16, 19, 22, 25 °C). Sixteen subjects (8 females and 8 males) were recruited and exposed for 2 h. Females were found to be more sensitive to and felt more uncomfortable with vertical temperature gradient ($p < 0.05$) than males in the early phase (first 20 min) of the exposure. Nevertheless, the sex difference in thermal comfort vanished with increased exposure time.

Fig. 10 compares the difference of perceived thermal sensations between females ($n = 66$) and males ($n = 32$) when vertical temperature gradient rises from 0.4 to 8.4 °C/m. A significant difference with a medium or larger effect size is observed only for feet at 8.4 °C/m. The influence of sex is negligible when the vertical temperature gradient is within 5 °C/m.

3.7. Potential impact on industry standards and practices

The experiment showed that 5 °C/m is an acceptable vertical temperature gradient; this corresponds to a 5 °C difference between the head (1.1 m) and feet (0.1 m) for seated occupants. ASHRAE 55 (2017) [1] stipulates that the maximum allowed vertical temperature difference (°C), instead of vertical temperature gradient (°C/m), between head and feet is 3 °C for seated and 4 °C for standing occupants. Since occupant behaviors are generally unknown in the design phase and may not be static during building system operation, it is more convenient and maybe less confusing to use vertical temperature gradient rather than temperature difference for designers, engineers, and practitioners.

The revised limit was verified by testing seated participants only, but we expect that standing occupants would tolerate similar or higher vertical temperature gradient between head and feet because, in most practical conditions, standing occupants will have a higher metabolic rate than that while seated, which reduces their thermal sensitivity [38]. Also, complaints of local discomfort with vertical temperature gradient are highly associated with cold feet, according to Table 3. A seated occupant is likely to have less circulation in legs and feet than a standing occupant. Such a scenario is common when a person sits for an extended period in a confined space like air-cabin or bus. Therefore, we would expect that the allowable stratification between head and feet for standing people likely exceeds that while sitting, and that therefore the limit of 5 °C/m would be a conservative number for the standing condition. The 5 °C/m limit leads to an acceptable temperature difference, 8 °C, between feet (0.1 m) and head (1.7 m) for standing, which is also supported by two recent studies [7,8]. In practice, if the feet are cold it may be easier and energy-efficient to warm up the feet locally instead of warming up the entire space.

The new limit may have positive energy implications. For example, the ASHRAE design guideline for displacement ventilation systems specifies 2 °C/m as the maximum allowable vertical temperature gradient between the head and feet level [39]. This limit, more conservative than in ASHRAE 55 and ISO 7730, results in unnecessarily high supply airflow rates and diffuser sizes in order to meet indoor cooling loads. A new limit of 5 °C/m might significantly improve energy saving without causing dissatisfaction with local discomfort. An even higher limit could be obtained if the

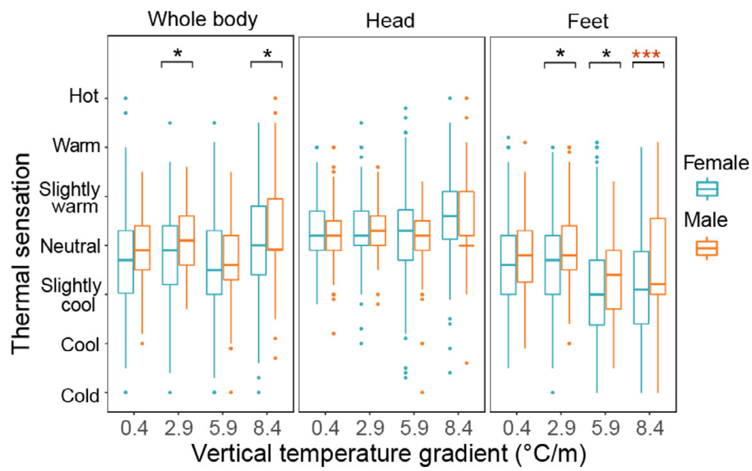

Fig. 10. Effect of sex on perceived thermal sensations at various vertical temperature gradients between head and feet. (Statistical significance: * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$; Stars in red refer to medium or higher effect sizes based on Cohen's d; |d | < 0.147 "negligible", |d| < 0.33 "small", |d| < 0.474 "medium", otherwise "large"). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

space is design to achieve a thermal sensation close to the allowed upper limit of 0.5, this may lead to additional energy savings.

3.8. Limitations

The models proposed here are based on chamber tests with 98 healthy college-age subjects who might have different sensitivity towards vertical temperature gradient and local discomfort than other populations. Another limitation of this study might be that female subjects outnumbered male subjects (66 *vs* 32). We had not attempted to balance the numbers of female and male participants in the study because a previous review of the field found no consistent evidence to support differences in thermal comfort between females and males [40]. Nevertheless, we acknowledge the potential difference in the acceptability between males and females for the high vertical temperature gradient, 8.4 °C/m. However, the difference becomes negligible within 5 °C/m that is of interest for design guidelines. Furthermore, all subjects were seated during the experiment, further studies might be needed for standing subjects in future.

The low thermal sensation at feet could be caused by the combined effects of air temperature and air movement since airflow was delivered at the floor level. Subjects were allowed to move their feet during the testing to maintain the experiment's ecological validity, so self-generated air movement was not avoided. The maximum acceptable temperature gradient might be higher if air movement were zero. In this study, we did not differentiate the overcooling at ankle level is caused by low temperature or high air speed. Even though it is estimated that the air speed at ankle level is lower than 0.2 m/s, it is beneficial to measure the air velocity in future studies.

Clothing insulation was not strictly controlled in this study. The main reason is the goal of this study is to support the development of new thermal comfort standards on vertical thermal gradients that could be applied in real buildings. In real buildings it is rare to know what clothing the occupants would wear. It might be not so strict from the perspective of a traditional chamber experiment, but we think it is more realistic and applicable for real buildings. Additionally, we did not expect a large clothing variation for a subject over the entire experiment due to the low variation in outdoor air temperature at 6 AM that was correlated to clothing insulation according to ASHRAE Standard 55 [1]. Even though the overall clothing insulation was similar, how the clothing insulation was distributed in the body would influence subjects' response to vertical temperature gradient. Given the same vertical temperature gradient and similar whole-body clothing insulation, subjects with thicker pants and thinner shirts might feel more comfortable than those with thinner pants and a thicker shirt. Nevertheless, these random effects could be reduced or even canceled since each subject participated in all four vertical temperature gradients and due to a large sample size (392 subject-test in total). It is also worthy to keep in mind that in most working environments there is sufficient dress code flexibility, in particular for cold conditions. Last but not least, we have more female subjects than male subjects in this study, as female might be more sensitive to ankle level overcooling due to dress coding. Our experiment actually might overestimate the effect of thermal gradient on occupants' comfort level.

As observed in the literature review, the acceptable thermal gradients depend on the overall thermal sensation. Fig. 9 in the manuscript shows how the acceptable vertical temperature gradient change with thermal sensation. From the figure can be deduced that a temperature gradient of 5 °C/m would not be acceptable at the lower end of the comfort zone. Beside the figure, we implemented the model in the CBE Thermal Comfort Tool (https://comfort.cbe.berkeley.edu/ click "Local discomfort" and look for "CBE vertical temperature gradient"). The tool allows assessing what happen to the vertical temperature gradient if any of the input parameters of the PMV changes. Please note the thermal sensation of the subjects varied between cold and warm (Fig. 4).

As for why occupants in warmer environment could accept larger thermal gradients, the experiment was conducted from November to December, when "warm" would be perceived as a positive and comfortable stimulus, even in the relatively mild cool weather in Berkeley, California. This might explain the reason why in this study, "Warmer" was more often preferred than "Cooler." The impact of seasonal factors may warrant further investigation. The self-reported acceptability of perceived air quality and acceptability of acoustics on the scale from −3 (clearly unacceptable) to 3 (clearly acceptable) was 1.56 ± 1.19 and 1.29 ± 1.38 (mean ± standard deviation), respectively. However, many other environmental factors were not measured or controlled in this study, such as relative humidity, lighting, local air speed, noise, and pollutants other than CO_2.

4. Conclusions

We conducted a blind within-subject laboratory experiment to understand how the vertical temperature gradient influences percentage dissatisfied with local head or feet discomfort. We found that the percentage dissatisfied with vertical temperature gradient increases only slightly for the whole body (<10%) when vertical temperature gradient rises above 3 °C/m at the given setup. We also found the feet to be more sensitive than the head to ambient air temperature variation. The uncomfortable-cold-feet condition is more common than the uncomfortable-warm-head condition.

We developed a logistic regression model to predict percentage dissatisfied for local discomfort as a function of whole-body thermal sensation and vertical temperature gradient. The predicted percentage dissatisfied is 5% when vertical temperature gradient is roughly 5 °C/m. A warmer whole-body thermal condition, e.g., by increasing room air temperature, or locally warming feet can reduce the dissatisfaction.

This study found that the percentage dissatisfied with vertical temperature gradient is less than as described in ASHRAE 55 [1] and ISO 7730 [2]. A vertical temperature gradient between head and feet up to 5 °C/m would likely be acceptable in thermally stratified environments when the subject is thermally neutral.

Declaration of Competing Interest

The authors declare no competing interests.

Acknowledgment

This research is funded by the Republic of Singapore's National Research Foundation through a grant to the Berkeley Education Alliance for Research in Singapore (BEARS) for the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) Program. BEARS has been established by the University of California, Berkeley as a center for intellectual excellence in research and education in Singapore. We would like to thank Fred Bauman for his assistance in the experimental setup. The authors also appreciate the 96 subjects who participated in the study.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2020.110085.

Appendix

Appendix A

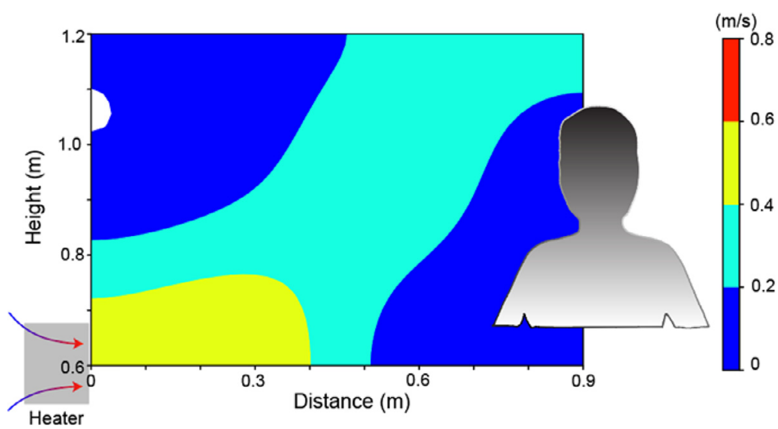

Fig. A1. Mid-plane air speed distribution in front of a fan heater (1500 W) that was placed 0.6 m above the floor and 0.8–1.0 m away from a subject. The air speed was tested at the maximum fan setting, higher than the conditions in the experiment. The ambient temperature for the air speed measurement was 23.3 °C.

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