Predicted Percentage Dissatisfied with Ankle Draft

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Abstract

Draft is unwanted local convective cooling. The draft risk model of Fanger et al. (*Energy and Buildings* **12**, 21-39, 1988) estimates the percentage of people dissatisfied with air movement due to overcooling at the neck. There is no model for predicting draft at ankles, which is more relevant to stratified air distribution systems such as underfloor air distribution (UFAD) and displacement ventilation (DV). We developed a model for predicted percentage dissatisfied with ankle draft (PPD_{AD}) based on laboratory experiments with 110 college students. We assessed the effect on ankle draft of various combinations of air speed (nominal range: 0.1-0.6 m/s), temperature (nominal range: 16.5-22.5 °C), turbulence intensity (at ankles), sex, and clothing insulation (< 0.7 clo; lower legs uncovered and covered). The results show that whole body thermal sensation and air speed at ankles are the dominant parameters affecting draft. The seated subjects accepted a vertical temperature difference of up to 8 °C between ankles (0.1 m) and head (1.1 m) at neutral whole body thermal sensation, 5 °C more than the maximum difference recommended in existing standards. The developed ankle draft model can be implemented in thermal comfort and air diffuser testing standards.

Keywords: *Thermal comfort; Draft risk model; Local thermal discomfort; Thermal stratification; Displacement ventilation; Underfloor air distribution*

Practical Implications

The proposed draft risk model provides a simple tool to estimate draft at ankles and lower legs in buildings or vehicles, when high speed and low temperature airflow is present near floor level. Such phenomena can be found in indoor environments that are conditioned with stratified air distribution systems, that include cold descending airflow along external walls or windows, and that employ supply air diffusers below seats. The model suggests that the maximum air speed at the ankles should not exceed 0.22 m/s and 0.57 m/s for <20% dissatisfaction when the whole body thermal sensation is in the cooler and warmer limit of the thermal neutrality range (predicted mean vote, PMV = -0.5 and 0.5), respectively. For thermally neutral conditions (PMV = 0), the maximum air speed at ankles should be limited to 0.13 m/s (0.39 m/s) to ensure that <10% (<20%) are dissatisfied with ankle draft.

1. Introduction

Draft, unwanted local cooling due to air movement, causes occupant dissatisfaction in indoor spaces. Stratified air distribution systems, such as displacement ventilation (DV) and underfloor air distribution (UFAD), supply conditioned air at the floor, and are intended to maintain a thermally stratified environment. The high speed and low temperature airflow at

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the floor level can cause draft at the ankles and lower legs. In addition, winter downward airflow along cold inner surfaces due to inadequate insulation of outer walls or windows can induce draft to occupants seated in perimeter zones.[1] An early study found that 30% of 453 employees responded with “Yes” to the question of “are you disturbed by draft?” in 15 large-space offices in Switzerland.[2] Another field survey regarding thermal comfort in ten office buildings with displacement ventilation showed that 24% of 227 office workers complained about being bothered daily by draft, mainly at the lower legs.[3] In vehicle cabins, air currents near the floor can result in discomfort for the feet.[4]

Many factors influence the intensity of draft discomfort. Draft risk increases with increasing air speed and turbulence intensity, while it decreases with increasing air temperature.[5,6] Several studies provide supporting evidence, from the earliest research by Houghten et al.[7] to investigations in recent decades.[8-11]

In addition to environmental conditions, draft risk might also vary with whole body thermal sensation, sex, and clothing. A field study in industrial spaces indicated that local discomfort due to draft was more likely to occur for people feeling cool or cold than those feeling thermally neutral or warm.[12] Other studies have also reported that, together with thermal conditions, sensation of draft varied with people’s thermal sensation.[10,13] Nemecek and Grandjean[2] found that female office workers were much more likely to complain about draft than their male colleagues (55% vs. 24%), which is aligned with the finding of a meta-analysis showing that females are more likely than males to express thermal dissatisfaction.[14] Also contributing to the difference might be that women often having less clothing insulation for lower legs as compared to men (e.g., skirts or dresses versus long pants and open versus closed shoe styles). When the clothing ensembles are the same for men and women, the two sexes perceived draft almost equally.[8] Nielsen[15] also found no difference in draft discomfort between sexes by interviewing approximately 6000 workers in cold workplaces in Denmark.

Draft risk may be affected by thermal stratification as well. Laboratory experiments with human subjects have shown that most subjects at neutral overall thermal sensation who expressed dissatisfaction with thermal stratification had slightly cool feet when the temperature difference between the head (1.1 m) and ankle (0.1 m) levels was 7.5 °C.[16] This finding suggests that draft risk at ankles may be related to a vertical thermal gradient. However, Wyon and Sandberg[17] and Yu et al.[18] showed that a vertical thermal gradient, up to 4 °C/m and 5 °C/m respectively, insignificantly affected the local body discomfort in the application of displacement ventilation systems.

Current thermal comfort standards, such as ISO 7730[19] and EN 15251,[20] employ the draft model proposed by Fanger and colleagues.[5,6] The model, described in Equation 1, was developed by curve-fitting experimental data utilizing a simple empirical model of human skin heat transfer. It expresses the percentage dissatisfied (PD) with draft as a function of convective heat loss.

$$PD = (3.143 + 0.3695\, V \cdot TI)(34 - t_a)(V - 0.05)^{0.6223} \qquad (1)$$

where V is mean air speed (m/s), TI is turbulence intensity (from 0 to 100), and t_a is air temperature (°C). The model relates air speed, temperature, and turbulence intensity to the percentage dissatisfied with air movement at the neck. Based on the form of Equation 1, Griefahn et al.[21] and Wang et al.[22] updated the model to incorporate metabolic rates and time variation, respectively. However, none of these models accounts for the effect of thermal sensation as an input variable. The model of Fanger et al. was based on data from subjects whose overall thermal sensation was lower-than-neutral, which causes an overestimation of draft risk for people at neutral and warmer thermal sensations.[23] Toftum and Nielsen[10] performed a logistic regression to analyze the percentage of subjects dissatisfied with draft at the head region at different air temperatures, speeds, and whole body thermal sensation (from -1.2 to 0.5 on the 7-point ASHRAE scale). The study revealed that only the thermal sensation and air speed significantly influenced the subjective perception of draft discomfort. However, that study included only ten subjects and few environmental parameters.

Existing draft risk models all focus on the head and neck region. There is no draft risk model for ankles in part because the head and neck were identified as the most sensitive body parts for draft discomfort when common air distribution systems supplied air at the ceiling. Owing to the increasing prevalence of DV and UFAD systems, however, there is a need to consider ankles and lower legs as sensitive body sites for overcooling and draft risk. That context motivates the study reported here.

This study consists of two phases. Conducted in summer 2013, the first phase experimentally evaluated local draft risk at ankles for females with their ankles and lower legs uncovered.[24] The first phase revealed a higher draft discomfort at ankles than expected and identified the need for more experiments before developing a draft risk model. The second phase of the study collected additional data during spring and summer 2015.

This paper presents the combined results of the two phases along with their interpretation. The main objective is to develop a model to assess the predicted percentage dissatisfied with ankle draft (PPD_{AD}). The paper also investigates the maximum acceptable limit of vertical temperature difference for the application of DV and UFAD systems. We also examined the influence of environmental variables (e.g., air temperature and speed) at ankles, sex, and clothing insulation (lower legs uncovered and covered) on the subjective sensation of draft.

2. Methods

We describe here the environmental conditions, experimental procedure, human subjects, and statistical analysis. This section also reports the multiple variable linear regression and logistic regression methods used in the parameter analysis and in the development of PPD_{AD}, respectively. A more detailed description of the experimental methods is provided in Schiavon et al.[24] Descriptions of the experimental facilities, their configuration, and the survey questionnaire used in the previous paper are not repeated here.

2.1. Environmental conditions

The second phase of the study assessed the percentage dissatisfied with draft at ankles for two clothing conditions: lower legs covered and uncovered. We controlled the thermal environments at subjects' head and ankle levels separately, using two separate air distribution systems.

The experimental conditions at the head level were determined in advance to create whole body thermal neutrality for subjects. For zero predicted mean vote (PMV), the CBE thermal comfort tool,[25] which complies with ANSI/ASHRAE Standard 55,[26] recommends room air temperatures of 25 °C and 26 °C for the clothing conditions of lower legs covered (e.g., thin trousers) and uncovered (e.g., walking shorts), respectively. The upper body clothing was assumed to be long sleeve shirt and T-shirt, respectively, for the two conditions. We assumed other environmental conditions to be constant (relative humidity = 45%, air speed = 0.1 m/s, and metabolic activity = 1.1 met). The air temperature in the climatic chamber was equivalent to the mean radiant temperature because of the high envelope insulation, independent control of window surface temperature, and outside shading. We did not control the floor temperature and assumed that radiation asymmetry was negligible for the floor and other interior surfaces.

Subjects were seated at three workstations. The measured air temperature at the head level was 26.3 ± 0.3 °C for the lower leg uncovered condition and 25.3 ± 0.2 °C for the covered condition. For both conditions, the average measured relative humidity was 45 ± 5%. Air speeds at 0.6 m and 1.1 m above the floor were lower than 0.1 m/s (effectively still air) for all three workstations and for each clothing condition.

The tested air speeds (approximately 0.1 to 0.7 m/s) and temperatures (approximately 17 to 22 °C) at the ankle level in the two research phases covered the ranges of supply air conditions specified in DV and UFAD guidelines.[27-29] We characterized but did not control air turbulence intensity. The experiment consisted of an extensive number of environmental tests (37 in total). Table 1 summarizes the experimental condition for each test. Please note that throughout this paper, the air speed, temperature, and turbulence intensity refer to the values measured at the ankle level (0.1 m), except where otherwise specified.

2.2. Experimental procedure

Each two-hour test was split into six twenty-minute sessions comprising three adaptation sessions and three test sessions. The first phase study suggested that thermal steady-state was achieved within 5 min for the tested conditions. In addition, the procedure was designed to encourage subjects to start tests with a neutral whole body thermal sensation.

Figure 1(a) illustrates the test schedule of each lab visit. Subjects were split into two groups. Each subject began the test by sitting in the adaptation zone (at the back of the test room) for 20 min to adapt so as to start the test in a neutral thermal condition. The first group of subjects (Group I) was then guided to sit at the three workstations for 20 min, maintaining their feet flat on the floor within a prescribed region. Group I subjects were then returned to the adaptation zone for another 20 min. The subjects of Group II followed the same schedule, starting 20 min later than Group I. The two groups alternated between adaptation and test sessions until all six intervals were completed for both groups.

During the two-hour test, each subject sat for 20 min at each of the three workstations, with the corresponding exposures to different air speeds and temperatures shown in Table 1. At the end of each session, participants used an online questionnaire to answer the survey questions described in the section “Questionnaire” of Schiavon et al.[24]

The study procedure allowed subjects to adjust clothing on the upper parts of their bodies to maintain whole-body thermal neutrality; however, clothing change on the lower parts was prohibited. The adaptation session after each exposure enabled the subjects to return to whole-body and local thermal neutrality before the next exposure.

Table 1. Test conditions at the ankle level (0.1 m above the floor).

Phase	Nominal speed (m/s)	Measured speed (m/s)	Nominal temperature (°C)	Measured temperature (°C)	Measured turbulence intensity (%)	Number of participants (F: female; M: male)	Clothing at lower legs
Phase 1 (Schiavon et al. 2016)	0.2	0.16	21.5	21.7	33	30 F	Not covered
	0.2	0.19	19.5	19.4	42	30 F	Not covered
	0.2	0.24	20.5	21.0	26	30 F	Not covered
	0.3	0.32	21.5	21.6	25	30 F	Not covered
	0.3	0.33	18.5	18.9	26	30 F	Not covered
	0.3	0.35	20.5	20.6	25	30 F	Not covered
	0.6	0.52	21.5	21.1	26	30 F	Not covered
	0.6	0.59	17.5	18.0	31	30 F	Not covered
	0.6	0.70	19.5	19.7	35	30 F	Not covered
Phase 2 (this paper)	0.1	0.12	18.5	18.8	17	24 M	Not covered
	0.1	0.10	19.5	19.7	18	14 M	Not covered
	0.1	0.12	20.5	20.5	22	11 M	Not covered
	0.1	0.09	21.5	21.7	20	36 F +11 M	Not covered
	0.1	0.13	22.5	22.0	13	9 M	Not covered
	0.2	0.15	18.5	18.2	13	12 M	Not covered
	0.2	0.17	19.5	19.9	11	14 M	Not covered
	0.2	0.24	21.5	21.7	11	9 M	Not covered
	0.2	0.22	22.5	22.2	14	13 M	Not covered
	0.3	0.30	18.5	18.5	8	36 M	Not covered
	0.3	0.34	19.5	19.8	6	11 M	Not covered
	0.3	0.32	20.5	20.0	5	14 M	Not covered
	0.3	0.26	21.5	21.8	9	27 M	Not covered
	0.4	0.37	21.5	21.6	7	13 M	Not covered
	0.1	0.11	17.5	17.3	16	14 F + 16 M	Covered
	0.1	0.06	19.5	19.0	33	6 F + 5 M	Covered
	0.1	0.09	20.5	20.6	26	21 F + 21 M	Covered
	0.1	0.09	21.5	21.8	26	16 F + 19 M	Covered
	0.1	0.10	22.5	22.3	24	10 F + 37 M	Covered
	0.2	0.21	16.5	16.3	10	5 F + 10 M	Covered
	0.2	0.20	17.5	17.6	10	29 F +27 M	Covered
	0.2	0.21	18.5	18.9	11	9 F + 10 M	Covered
	0.2	0.20	20.5	20.3	12	14 F + 16 M	Covered
	0.3	0.33	16.5	16.7	7	6 F + 5 M	Covered
	0.3	0.31	18.5	18.3	8	11 F + 13 M	Covered
	0.3	0.31	19.5	19.2	6	14 F + 16 M	Covered
	0.3	0.28	21.5	21.3	8	11 F + 13 M	Covered
	0.4	0.41	17.5	17.6	5	2 F + 5 M	Covered

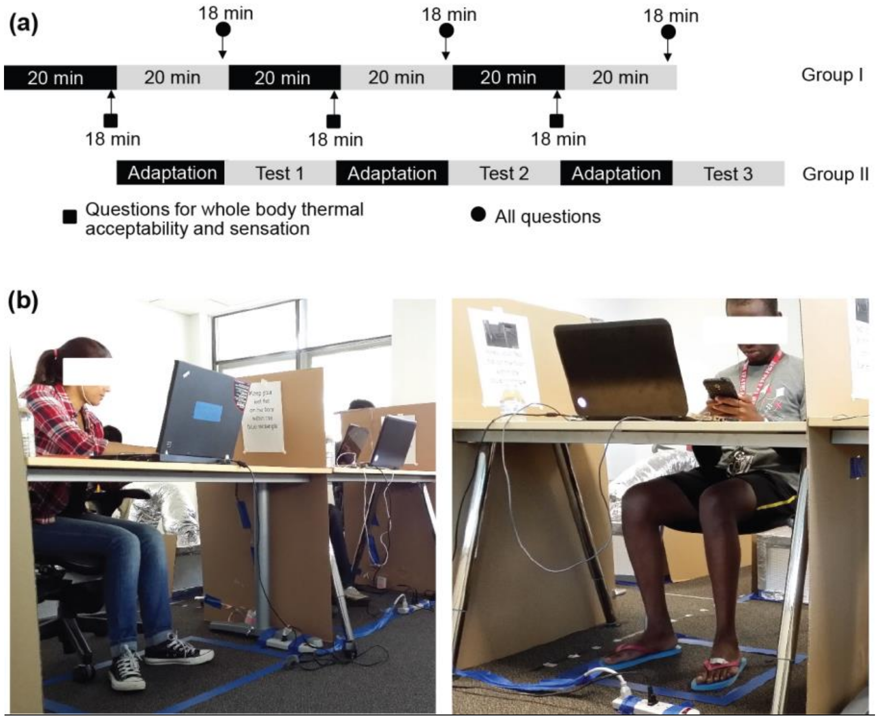

Figure 1. Experimental procedure and clothing conditions; (a) Test procedure of the two groups of subjects for each lab visit; (b) Clothing conditions for lower legs covered and uncovered in the experiments. Clothing adjustment for upper body parts was encouraged to maintain whole body thermal neutrality during the test. Subjects had to keep their feet on the floor within the blue area.

2.3. Subjects

We hired a large number of subjects for this study. The subjects in first phase were 30 female college students.[24] In the second phase, 28 female and 52 male college students participated. The subjects were compensated for participating in the experiments. The UC Berkeley Committee for Protection of Human Subjects approved (CPHS #2010-04-1312) the research protocol and all subjects signed an informed consent form before the tests. The anthropometric data of all the 110 subjects is summarized in Table 2. All the subjects were non-smokers.

Prior to participating in the experiment, subjects attended a training session to become familiar with the test room, procedure, and survey questions. We instructed the subjects to have enough sleep and to eat normal meals before arrival at the lab. Drugs and alcohol use were to be avoided during the 24 h prior to the experiment. We also asked subjects to avoid intensive exercise during the last hour before each experiment. All subjects reported that they were in good health. We offered them the opportunity to reschedule their lab visits if needed, which provided them flexibility and reduced the likelihood of subjects participating while unwell. On average, each subject participated in six test conditions.

Table 2. Anthropometric data (average ± standard deviation) for all subjects participating in the two research phases

	Age (years)	Height (m)	Weight (kg)	BMI[§] (kg/m^2)	Number of subjects
Female[†]	24.1 ± 6.8	1.62 ± 0.07	55.8 ± 6.5	21.2 ± 2.2	30
Female[‡]	21.0 ± 3.0	1.64 ± 0.07	58.4 ± 6.8	21.8 ± 2.3	28
Male[‡]	22.8 ± 3.9	1.77 ± 0.06	71.1 ± 10.8	22.4 ± 4.2	52
Total	22.7 ± 4.8	1.69 ± 0.10	63.1 ± 11.6	21.9 ± 2.8	110

[†] Participants in the first phase of the study.[24]
[‡] Participants in the second phase of the study.
[§] Body mass index = weight (kg)/[height (m)]^2.

During the experiment, we instructed the subjects to be dressed in typical summer office clothes, either with lower legs uncovered or covered. Figure 1(b) illustrates the two clothing conditions. For the uncovered condition, the subjects had bare lower legs, such as walking shorts (0.08 clo), and sandals ("flip-flop" style) (0.02 clo) without socks. In the second test condition, where their lower legs were covered, the subjects wore long thin trousers/jeans (0.15 clo), flat shoes (0.02 clo), and socks (0.02 clo) to completely cover their lower legs, ankles, and feet. During the experiments, subjects were reminded to maintain whole body thermal neutrality by adjusting their upper-body clothing (e.g., through use of a light jacket or long sleeve shirt). From observations made during these experiments, the estimated clothing insulation based on the CBE online comfort tool was in the range of 0.3 to 0.7 clo, depending on experimental conditions.[25] We did not record or measure clothing insulation during tests, since subjects were allowed to adjust their upper body clothing. However, the average difference in clothing insulation at the lower body for the two conditions was only 0.09 clo, based on CBE online comfort tool.[25] We assigned one laptop computer to each workstation, and the subjects were allowed to read or type at the laptop; that activity corresponds to a metabolic equivalent value of 1.1-1.2 met according to ANSI/ASHRAE Standard 55.[26] More details about the experimental procedure can be found in Schiavon et al.[24]

2.4. Statistical methods

We report the summarized data (e.g., whole body thermal sensation) using the median value together with the 25th and 75th percentiles in parenthesis, such as -0.08 (-0.75, 0.21). The previous study described the statistical tests to compare differences among groups and also correlations between pairs of variables using both parametric and nonparametric data.[24] In this paper, we applied the same statistical methods, utilizing RStudio, version 0.98.1102.[30]

We analyzed the percentage dissatisfied with draft at ankles using subjects' responses to the questions about ankle air movement acceptability ("Rate your acceptance of air movement at your ankles") and ankle thermal sensation ("Rate your thermal sensation of your ankles"). The subjects reported ankle air movement acceptability using a slider with continuous non-zero values from very unacceptable (-3) to very acceptable (3) with a gap between just unacceptable (-0.1) and just acceptable (0.1). In addition to ankle air movement acceptability, the subjects reported their ankle thermal sensation using a slider with the 7-point ASHRAE scale.[26] Conditions were classified to be "discomfort caused by draft" when subjects reported negative values for both ankle air movement acceptability and ankle thermal sensation. Since draft is defined as unacceptable air movement causing undesired cooling, conditions such that air movement was not acceptable but the ankles were warm or hot are not assessed in this study. These conditions, which constitute only 2.4% of the dataset, were omitted from the analysis of ankle air movement acceptability and from the development of the PPD_{AD} model.

We analyzed data using multivariable linear regressions for parameters with numerical output, such as ankle air movement acceptability (*AMA*), and using logistic regression for parameters with binary output, for instance, acceptability (acceptable/unacceptable). The assumptions (e.g., normality and multicollinearity) of each linear regression model were checked.

First, we assessed whether using a multivariable linear regression model (Equation 2) was more or less accurate for predicting Fanger et al.'s measured results of the percentage dissatisfied (PD_{Fanger}), compared to their curve-fitting heat-transfer approach (Equation 1). We then developed a PPD_{AD} model for local thermal dissatisfaction at ankles by applying the logistic regression with the form of Equation 3. This logistic regression correlates ankle air movement acceptability (acceptable/unacceptable) with ankle air speed, temperature, turbulence intensity, whole body thermal sensation, sex, and clothing.

$$PD_{Fanger} = \bar{\alpha} + \overline{\beta_1} t_a + \overline{\beta_2} V + \overline{\beta_3} TI \tag{2}$$

$$\ln\left(\frac{PPD_{AD}}{1 - PPD_{AD}}\right) = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \cdots + \beta_n X_n \tag{3}$$

Here $\bar{\alpha}, \alpha, \overline{\beta_1}, \overline{\beta_2}, \overline{\beta_3}$ and β_i $(i = 1, n)$ are coefficients, and X_i (i = 1, n) are the independent variables affecting PPD_{AD}. The symbol "ln" represents the natural logarithm.

For the logistic regression (Equation 3), we statistically analyzed the contribution of each variable and kept only those that significantly influenced PPD_{AD}. The selection was based on tests of the statistical significance ($p < 0.05$) of each variable in the regression. We verified the selection by comparing the regressed models with and without each variable. If the inclusion of a variable improved the model insignificantly, then the variable was excluded. This process employed ANOVA together with F-statistics and chi-squared tests for linear and logistic regressions, respectively. We also applied 10-fold cross validation to ensure that all of the variables were appropriately selected by comparing the mean square error (MSE) of a model with a variable added to the MSE of a model with the same variable omitted.[31] The stepwise method was not applied in the variable selection process because of its bias in parameter estimation.[32,33]

3. Results

We present the results pertaining to ankle air movement acceptability, thermal stratification, and the development of the PPD_{AD} model. Results concerning thermal sensation (section S1) and the effect of thermal experience and sensitivity on whole body thermal acceptability (section S2) can be found in the Supporting Information.

3.1. Ankle air movement acceptability

This study assesses the dissatisfaction with draft at ankles based on the subjective responses to questions about ankle air movement acceptability (*AMA*). The *AMA* votes are not normally distributed ($W = 0.96$, $p < 0.001$); however, the deviation is mainly confined to small ranges at the two tails. Figure 2 shows how *AMA* varies with three parameters: air speed at ankles, whole body thermal sensation (*TS*), and ankle thermal sensation (*ATS*). It is noteworthy that *AMA* is correlated more strongly with *TS* (Spearman $\rho = 0.38$, $p < 0.001$) and with *ATS* (Spearman $\rho = 0.52$, $p < 0.001$) than it is with air speed at ankles. These findings support a view that thermal sensation parameters (whole body and locally at the ankle) are major factors in assessing dissatisfaction with draft, consistent with previous studies.[10,18,24]

To further investigate possible influencing factors, we developed a multivariable linear regression for *AMA* as a function of ankle air speed and temperature, turbulence intensity, clothing insulation (lower legs covered or uncovered), sex, and thermal sensation (Equation S1 and Table S1 in the Supporting Information). We did not include ankle thermal sensation in the regression because it is difficult to estimate compared to the whole body thermal sensation that can be assessed using the PMV model described in ANSI/ASHRAE Standard 55.[26] We describe how to estimate whole body thermal sensation in the “Discussion” section.

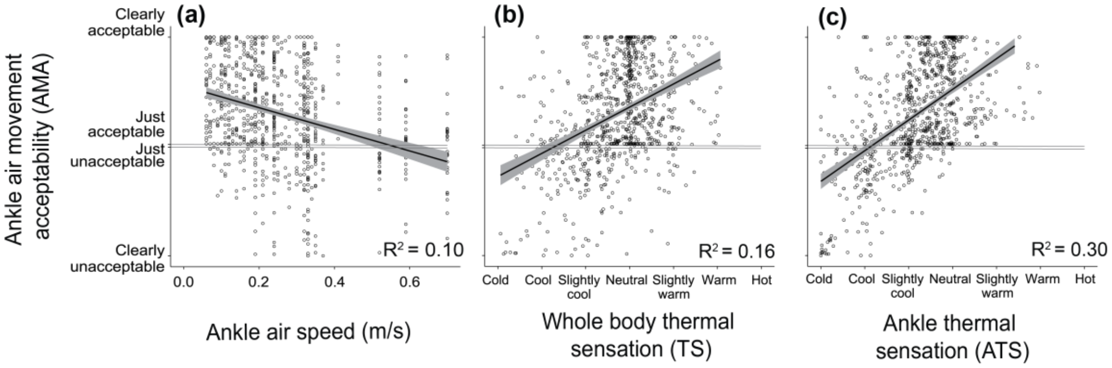

Figure 2. Air movement acceptability correlated with (a) air speed at the ankles, (b) whole-body thermal sensation, and (c) ankle thermal sensation. The shaded areas denote 95% confidence intervals of the mean responses.

The multivariable linear regression shows that the whole body thermal sensation ($p < 0.001$) and air speed ($p < 0.001$) at ankles significantly affect *AMA*. Clothing (lower leg covered and uncovered) has a marginally significant effect ($p = 0.03$) on *AMA*. The average *AMA* with lower legs uncovered is slightly smaller than that with lower legs covered. The average difference is approximately 0.23 on the scale ranging from -3 to 3, i.e., only 4% of the full range. The difference could be a consequence of the small difference (0.09 clo) in clothing insulation for the two conditions. Covering lower legs by wearing thin trousers and socks does not appear to reduce draft risk significantly. Therefore, we decided to omit the clothing factor because of the small effect size and the common simultaneous presence of the two clothing conditions in building occupants. The adjusted R^2 for the regression including only the parameters of whole body thermal sensation and ankle air speed is 0.22, which is a typical value for human subject tests pertaining to thermal comfort.[34-36] Including other factors individually or cumulatively, such as air temperature at ankles, turbulence intensity at ankles, and sex does not improve prediction of *AMA* with statistical significance ($p > 0.05$).

3.2. Thermal stratification and whole body thermal acceptability

In this section, we present the impact of thermal stratification on whole body thermal acceptability. A concern is that an excessive temperature difference between the head (1.1 m) and ankles (0.1 m) could result in low thermal acceptability.[17,19,37,38]

Figure 3 shows the predicted percentage dissatisfied with whole body thermal acceptability (PPD_{TA}) as a function of thermal stratification using a logistic regression for three thermal sensations, $TS = -1$, $TS = 0$, and $TS = 1$, representing slightly cool, neutral and slightly warm, respectively. The independent variables in the logistic regression include air temperature difference between the heights of 0.1 m and 1.1 m above the floor, thermal sensation, and air movement acceptability at the ankles because other variables affect PPD_{TA} insignificantly ($p > 0.05$). Even among the three variables, only TS and AMA significantly ($p < 0.05$) influence PPD_{TA}. Equation S2 shows the regressed logistic equation.

The curves in Figure 3 clearly show, and the data analysis confirms, that there is no effect of stratification on thermal acceptability, even for a temperature gradient as large as 8 °C/m. This result implies that occupants can accept a much greater thermal stratification than the 3 °C/m value specified in current standards. These findings are consistent with results of a simulation study in stratified environments[39] except that we did not find a large degradation of acceptability for slightly cool and warm conditions. It is worth noticing that we obtained lower thermal dissatisfaction than predicted by the PMV-PPD (predicted percentage dissatisfied) model for the three thermal sensations assessed.

Again, the most important parameter for thermal acceptability is whole body thermal sensation. Note that we removed data points from the analysis where dissatisfaction with regard to thermal acceptability was caused by local air movement (draft) at ankles. These data points, which were identified on the basis of the negative responses to the questions about ankle air movement acceptability and whole body thermal acceptability, accounted for 11% of the total dataset.

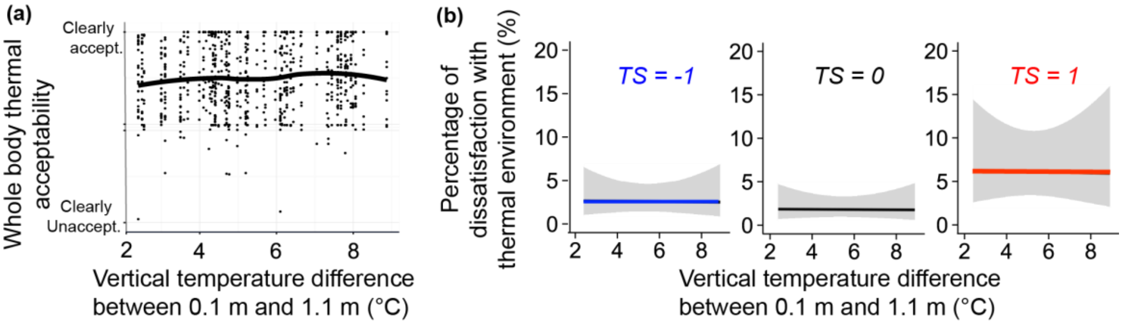

Figure 3. Whole body thermal acceptability and the percentage dissatisfied with the thermal environment for different vertical temperature differences. (a) Scatter and curve fitting (LOESS) of whole body thermal acceptability. (b) Percentage dissatisfied with the thermal environment for three thermal sensations: $TS = -1$ (slightly cool), $TS = 0$ (neutral), and $TS = 1$ (slightly warm). The shaded areas represent 95% confidence intervals of the mean responses; the large uncertainty for slightly warm conditions ($TS = 1$) is due to the small number of data points.

3.3. Development of a PPD_{AD} model

Using the data collected by Fanger and coworkers,[5,6] we next compare the multiple variable linear regression approach with the curve-fitting empirical heat-transfer model.[6] The purpose is to assess whether using a linear model, which is easier to implement and solve in simulation tools and for control system applications, produces an acceptable fit to the data. Then, we describe the development of a new PPD_{AD} model that focuses on the draft at ankles.

3.3.1. Multivariable linear regression approach vs. empirical heat-transfer model

We developed a multivariable linear model using the same input variables (air temperature, speed and turbulence intensity) and experimental data collected by Fanger et al.[6] as in the development of the existing draft risk model (Equation 1). The model is reported in Equation S3. Then we compared the performance of the two models using the data from Fanger et al. Figure 4 shows the predicted values using the two different models compared to the measurements. In Figure 4, the correlation between the predicted and measured data using the linear regression approach (Spearman ρ = 0.96, p < 0.001) is comparable to and even slightly better than using draft risk model of Fanger et al. (Spearman ρ = 0.95, p < 0.001). Additionally, the mean squared error of the prediction using the multivariable linear model (Equation S3) is smaller (37 vs. 52) than that using the model described by Equation 1. Figure S3 shows the combinations of air speeds and temperatures predicted by the linear regression compared to those calculated by the model of Fanger et al. for a fixed percentage (20%) of persons dissatisfied with draft. The mean deviation of predictions using the two models is approximately 7%. The multivariable linear regression approach provides slightly better prediction while, at the same time, being simpler. We use this same approach for the development of PPD_{AD}.

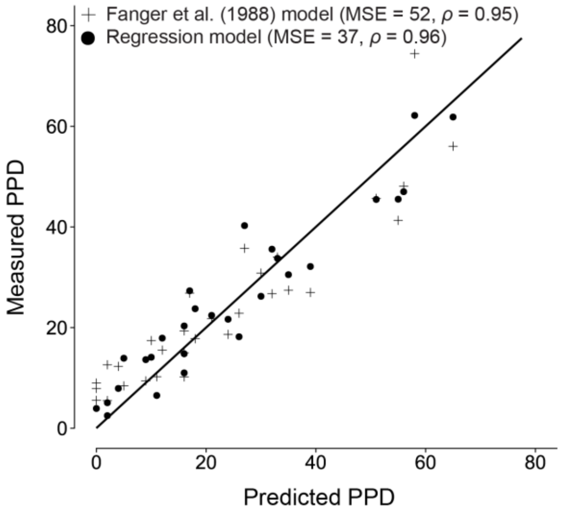

Figure 4. Comparison of predicted percentage dissatisfied (PPD) using multivariable linear regression with that using the draft risk model of Fanger et al.[6] (Equation 1). The diagonal line represents the perfect correspondence between prediction and measurement. MSE = mean squared error.

3.3.2. PPD_{AD} model

This subsection describes the development of a model to predict the percentage dissatisfied due to draft at ankle. In the logistic regression, we considered the following variables: air temperature at ankles, air speed at ankles, turbulence intensity at ankles, whole body thermal sensation, sex, and clothing insulation (lower legs and ankles covered or uncovered). Table 3 summarizes the logistic regression for PPD_{AD} (Equation 4) with six variables. Thermal sensation and air speed significantly affect PPD_{AD}. Air temperature, turbulence intensity, sex, and clothing insulation in the investigated ranges do not show significant influence on PPD_{AD}. However, the influence of clothing might be significant if the clothing insulation for lower legs covered were to be much greater (> 0.7 clo) than that for lower legs uncovered, an aspect that was not tested in this study.

We find that the PPD_{AD} can be effectively predicted using only two variables: air speed at the ankle and thermal sensation. Toftum and Nielsen[10] also found that only two variables significantly influence draft risk when air movement was generated by fans situated behind subjects. It is worth noting that the model was developed based on the statistical analysis of measured data in certain ranges. For example, the clothing insulation was in the range of 0.3 to 0.7 clo, and the average estimated difference for the two conditions was only 0.09 clo. We caution that the influence of each parameter in the model is valid only within the investigated ranges.

$$\begin{aligned} &\ln\left(\frac{PPD_{AD}}{1-PPD_{AD}}\right) \\ &= \alpha + \beta_1 t_{a,ankle} + \beta_2 V_{ankle} + \beta_3 TI_{ankle} + \beta_4 TS \\ &+ \beta_5 Sex(0\ for\ female, 1\ for\ male) \\ &+ \beta_6 Clo\ (0\ for\ lower\ legs\ covered, 1\ for\ lower\ legs\ uncovered) \end{aligned} \tag{4}$$

In Equation 4, $t_{a,ankle}$ is the air temperature at ankles (°C), V_{ankle} is the air speed at the ankle (m/s), and TI_{ankle} is the turbulence intensity measured at the ankle (from 0 to 100), and TS is the whole body thermal sensation (-3 = cold to 3 = hot).

Equation 5 shows the final model of PPD_{AD} with only two independent variables: thermal sensation and ankle air speed. The equation is reported in both SI (airspeed in meters per second) and IP (airspeed in feet per minute) units. The estimation of thermal sensation will be discussed in the "Discussion" section. The negative coefficient for TS denotes that PPD_{AD} decreases with an increase in thermal sensation.

Table 3. Results of logistic regression of PPD_{AD} for air movement acceptability at ankles (Equation 4).

Coefficient	α	β_1	β_2	β_3	β_4	β_5	β_6
Value	**-5.181**	0.122	**2.835**	0.0062	**-1.05**	-0.096	0.223
Significance (p)	< **0.001**	> 0.05	< **0.001**	> 0.1	< **0.001**	> 0.1	> 0.1

Note: Numbers in bold indicate that the corresponding parameters are statistically significant ($p < 0.05$).

SI $$\ln\left(\frac{PPD_{AD}}{1-PPD_{AD}}\right) = -2.58 + 3.05\,V_{ankle} - 1.06\,TS \quad (V_{ankle}\text{ in m/s})$$

(5)

IP $$\ln\left(\frac{PPD_{AD}}{1-PPD_{AD}}\right) = -2.58 + 0.015\,V_{ankle} - 1.06\,TS \quad (V_{ankle}\text{ in fpm})$$

The model was developed based on values of V_{ankle} in the range 0.06 to 0.7 m/s, clothing insulation smaller than 0.7 clo, and TS ranging from cold -2.9 to warm 2.1. Thermal comfort standards, such as ANSI/ASHRAE 55,[26] typically recommend acceptable PMV values ranging from -0.5 to 0.5. Therefore, the proposed PPD_{AD} model can cover the conditions of V_{ankle} up to 0.7 m/s and all practical ranges of thermal sensation. The model only applies for lightly clothed (< 0.7 clo) occupants.

The model described in Equation 5 can be transformed and expressed as in Equation 6.

SI $$PPD_{AD} = \frac{exp(-2.58 + 3.05\,V_{ankle} - 1.06\,TS)}{1 + exp(-2.58 + 3.05\,V_{ankle} - 1.06\,TS)}$$

(6)

IP $$PPD_{AD} = \frac{exp(-2.58 + 0.015\,V_{ankle} - 1.06\,TS)}{1 + exp(-2.58 + 0.015\,V_{ankle} - 1.06\,TS)}$$

Figure 5 depicts PPD_{AD} at various air speeds and thermal sensations using Equation 6. The PPD_{AD} decreases with increasing thermal sensation and it increases with increasing air speed at the ankles. In a given environment with DV or UFAD mechanical ventilation systems, it is possible to reduce the percentage dissatisfied with draft at the ankles by means of increasing occupants' whole body thermal sensation, such as by increasing the temperature set point. Figure 5 shows that PPD_{AD} is greater than 20% even in the conditions of low air speed if occupants feeling slightly cool (TS = -1) or cooler. According to standards,[19,26] acceptable thermal comfort is achieved when TS is within the range -0.5 to 0.5. On the cool side of thermal neutrality (TS = -0.5), the maximum air speed at ankles should be lower than 0.22 m/s to have the maximum percentage of dissatisfied occupants be no greater than 20%. Less than 10% dissatisfied cannot be achieved for cases in which the thermal sensation is -0.5. Also, air speed should not exceed 0.3 m/s and 0.57 m/s for 10% and 20% PPD_{AD}, respectively, when thermal sensation is on the warm side of neutrality (TS = 0.5). For conditions at the center of thermal neutrality (TS = 0), the ankle air speed is limited to 0.13 m/s and 0.39 m/s for 10% and 20% PPD_{AD}, respectively.

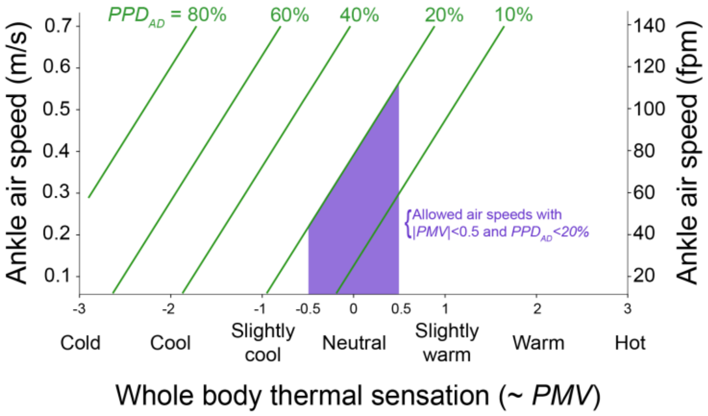

Figure 5. Allowed air speeds (in meters per second, left, and feet per minute, right) at ankles as a function of the whole body thermal sensation for lightly clothed occupants (clothing insulation < 0.7 clo).

4. Discussion

4.1. Maximum vertical thermal gradient

Adhering to existing limits on the maximum vertical temperature difference specified by thermal comfort standards might reduce the energy and ventilation efficiency of DV and UFAD systems.[29,40-44] The maximum vertical temperature difference between the feet (0.1 m) and head (1.1 m) for a seated occupant is 3 °C according to ANSI/ASHRAE Standard 55[26] and ISO 7730.[19] The basis for this limit is one study of 16 subjects sitting in a chamber with dimensions of 2 m (length) × 1.4 m (width) × 2 m (height).[16] It is possible that sitting in such a confined space for three hours resulted in psychological discomfort that combined synergistically with thermal discomfort to erode thermal acceptance. Experiments conducted in more realistic indoor spaces with DV systems suggest that occupants can accept a greater thermal gradient than 3 °C/m.[17,18] For instance, Wyon and Sandberg[17] tested 207 subjects and concluded that thermal gradients due to displacement ventilation up to at least 4 °C/m are likely to be acceptable if air quality is satisfactory and if individual control is provided. Yu et al.[18] found that the percentage of those thermally dissatisfied, based on an experiment with 60 subjects, was smaller than 10% for vertical thermal gradients up to 5 °C/m when subjects were at thermal neutrality overall.

In the present study, we found that the thermal gradient has a negligible effect on whole body thermal acceptability, and that people with thermally neutral sensation can accept a vertical thermal difference between feet and head, while seated, of up to 8 °C, corresponding to a thermal gradient of 8 °C/m. The simulation work by Zhang et al.[39] also pointed out that an acceptable head to feet temperature difference could be as high as 7 °C if an individual were at the center of his/her thermal comfort zone. Since Olesen et al.[16] allowed subjects to adjust their clothing conditions to maintain thermal neutrality, it is unknown why their subjects exhibited a low tolerance for thermal stratification. More studies are required to investigate the limit of thermal stratification at different thermal sensations, especially with a large sample size of subjects and in chambers that resemble real office environments.

4.2. Estimating whole body thermal sensation in stratified environments

A major difference between the proposed PPD_{AD} model (Equation 6) and the model of Fanger et al.[6] (Equation 1) is the inclusion of whole body thermal sensation (*TS*) as an input variable. This paper and previous studies[10,23] have shown that *TS* is one of the most important parameters for draft risk assessment. The thermal sensation of an occupant in a uniform environment can be estimated using the PMV method that is described in ANSI/ASHRAE Standard 55[26] and ISO 7730.[19] The PMV model assumes that the whole body is exposed to a homogeneous thermal environment.

In the thermally non-uniform indoor spaces with DV or other stratified airflow systems, feet and lower legs are often exposed to greater cooling effects because of higher air speeds and lower temperatures compared to other body segments. In such conditions, the PMV model may not be accurate. Thermal sensation could be estimated with advanced non-uniform thermal comfort models;[45-48] however, these models are difficult to use in engineering design practice compared to the PMV. Here we argue that it is reasonable to use the PMV model for the estimation of thermal sensation for these reasons: (1) heat loss from the feet and lower legs is only a small fraction of whole-body heat loss; and (2) the greatest variation of airflow characteristics in spaces with stratified systems occurs in areas mainly in the lower 0.15 m of the room.[28]

What follows is an example of the calculated proportion of heat loss from feet and lower legs of an occupant, based on radiant and convective heat transfer coefficients measured by de Dear et al.[49] Given air temperatures (25 °C for the upper body, 20 °C for the lower legs and ankles), air speeds (0.05 m/s for the upper body, 0.2 m/s for the lower legs and ankles), skin temperature (34 °C) and clothing insulation (0.5 clo), the calculated heat loss from the uncovered feet and lower legs (0 clo) only accounts for 12% of the total body heat loss. This fraction decreases to 9% when the lower legs are covered (0.5 clo). As such, the asymmetric environment at the lower body parts has a relatively small influence on whole body thermal sensation. We suggest that the input speed and temperature for the PMV calculation should be the average values at pelvic region (0.6 m) and head level (1.1 m) for sitting, and at 1.1 m and 1.7 m for a standing position. Figure S4 proves that for our experiments, the calculated PMV using the suggested heights is close to the measured thermal sensation and significantly different from the PMV calculated using the three heights specified in ANSI/ASHRAE 55.[26]

4.3. Implications for air diffuser selection

Air diffusers are selected to meet the requirements of thermal comfort and air distribution. The diffuser selection method for overhead air distribution systems utilizes the air diffusion performance index (ADPI).[50,51] ASHRAE Standard 70[52] requires diffuser manufacturers to report the performance (e.g., throw length) of their products in distributing air to maximize thermal comfort and minimize draft risk. However, the standard does not include test guidance for DV and UFAD diffusers and the ADPI does not properly address thermal comfort and draft risk. Skistad et al.[29] defined an adjacent zone in front of a diffuser where high air speed may cause draft. The length of the adjacent zone is typically calculated as the distance from the diffuser to a point where the maximum speed has decreased to a value that could be decided arbitrarily by the manufacturers. According to the reported adjacent zone by manufacturers, a designer would be able to specify diffuser locations to ensure that occupants would be outside the adjacent zone. The typical air speed for defining the adjacent zone is a fixed value of 0.2 m/s.[29] The proposed model is a function also of the thermal sensation or PMV. For PMV = 0, air speed should be < 0.39 m/s and < 0.13 m/s for PPD_{AD}

≤ 20% and PPD_{AD} ≤ 10%, respectively. These air speed limits would result in smaller or larger adjacent zones than the 0.2 m/s value, depending on the target comfort level.

4.4. Limitations

The experiments reported here are based on 110 healthy college students who might have different thermal perception and air movement acceptability from people of other ages. We did not consider the effect of activity level on the perception of draft; all of our subjects were performing light office work while seated. The clothing insulation investigated in this study spanned a narrow range, from 0.3 to 0.7 clo. The difference in clothing insulation for lower leg covered and uncovered was small (0.09 clo). In addition, not all subjects participated in the whole study with all experimental conditions; thus, differences among individual subjects' experiences and expectations could contribute to uncertainty in the results.

We measured the airflow characteristics at the ankle positions at the end of each test day, when sitting subjects were absent. We found that that their presence or absence has a negligible effect on the measurement results. Nevertheless, variations of airflow characteristics and the ventilation systems across each day were not considered.

5. Conclusion

In two phases, we experimentally assessed the factors affecting draft at ankles. Using measured data, we developed a model to predict the percentage of occupants who would be dissatisfied because of ankle draft (PPD_{AD}). The new model can be applied in buildings with stratified systems or with cold-descending airflow along external walls or windows, or in vehicles with conditioned air supplied at the floor level. Two important input variables to the model are whole body thermal sensation and air speed at ankles. The study results show that additional inclusion of air temperature (16.5-22.5 °C), turbulence intensity (5-42%), sex, and clothing insulation (< 0.7 clo) individually or cumulatively in the investigated ranges does not significantly improve the model's prediction accuracy. This model fills an important gap in assessing thermal comfort related to stratified air distribution systems.

We found that vertical thermal stratification has little influence on whole body thermal acceptability. When indoor occupants attain whole body thermal neutrality, they find acceptable thermal stratification producing as much as an 8 °C difference between feet (0.1 m) and head (1.1 m) levels. This finding implies that spaces with high cooling loads can use energy-efficient systems like DV and UFAD without causing thermal discomfort owing to vertical thermal gradients.

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Supporting Information

S1. Thermal sensation

Figure S1(a) shows the boxplots of the whole body thermal sensation at the beginning of the test and at the end (after 20 min). The figure shows that subjects started the test in thermally neutral conditions (median (first, third quartile); thermal sensation = 0.04 (-0.08, 0.59)). According to the research of ASHRAE project 843,[1] one of the major drawbacks of the model of Fanger et al.[2] was that mean thermal sensation of the human subjects in those experiments was cooler than neutral before starting the test. Figure S1(a) also shows that thermal neutrality (thermal sensation = -0.08 (-0.74, 0.27)) was observed at the end of the tests. The neutral thermal sensation allows developing a new draft risk model not biased toward hot nor cold thermal sensation, which is an important factor influencing draft risk.[3]

Figure S1(b) shows that thermal sensations at head and ankles levels are 0.00 (-0.81, 0.34) and -0.65 (-1.18, -0.11), respectively. Among the four body parts, the hands and torso show insignificantly different thermal sensation (*p* = 0.47). The distributions of local thermal sensations are not normal. Whole body thermal sensation is slightly more correlated with thermal sensation at the ankle (Spearman rho = 0.61, $p < 0.001$) than that at the head (Spearman rho = 0.56, $p < 0.001$), supporting the finding that body parts with thermal sensation far from neutrality have a stronger weight on whole body thermal sensation than do those close to neutrality.[4] Neither the thermal sensation at the torso nor at the hands is correlated with whole body thermal sensation.

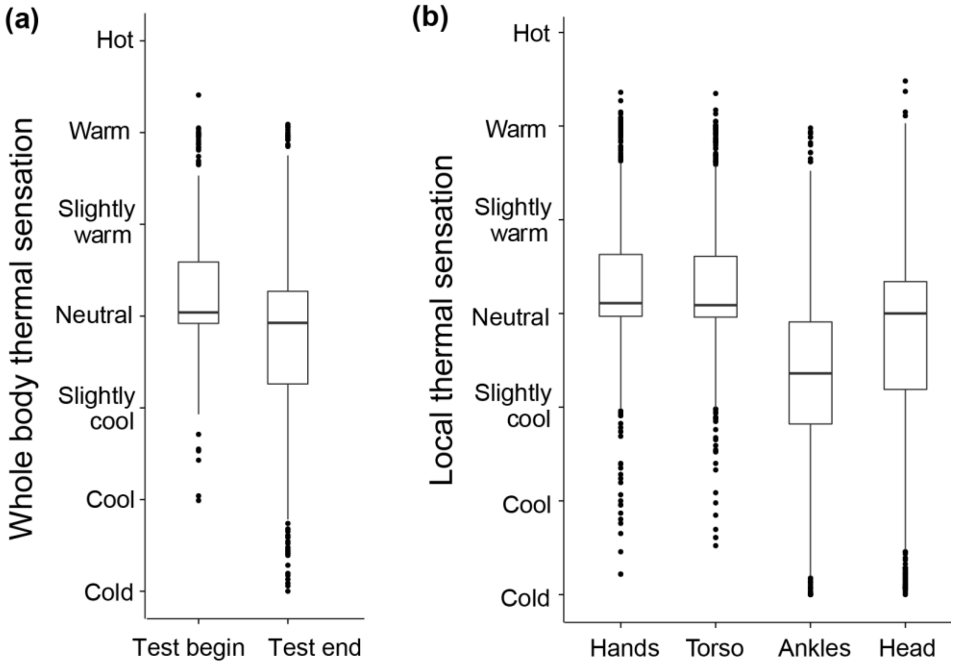

Figure S1. (a) Whole body thermal sensation at the beginning (adaptation) and end of the tests; (b) Local thermal sensation for different body parts at the end of the tests.

S2. Thermal experience and sensitivity on whole body thermal acceptability

Among the 110 subjects participating in this study, 109 and 108 of them answered the questions of “Have you suffered from cold hands or feet during the past two months?” and “How sensitive do you find yourself to indoor thermal conditions (temperature, draft and so forth)?”, respectively. Figure S2 shows the boxplots of whole body thermal acceptability for different categories of thermal experience and sensitivity. The numbers of responses for each category are not equal, as subjects participated in different numbers of tests.

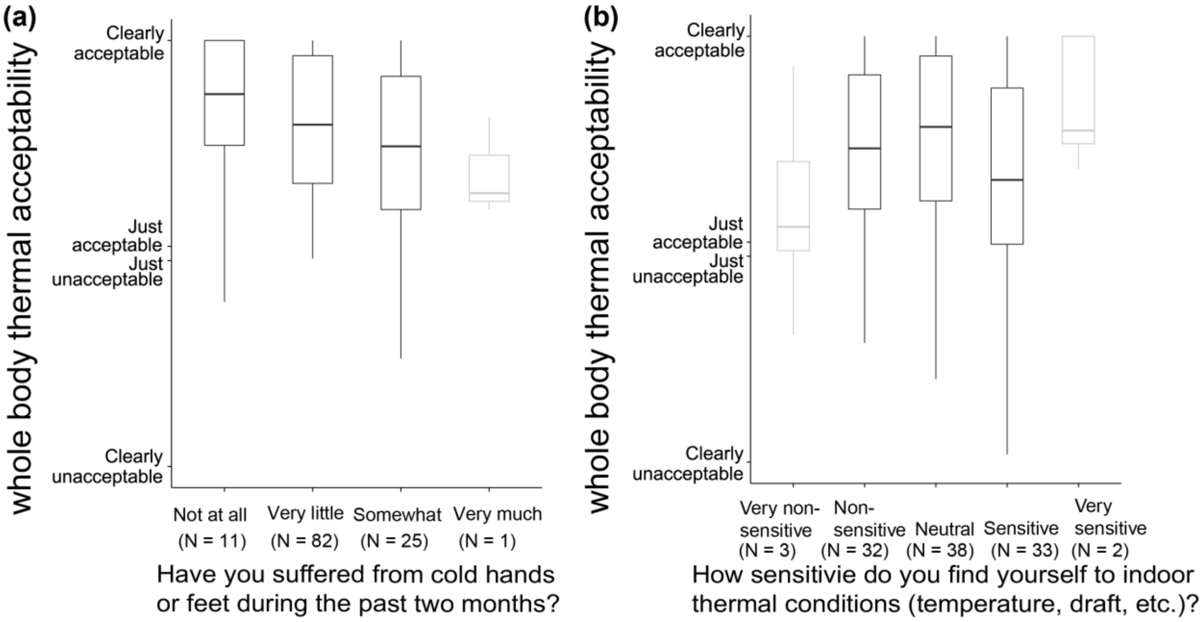

Figure S2. Whole body thermal acceptability for different (a) cold extremity experience and (b) sensitivities; “N” represents the number of subjects.

In the data displayed in Figure S2(a), there was a statistically significant difference (Krushal-Wallis rank sum test, $p < 0.001$) of thermal acceptability among the groups having different thermal experiences in past two months, which suggests that cold extremity experience might affect acceptability of the thermal environment. Specifically, people who did not suffer from cold hands or feet in the past two months reported a higher median thermal acceptability than those with cold extremities experience. However, there is no significant difference ($p = 0.20$, Wilcoxon rank sum test) of the median thermal acceptability found between the groups of “Very little” and “Somewhat” cold experience in the past two months. Figure S2(b) shows the distribution of the thermal acceptability for the subjects with various thermal sensitivities. We did not analyze the groups of “Very non-sensitive” and “Very sensitive” owing to small sample sizes, $N = 3$ and $N = 2$, respectively. The statistical analysis shows that the “Sensitive” group has a significantly lower median thermal acceptability than those of the “Non-sensitive” and “Neutral” groups. The difference of median response between the groups of “Non-sensitive” and “Neutral” is not significant. The findings displayed in Figure S2 imply that both cold extremity experience and sensitivity to indoor thermal environment are related to people’s rating of thermal environments as acceptable.

S3. Ankle air movement acceptability

This section describes a multivariable linear regression for ankle air movement acceptability (*AMA*) varying with airflow characteristics at ankles, whole body thermal sensation (*TS*), sex, and clothing insulation. Equation S1 and Table S1 show the form and summary of the linear regression, respectively.

$$AMA = \alpha + \beta_1 V_{ankle} + \beta_2 t_{a,ankle} + \beta_3 TI_{ankle} + \beta_4 TS + \beta_5 Sex(0\ for\ female, 1\ for\ male) + \beta_6 Clo(0\ for\ lower\ legs\ covered, 1\ for\ lower\ legs\ uncovered) \tag{S1}$$

where *AMA* is air movement acceptability at the ankle; V_{ankle}, $t_{a,ankle}$, and TI_{ankle} are average air speed (m/s) at the ankle, temperature (°C) at the ankle, and turbulence intensity (from 0 to 100) at the ankle, respectively; *TS* is the whole body thermal sensation; and *Sex* and *Clo* represent sex and clothing insulation, respectively.

Table S1. Summary of the linear regression of air movement acceptability described in Equation S1.

Coefficient	α	β_1	β_2	β_3	β_4	β_5	β_6
Value	**1.785**	**-1.828**	0.002	-0.0086	**0.520**	-0.031	**-0.234**
Significance (p)	< **0.01**	**<0.001**	0.94	0.1	< **0.001**	0.77	**0.03**

Note: Numbers in bold indicate statistical significance ($p < 0.05$).

S4. Thermal stratification and whole body thermal acceptability

We present the logistic regression (Equation S2) of predicted percentage dissatisfied for whole body thermal acceptability (PPD_{TA}) as a function of whole body thermal sensation (*TS*), ankle air movement acceptability (*AMA*), and air temperature difference (Δt_a) between the heights of 1.1 m and 0.1 m.

$$\log\left(\frac{PPD_{TA}}{1 - PPD_{TA}}\right) = -3.96 + 0.83\, TS^2 + 0.45\, TS - 0.41\, AMA - 0.0087\, \Delta t_a \tag{S2}$$

S5. Comparing multivariable linear regression with empirical heat transfer model

This section compares the predictions of draft risk based on the measurements of Fanger et al. using two approaches: multivariable linear regression (Equation S3) and curve-fitting an empirical heat-transfer model (Equation 1). Figure S3 presents the combinations of air speeds and temperatures that result in 20% dissatisfied with draft at turbulence intensities of 10%, 20%, and 40%. The percentage dissatisfied with draft using the linear regression are slightly lower in the temperature range from 18 to 22 °C but higher from 22 to 26 °C, compared to those predicted by the model of Fanger et al. The reason might be the relatively small datasets in these two temperature ranges: five data points at both 20 °C and 26 °C compared to 20 points at 23 °C. The mean deviation of predictions using the two approaches shown in Figure S3 is approximately 7%.

$$PD_{Fanger} = -27.7 + 483.1\, V - 14.7\, V \cdot t_a + 0.48\, TI \tag{S3}$$

In Equation S3, PD_{Fanger} is the calculated percentage dissatisfied with draft (%) using the raw data collected by Fanger et al.,[2] *V* is air speed (m/s), t_a is air temperature (°C) and *TI* is turbulence intensity (from 0 to 100). For $V < 0.05$ m/s, use $V = 0.05$ m/s; for $PD_{Fanger} > 100\%$ use $PD_{Fanger} = 100\%$.

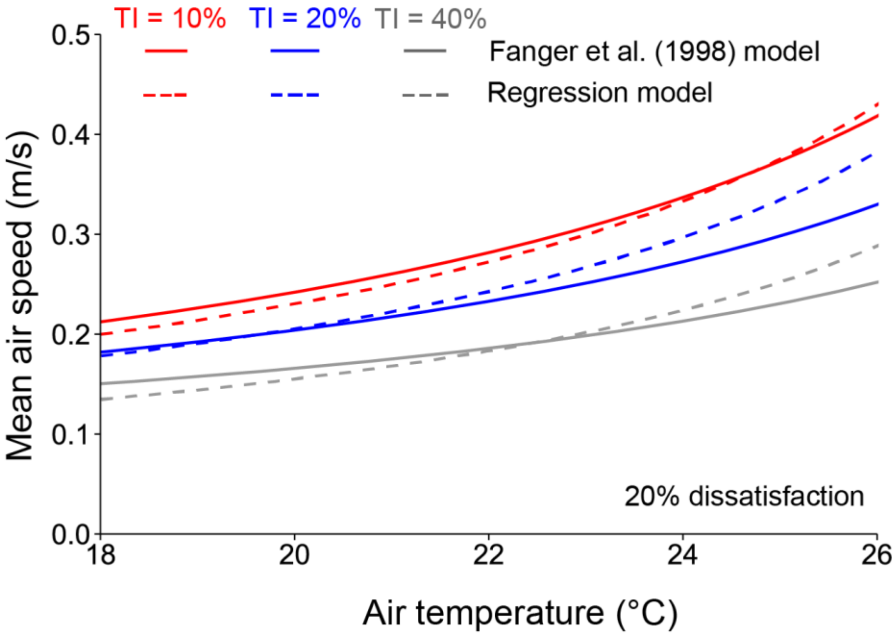

Figure S3. Combinations of air speeds and temperatures predicted by the linear regression (Equation S3) compared to those calculated by the model of Fanger et al. (Equation 1), when considering a fixed percentage dissatisfied with draft (20%).

S6. Estimating whole body thermal sensation in stratified environments

Figure S4 compares measured whole body thermal sensation with predicted mean vote (PMV) values with the air temperatures and speeds averaged based on different numbers of heights. ANSI/ASHRAE Standard 55[5] recommends to use the values at three heights (0.1 m, 0.6 m, and 1.1 m for seated occupants) for the PMV calculation. However, Figure S4 shows that the median calculated PMV value using the three heights has a lower thermal sensation value than reflected in the measurement results. The calculation using environmental conditions only at the upper body (0.6 m and above) renders a more realistic PMV.

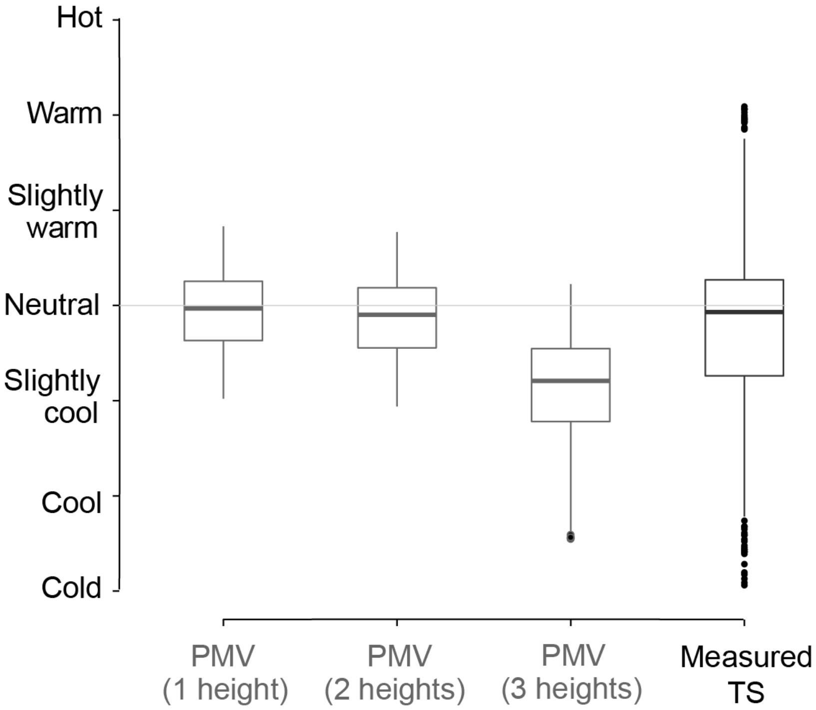

Figure S4. Comparison of tested whole body thermal sensation with the calculated PMV values (for a seated person) based on different input air speeds and temperatures. “1 height” denotes that the input air speed and temperature for PMV calculation are measured at one height of 1.1 m above the floor; “2 heights” represents that the input values are averaged at two heights of 1.1 m and 0.6 m; “3 heights” means that the input values are averaged at three heights: 0.1 m, 0.6 m, and 1.1 m. The predictions assume that mean radiant temperature = air temperature; relative humidity = 45%; metabolic rate = 1.1 met; clothing insulation = 0.55 clo.

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