Sensation of draft at uncovered ankles for women exposed to displacement ventilation and underfloor air distribution systems

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ABSTRACT

Draft is defined as unwanted local convective cooling. Existing draft risk models, developed in the 1970s, focus on air movement at the neck. The purpose of the present study is to experimentally evaluate ankle draft risk for women with uncovered ankles because of current widespread use of displacement ventilation and underfloor air distribution systems and changes in dress customs. Thirty female university students participated in nine double-blind randomized tests. The subjects wore sandals with lower legs, ankles and feet uncovered. Exposures occurred in an environmental chamber resembling an office environment. The operative temperature at 1.1 m above the floor was maintained at 24.1 ºC. The measured air speeds at the ankle varied between 0.16 and 0.59 m/s and the air temperature at the ankle varied between 18.0 and 21.7 °C. Subjective responses were obtained to assess these parameters: thermal acceptability, comfort, preference and sensation, air movement acceptability and preference, local thermal sensation and comfort, and perceived air quality. Subjects were more sensitive to ankle draft than expected. For all the tested conditions, between 20 and 37% of the subjects found the overall thermal environment not acceptable, while between 23 and 57% of the subjects found air movement at the ankle unacceptable. These dissatisfaction percentages are higher than those of international, American and European standards, indicating the need to develop a draft risk model for displacement ventilation and underfloor air distribution systems.

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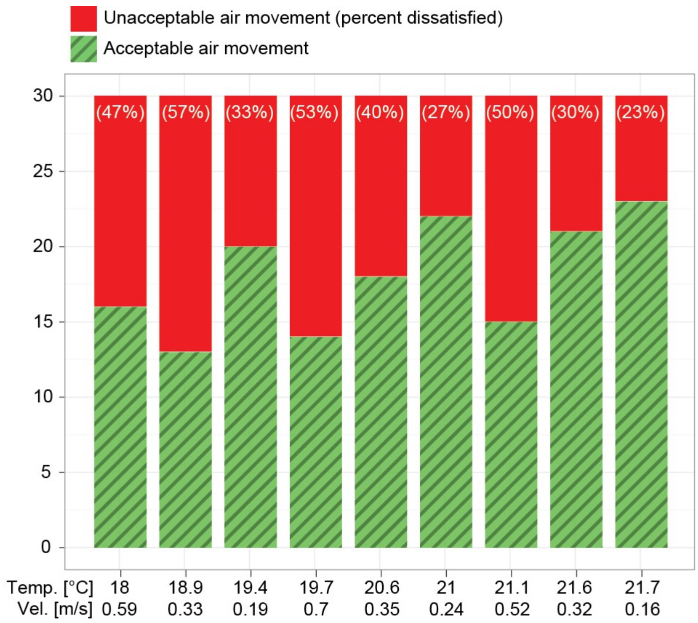
GRAPHICAL ABSTRACT

Female with uncovered lower legs, ankle and feet



KEYWORDS

Thermal comfort; Air movement; Draught (draft); Displacement ventilation; Underfloor air distribution (UFAD).

1. INTRODUCTION

Draft is defined as unwanted local convective cooling of the body caused by air movement [1]. McIntyre [2] gave a broader definition of draft, describing it as an unwanted local cooling of the body. However, this broader definition, including also the effect of radiant heat transfer, has never been adopted in thermal comfort standards.

The main factors that affect draft are air temperature and air speed [1,3,4], air turbulence [5,6], metabolic rate [7,8], body parts exposed and their clothing insulation level, and overall thermal comfort and sensation [9,4,10–12]. The characteristics of air velocity fluctuation (e.g. turbulence, spectral frequency, etc.) are also factors that may affect draft [13,14].

International [15] and European [16] thermal comfort standards specify permissible air speeds as a function of air temperature and turbulence intensity to avoid more than a certain percentage of persons dissatisfied owing to draft. The draft-risk criterion is based on the model developed by Fanger et al. [6], focusing on draft perceived at the rear neck. Fanger's draft-risk model was included in prior versions of ASHRAE Standard 55 [17], but has been absent since the 2010 release because it overestimates the percentage of unsatisfied people. Toftum et al. [11], based on human-subject tests, showed that there is a discrepancy between the percentage of subjects who were dissatisfied owing to draft and the number estimated by the model. This difference was most likely caused by lower-than-neutral thermal sensation of subjects during the original draft-risk tests conducted by Fanger. McIntyre [9] showed, based on human subject tests in a laboratory, that draft is linked to person's pre-existing feeling of warmth or cold. Air movement in air-conditioned and naturally ventilated spaces assumes a different connotation depending on a subject's thermal sensation. The same breeze that provides relief for subjects feeling warm can be perceived as a draft for those who feel cool.

Toftum [12] has described this dualistic aspect of air movement and its underlying causes.

According to the experiments performed by Fanger [18] subjects were found to be significantly less draft-sensitive on their unclothed ankles than on the neck. No difference was found between the draft sensitivity of men and women. Historically, the literature on draft focused on thermal discomfort at the neck, in part because most mechanical systems supplied air from ceiling diffusers. In modern buildings, however, it is less appropriate to characterize draft risk only at the neck level. The advent of alternative air distribution systems, such as underfloor air distribution (UFAD) and displacement ventilation (DV), and the possibility of downdraft generated by large glass façades when outdoor temperatures are low makes it necessary also to investigate the draft effect for other body parts, such as ankles [19–21].

A field survey of 227 occupants' response to the indoor environment in ten Danish office buildings with displacement ventilation showed that 24% complained that they were daily bothered by draft, mainly at the lower leg [22]. A study with smaller sample size (33 occupants) in a Canadian office building conditioned with a UFAD system did not show issues related to draft at the ankles [23]. Draft risk at the ankle was also not found in a lab study utilizing 33 human subjects considering UFAD systems in which air speeds at the feet area were kept below 0.1 m/s [24].

In 1938, Houghten et al. found that equal declines in skin temperature at the neck and at the ankles produced equal discomfort sensations [3]. However, since the subjects were wearing trousers, socks and shoes, the air temperature at the ankle level had to be lower and the air velocity higher than at the neck level to obtain the same reduction in skin temperature. Nowadays, owing to the widespread use of UFAD systems and also to shifts in common dress codes that allow for uncovered ankles in offices, a new need has emerged for an assessment of draft risk at the ankles [25–28].

There are few scientific data available on the optimal operating conditions (air speed and temperature) for design of displacement ventilation and underfloor air distribution systems. The REHVA guidebook on displacement ventilation recommends keeping people outside the area near a diffuser in which the air speed is higher than 0.15 m/s in winter and 0.25 m/s in summer [20]. In this document, guidance is lacking about discharge temperatures or about the fact that people might have either covered or uncovered lower legs. In the study reported herein, we want to focus on conditions with high draft risk, i.e., for women with uncovered lower legs, ankles and feet. It is established that females are more likely than males to express thermal dissatisfaction, especially in cooler conditions [29], and that they are more likely to dress with slightly less thermal insulation than males during summer [30], including the common practice of having their lower legs uncovered.

The purpose of the present study is to experimentally evaluate ankle draft risk for women with uncovered ankles as would be associated with displacement ventilation and underfloor air distribution.

2. METHODS

2.1 Experimental facilities

The experiments were carried out at the environmental chamber at the Center for the Built Environment (CBE), University of California Berkeley.

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2.1.1 Climatic chamber

The CBE climate chamber (Figure 1A) measures 5.5 m × 5.5 m × 2.5 m, and features controlled air temperature to an accuracy of ±0.5 °C and controlled relative humidity to ±3%. The chamber is described in detail by Arens et al. [31]. The chamber is configured to appear as a realistic office, so as to attenuate the psychological influence of being a human subject in a laboratory experiment. The chamber has windows on two sides, which face south and west. The windows are well shaded by fixed external shades. The surface temperature of the windows is controlled by a dedicated air supply system. The temperature of the inner glass pane is controllable and was kept isothermal with the bulk interior air temperature throughout the experiments.

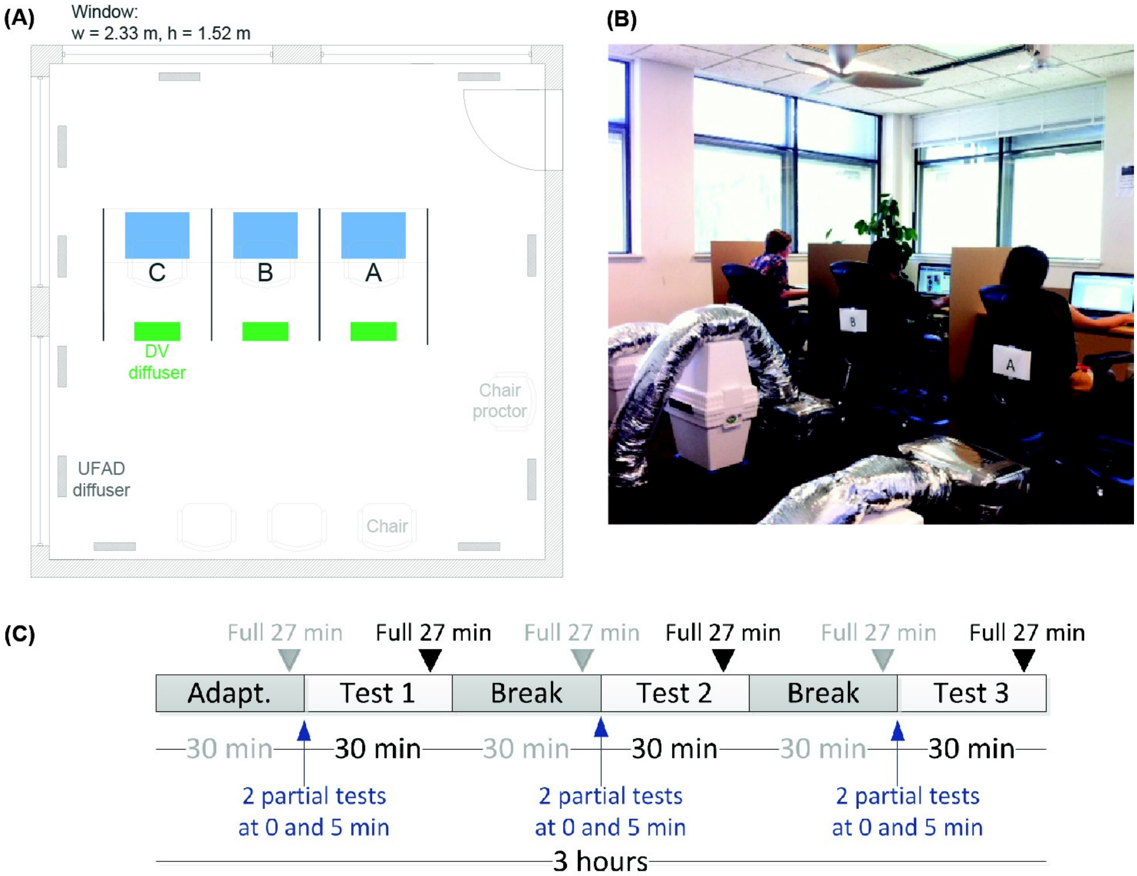

Figure 1. Climatic chamber: a) layout of the test chamber; b) photo of the room arrangement; c) test schedule. Full and partial surveys have been used.

Figure 1 shows the experimental configuration. The chamber simulated a typical open plan office. Three workstations (WS) were arrayed so that three subjects could be tested simultaneously. Each workstation was equipped with a displacement diffuser, a laptop computer and an office chair. Mesh office chairs were used, with a measured clothing insulation of 0.02 clo.

2.1.2 Air distribution system

Diffuser: A displacement diffuser unit (0.51 m by 0.20 m) was built using two layers white painted perforated metal panels and plywood. The perforated face of the diffuser was painted white to mimic commercially available displacement diffusers. To obtain a homogeneous air velocity at the face of the diffuser, two different styles of perforated panels were used. The distance between the panels was 30 mm. The panel facing the outside had a free area of 20%. The panel facing the inside of the diffuser had a free area of 13%. The diffuser was positioned at a minimum distance of 0.7 m away from the legs of the subjects. An air damper regulated the flow and the air speed at more than five duct diameters from the inlet of the diffuser. The average turbulence intensity due to the tested diffusers within the foot placement area was 30% (SD = 5.4%).

Air was brought to the three tested diffusers from an independent air-handling unit through an insulated duct. The difference between the air temperatures coming out from the three diffusers was less than 0.2 °C. The diffusers were located behind the chair and therefore the airflow came from behind the subjects.

Overall system: An underfloor air system was employed to bring conditioned air into the space so as to maintain the desired room temperature at head height. Ten linear diffusers were used (0.46 m by 0.09 m). The incoming air speed was less than 0.3 m/s at 0.1 m above the diffuser. The diffusers were situated far from the desk and close to the wall perimeter where the subjects rested during breaks. The air was exhausted through a 0.61 x 0.61 m ceiling return grill. The outdoor flow rate in this study was higher than 105 L/s. Since the maximum number of occupants was seven (six subjects and one experimenter), the minimum outdoor air supply

2.1.3 Measuring instruments and measurement uncertainty

Air temperature was measured at 0.1 and 1.1 m at less than 0.5 m away from each person at each of the three workstations. The air temperatures were monitored continuously with thermistors (TMC1-HD connected to HOBO U12-013, Onset Computer Corporation, MA, USA). All the sensors were shielded against radiant heat transfer with an aluminized Mylar cylinder. The sensors were calibrated prior to the measurements (Fluke 9102S dry-well calibrator, WA, USA). The obtained accuracy was ±0.2 °C or better. Floor temperature was not measured.

A multichannel low velocity thermal anemometer with omnidirectional velocity transducers (Sensor HT-400, Poland) was used to perform mean air speed, turbulence intensity and air temperature measurements at 0.1 m height, corresponding to where the ankles were located during the tests. The characteristics of the anemometer comply with the requirements for such instruments specified in appropriate standards [32,33]. The air speed was measured at 0.1 m, because that is the standard height specified in American, European and international standards; also, field measurements showed that it tends to be the height with the highest speed [34]. The accuracy of the hot wire anemometer was 0.02 m/s ± 1% of the readings for an air speed range between 0.05 and 1 m/s, and an accuracy of ±3% of the readings for an air speed range between 1 and 5 m/s.

2.2 Experimental conditions

The room was maintained at a relative humidity of 50%. The air temperature was kept at 24 °C (close to thermal neutrality, according to zero PMV for relative humidity = 50%, air speed = 0.15 m/s, clothing insulation = 0.75 clo, and metabolic activity = 1.2 met). In the chamber, the air temperature is equal to the mean radiant temperature owing to the high insulation and control of the surface temperature of the windows. The order of tests was randomized.

Three supply air temperatures were tested. The respective set-point temperatures were 15, 17.5 and 19.5 °C. Target air speeds and temperatures were

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selected based on laboratory measurements [35], field measurements [22] and interviews with manufacturers and HVAC designers. Even if the air temperature at the diffuser were equal, by the time that the air reached the target zone where the feet were located, the temperatures were higher than at the diffuser and different from each other. These differences were due to the different amount of air entrainment caused by the different air speeds. The obtained experimental conditions are summarized in Table 1.

Table 1. Test conditions

Supply air temperature set point (°C)[a]		Measured air temperature (°C)[b]	Measured air speed (m/s)[b]	Measured turbulence intensity (%)[b]
15	High	18.0	0.59	31
15	Medium	18.9	0.33	26
15	Low	19.4	0.19	42
17.5	High	19.7	0.70	35
17.5	Medium	20.6	0.35	25
17.5	Low	21.0	0.24	26
19	High	21.1	0.52	26
19	Medium	21.6	0.32	25
19	Low	21.7	0.16	33

[a] Set at the diffuser.
[b] The air temperature, speed and turbulence intensity were measured at 0.1 m height at six locations within the target zone (blue area in Figure 1A) under the desk. Subjects were asked to keep their feet within this area throughout the exposure period.

2.3 Experimental procedure

The duration of each test was three hours. The schedule of activities during testing is shown in Error: Reference source not foundC. We asked subjects to avoid exercise for one hour before arriving to the test chamber. At the beginning of each test, the subjects sat for 30 minutes in a mesh chair to let their body to adapt to thermal condition of the chamber. After this preconditioning period, subjects were asked to sit in succession on each of the three chairs under the influence of a diffuser for 30 minutes and then rest outside the influence of the jet for 30 minutes. During the three-hour session, each subject sat for 30 minutes at each of the three desks (with corresponding exposure to different air speed and temperature).

The testing duratinos were determined based on dynamic evolution of thermal sensation and human skin temperature reported in previous studies [36,37]. Subjects were allowed to adjust their clothing to maintain thermal neutrality of their whole body during the session, but they were not allowed to change their clothing on the lower part of the body. The break of 30 minutes after each exposure was designed to allow subjects to return to overall and local thermal neutrality before the next exposure.

We monitored and corrected if necessary the subjects' sitting posture during the experiment to maintain feet on the floor and to keep the ankles situated in the designated zone where the air speed and temperature were measured. Two pilot tests were conducted to verify that the diffusers, the HVAC systems and the survey worked as expected.

Overall, the experiment was designed to be double-blind. The human subjects and the proctor were not aware of the temperature or air speed being tested. One of the authors was present in the room during the tests, but was not aware of the temperature being tested.

2.4 Subjects

Thirty female subjects participated in the tests (see Error: Reference source not found for the subjects' anthropometric data). Only female subjects were selected because, according to meta-analysis by Karjalainen [29], females are more likely than males to express thermal dissatisfaction (odds ratio: 1.74, 95% confidence interval: 1.61–1.89). The study results suggested that females should primarily be used as subjects when examining indoor thermal comfort requirements, because if females are satisfied it is highly probable that males also will be satisfied. Similar conclusions were obtained by Kim et al. [38].

The subjects were instructed to dress in typical summer office clothes (roughly 0.6 clo). The subjects had bare lower legs. They wore sandals ("flip-flop" style) and no socks. The subjects were allowed to lean forward or backward as in real offices, but were not permitted to stand up or to move around during the tests. The subjects were allowed to move their legs within a marked area of 0.71 x 0.51 m and have a comfortable posture while seated while feet were maintained flat on the floor. During the tests, subjects read or typed at the computer (producing an expected energy dissipation rate of 1.1-1.2 met). Subjects self-reported that they were in good health. Good health was not defined and it was not independently verified. Indeed, as described below, four subjects self reported that they suffered very much from cold hands and feet. All the subjects were volunteers and were paid for taking part in the experiments. Subjects gave informed written consent and UC Berkeley Committee for Protection of Human Subjects approved (CPHS #2010-04-1312) the research protocol.

Before the test we asked: "Have you suffered from cold hands or feet during the past two months?" The subjects could answer 1-"not at all"; 2-"very little"; 3-"somewhat"; and 4-"very much". We used this question to test whether the subject might be affected by any of a variety of syndromes that cause cold extremities (e.g., primary vascular dysregulation) [39]. Nine of the subjects (30%) reported "not at all", 9 (30%) subjected reported "very little", 8 (27%) subjects reported "somewhat" and 4 (13%) subjects reported "very much".

Table 2. Anthropometric subjects data for the 30 female subjectsII[b]

Age (years)	(m)	(kg)	(kg/m^2)
24.1 ± 6.8[a]	1.62 ± 0.07	55.8 ± 6.5	21.2 ± 2.2

[a] Standard deviation.

[b] Body Mass Index = weight (kg)/[height (m)]^2.

Prior to participating in the tests all subjects attended a training session to become familiarized with the chamber, the test procedure and the survey questions. The subjects were instructed to eat normally before arrival at the lab and to have had enough sleep. Drugs and alcohol use were not allowed during the 24 hours prior to the experiment.

2.5 Questionnaire

The full survey questionnaire comprises six parts: (1) Overall thermal acceptability [clearly acceptable, just acceptable, just unacceptable, clearly unacceptable]; (2) Thermal comfort [very comfortable, comfortable, just comfortable, just uncomfortable, uncomfortable, very uncomfortable], thermal preference [warmer, no change, cooler], and thermal sensation, using a 7-point ASHRAE scale [32]; (3) Air movement acceptability at the ankles [clearly acceptable; just acceptable; just unacceptable; clearly unacceptable], and thermal preference at the ankles [warmer, no change, cooler]; (4) Thermal sensation for each of the following body parts: hands, torso, ankles and feet; (5) Air movement acceptability for each of the following body parts: hands, torso, ankles and feet; and (6) Air quality acceptability. The full questionnaire is shown in the on line supporting information.

The ASHRAE seven-point scale varies between cold and hot, as follows: cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (1), warm (2), hot (3). For this scale, subjects record their condition on a continuous scale. For acceptability, the subject marked their response on a continuous scale from clearly acceptable (+1) to just acceptable (+0.1) and from just unacceptable (-0.1) to clearly unacceptable (-1). In this scale, subjects are compelled to distinguish clearly between acceptable and unacceptable. A subject was considered to be dissatisfied because of draft when she reported uncomfortable air movement. The subjects assessed perceived air quality on the same acceptability scale. A subject was deemed to be dissatisfied with the air quality if she assessed the air quality as unacceptable.

The survey questions automatically appeared on the subjects' computer screen according to a preset schedule while they were doing their own tasks on the same computer. Two types of survey were given at the times described in Figure 1C, a complete one and a partial one that included only questions for the first four parts.

2.6 Statistical methods

The data distributions are reported as frequency box-plots. In a box-plot the thick horizontal line represents the median (M). The bottom and top of the box show the 25th and 75th percentiles, respectively. The vertical lines joined to the box shows the smaller of the maximum or 1.5 times the interquartile range of the data. Points beyond those lines are plotted as circles; they may be considered as outliers. Summary data are reported as median with 25th and 75th percentiles in parenthesis (e.g. 0.02 (-0.59,0.54)).

Whether the data were normally distributed was tested with the Shapiro-Wilk normality test [40]. Differences among non-normally distributed data were assessed with the paired Wilcoxon signed rank test [41]. Correlations between variables were reported on the basis of Spearman's rank coefficient if the variables were not normally distributed and with the Pearson correlation coefficient if the variables were normally distributed. For normally distributed data, the paired t-test and ANOVA were used. For non-normally distributed data, the Mann-Whitney U-test and Kruskal-Wallis test were used. Effect size for binary variables was calculated with the mean square contingency coefficient [42,43]. For all tests, the results were considered statistically significant when $p < 0.05$. The statistical analysis was carried out using R software version 2.15.1 [44]

3. RESULTS

The average operative temperature in the room core, measured at a height of 1.1 m was very stable during the experiment, equal to 24.1 °C (SD = 0.2 °C). The temperature at the ankle was different at each workstation and was a function of the supply air temperature and speed.

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3.1 Thermal sensation

Error: Reference source not foundA displays a boxplot of overall thermal sensation (TS) for all of the experiments as a function of time at which the question was asked. From the figure, it can be deduced that subjects were able to start the experiment in neutral conditions (median (first, third quartile)) TS = 0.02 (-0.59,0.54)). This evidence substantiates the expectation that the 30-minute acclimatization time before each test was sufficient to obtain neutral conditions. Furthermore, this finding resolves one of the main limitations of prior experiments that led to the development of the draft risk model [11], i.e. having subjects who were cool or cold before starting the test. Error: Reference source not foundA also demonstrates that exposure to the airflow on bare lower legs and ankles reduced the overall thermal sensation and that steady-state conditions were reached quickly, even within 5 minutes. Therefore, in the future, it would be possible to use a shorter exposure time to reduce experimental costs.

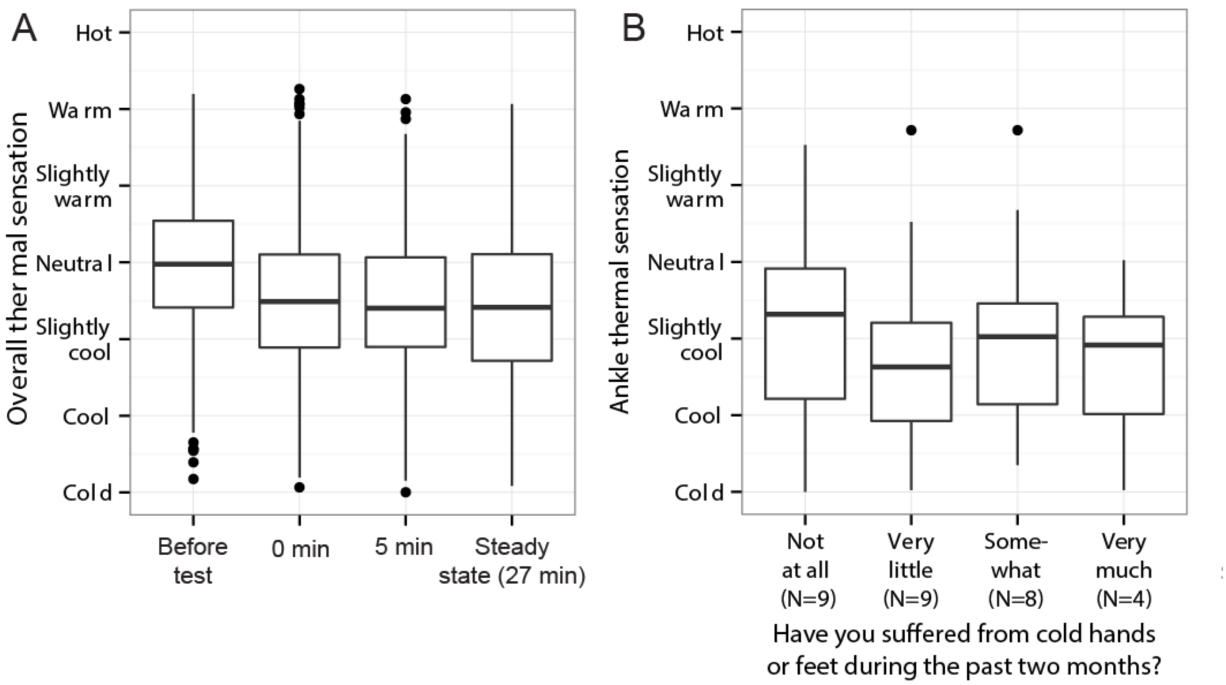

Figure 2. (A) Overall thermal sensation for all experiments: before starting the test, just after exposure, 5 minutes after exposure and at steady-state (27 minutes after exposure). (B) Ankle thermal sensation as a function of how subjects answered this question: “Have you suffered from cold hands or feet during the past two months?

3.1.1 Local thermal sensation

The local thermal sensation votes at the hand, torso, ankle and feet were not normally distributed (W = 0.98, $p < 0.001$). Local thermal sensation at the hand and torso were not statistically different ($p = 0.49$) and, likewise, local thermal sensation at the feet and ankle were not statistically different ($p = 0.21$). Consequently, only information about local thermal sensation at the hand and ankle are reported here. Hereafter are reported values obtained in steady state and for all the experiments. Hand thermal sensation is neutral (M = 0.15 (-0.04, 0.93)) and higher than ankle thermal sensation (slightly cool; M = -1.09 (-1.92, -0.56)). Hand and ankle thermal sensation are correlated (Spearman rho = 0.48, $p < 0.001$). The thermal sensation at the ankle is correlated to the overall thermal sensation (Spearman rho = 0.70, $p < 0.001$) more so than is the thermal sensation at the hand (Spearman rho = 0.59, $p < 0.001$). This evidence supports the idea that body parts that are far from neutrality have a stronger weight on overall thermal sensation than body parts for which the thermal sensation is near neutral [37].

3.1.2 Ankle thermal sensation and cold extremities syndrome

Error: Reference source not foundB shows the relationship between the ankle thermal sensation and the answer to the question: "Have you suffered from cold hands or feet during the past two months?" The answer to the question correlates significantly with ankle thermal sensation ($p < 0.002$ – Kruskal-Wallis rank sum test). People that do not suffer from cold hands and feet perceived the space significantly warmer than people who suffer very little ($p < 0.001$ – Wilcoxon rank sum test) and very much ($p < 0.025$). However, the "not at all" and "somewhat" responses are not statistically different ($p = 0.21$), which might be a consequence of the small sample size of each group.

3.2 Thermal acceptability

Error: Reference source not found displays the overall thermal acceptability of the environment in steady state conditions as evaluated by subjects at the end of each test. Across each of the nine test conditions, 20-37% of the subjects found the thermal environment to be not acceptable. For example, with an air temperature at the ankles of 21.7 °C and an air speed of 0.16 m/s and with air temperature at the head of 24.1 °C, 6 out of 30 subjects (20%) were dissatisfied. Before the beginning of the test, 91% of the subjects found the overall thermal environment acceptable. For each case considered separately, overall acceptability at the start of each test varied between 87 and 97%.

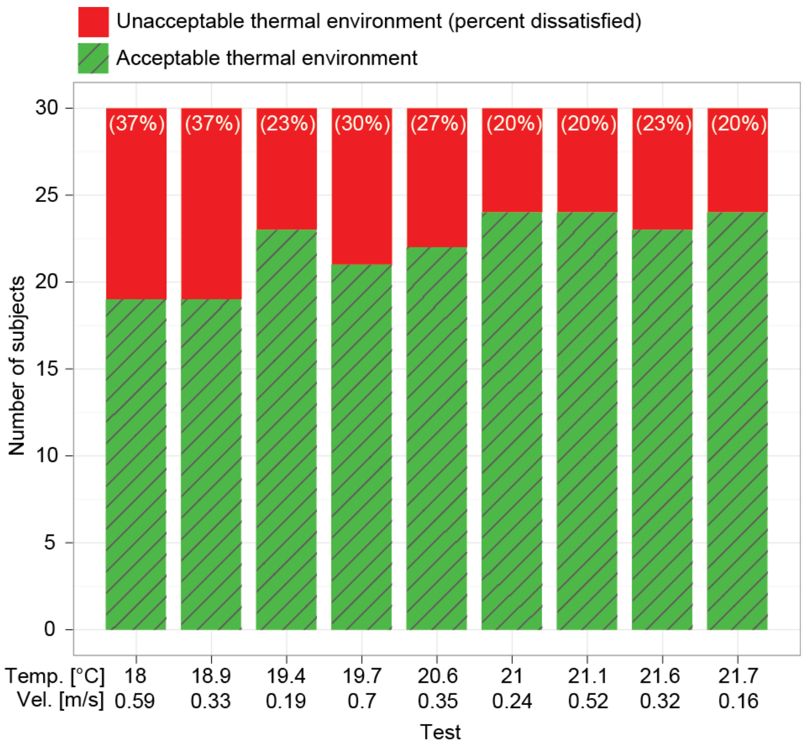

Figure 3. Overall thermal acceptability of the environment for the nine tests. Tests are identified with the dry-bulb air temperature and air velocity at the ankles.

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At the end of the questionnaire, we also asked the subjects the following hypothetical question, using the acceptability scale for their responses: “If the current thermal environment were the one at your daily desk, how would you rate it?” We compared these answers with those for overall “real“ thermal acceptability. The hypothetical acceptability answers were slightly lower than the real ones. Although the difference was statistically significantly (p <0.001), the effect size is small (median difference 0.10 in a scale from -1 to 1, i.e. a 5% difference). This finding means that the subjects do not distinguish substantially between what they determine to be acceptable or unacceptable in the lab and what they “predict” would be acceptable or unacceptable in a real environment. We caution that this evidence does not imply that subjects would actually give the same answer if tested in a real environment. However, it does suggest that they found the lab setting sufficiently similar to their expectations for an office environment to add confidence that these experiments are informative regarding real office conditions.

Zhang and Zhao [45] concluded that under uniform and non-uniform thermal conditions, thermal acceptability and thermal comfort are closely correlated. We also found that the answers to the two questions were highly correlated (Pearson correlation coefficient = 0.94, p < 0.001). Therefore, the results for thermal comfort are not separately reported here and, one can conclude, it is not necessary to ask both questions. Owing to the fact that thermal comfort standards are based on thermal acceptability, we may conclude that only the questions about thermal acceptability are needed in future studies of this type.

3.3 Ankle air movement acceptability

Air movement acceptability is the key parameter for this research. Draft risk assessment and models are based on it. The air movement acceptability answers are not normally distributed (W = 0.97, p < 0.001); however, the deviation from normality is not strong. In all, only 60% of the subject responses (N = 162 out of 270 answers) indicated that the air movement at the ankle level was acceptable (M = 0.1 (-0.15,0.39)). Error: Reference source not foundA depicts the proportions of subjects that rated, at the end of each test and for each of the nine tests, the ankle air movement as acceptable or unacceptable. Across the test conditions, 23 to 57% of the subjects found the ankle air movement to be unacceptable.

Error: Reference source not foundB shows the number of subjects who expressed a preference to have less air movement at the ankle, no change or more air movement. Clearly the majority wanted less air movement, and, even for people who rated the air movement to be acceptable, they might still prefer to have less air movement. Almost no one expressed a desire for more air movement. Acceptability of air movement is higher when a subject expressed the preference of having no change in air movement.

We also analyzed overall thermal preference (do you prefer to be warmer, no change or cooler). Thermal preference and local air movement preference are significantly correlated (χ^2 (4, N = 270) = 99.3, p < 0.001)). The cooler the people feel, the less air movement they want. The effect size (ϕ - phi coefficient, also known as the mean square contingency coefficient) is 0.6, proving a strong association between the two variables.

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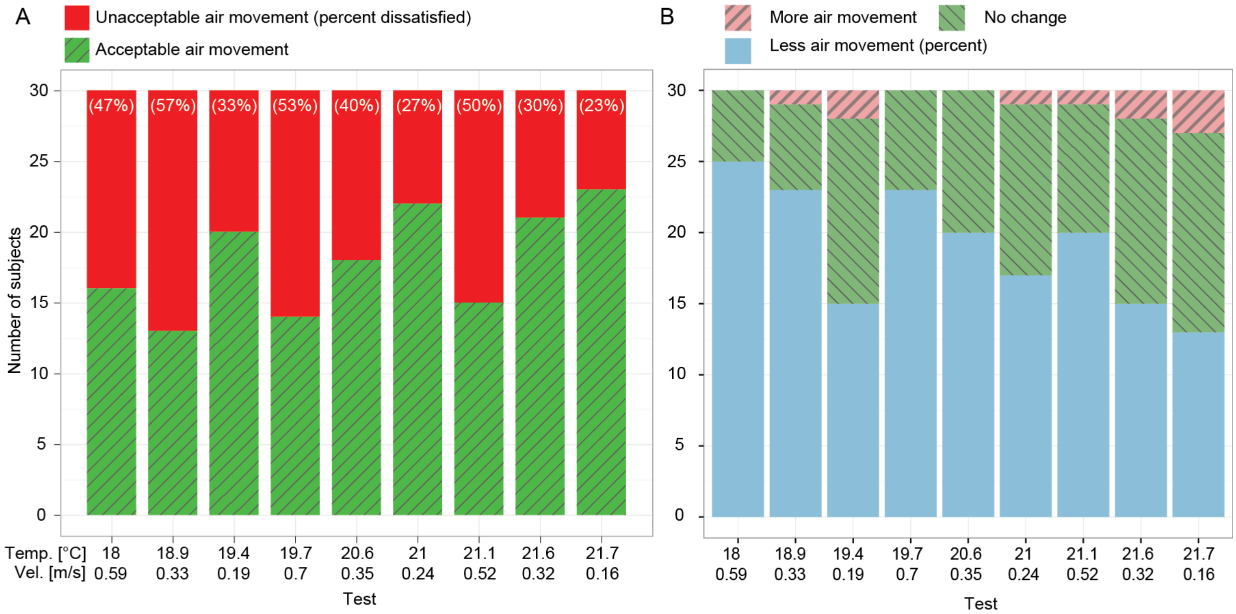

Figure 4. (A) Ankle air movement acceptability and (B) Air movement preference for the nine tests. Tests are identified with the dry-bulb air temperature and air velocity at the ankles. Error: Reference source not found presents the relationships between the ankle air movement acceptability and (a) the dry-bulb temperature at the ankles and (b) the air speed at the ankles. In this figure are also displayed the local regressions (Loess curves) and the 95% confidence intervals. The shade of the point provides information about air speed and temperature: darker shades correspond to higher air speeds and lower temperatures.

Figure 5 shows that, for the same experimental conditions (equally colored dots plotted vertically for a given temperature), the human subject acceptability widely varies between clearly unacceptable and acceptable. This type of outcome is commonly reported in human subject thermal comfort experiments and it underlines the large variation in human thermal perception [46]. Personal control of the thermal environment can, in principle, address this large difference. A key consequence of such variation for prediction is a relatively large confidence interval. A second feature of the data is that lower temperature and higher air speed tend to reduce the frequency at which ankle air movement is rated as acceptable. Figure 5 decomposes the effect of the dry-bulb temperature and air speed.

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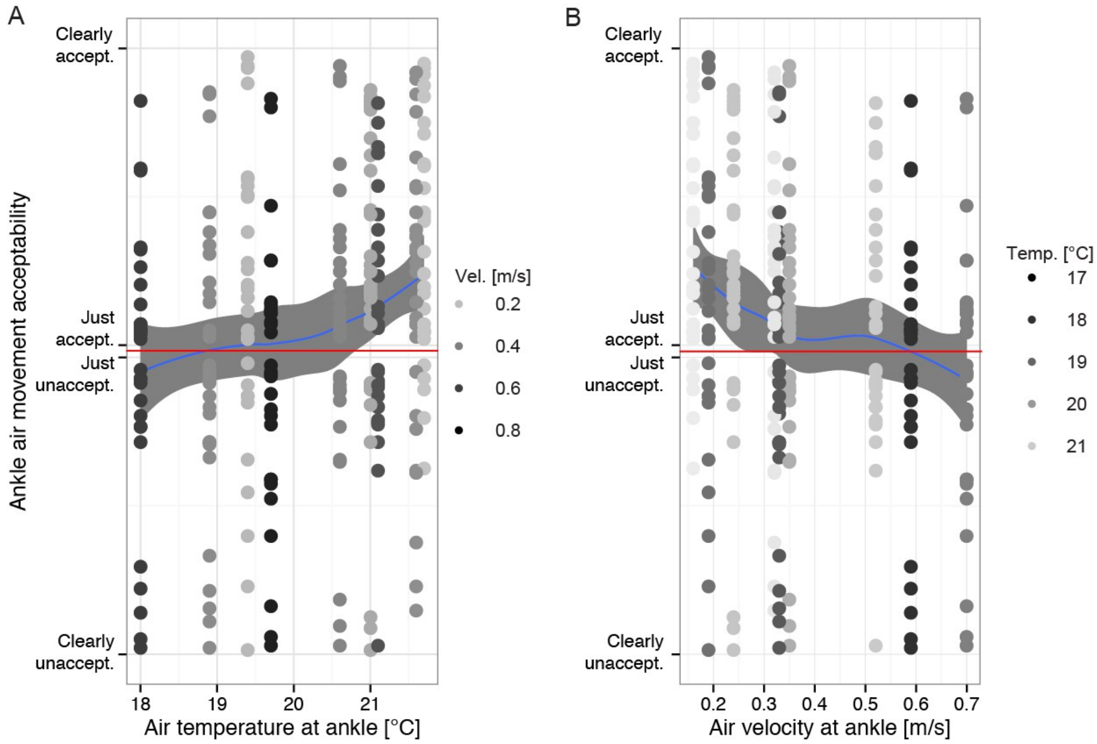

Figure 5. Air movement acceptability as a function of (A) the air temperature at the ankle and (B) air speed at the ankles. LOESS regressions and 95% confidence intervals for the mean response are also indicated. The darkness of the data points indicate (A) air speed at the ankles and (B) dry-bulb air temperature at the ankles.

3.4 Indoor air quality acceptability

Perceived indoor air quality was tested with this question: "Rate your acceptance of current air quality." The results were not normally distributed (W = 0.96, p < 0.001). Overall, 90% of the subjects found the air quality to be acceptable (M = 0.43 (0.17, 0.71)). The question was asked at the beginning and at the end of each test. The results show that the perceived acceptability of air quality diminished slightly across the experiment (p < 0.001, median reduced from 0.52 to 0.43, equivalent to a reduction of 1.5%). Error: Reference source not found displays the overall subject rating of air quality acceptability at the end of each of the nine tests. As expected, indoor air quality acceptability was not affected by the changes in air temperature and air speed at ankle height (Kruskal-Wallis chi-squared = 1.3, df = 8, p > 0.05). Air temperature and air speed at breathing height did not significantly change during the experiments.

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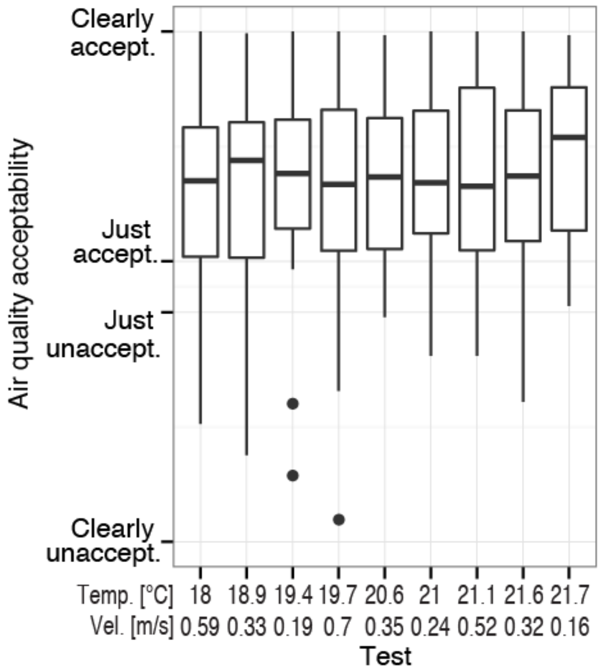

Figure 6. Indoor air quality acceptability ratings for the nine tests.

4. DISCUSSION

4.1 Thermal acceptability

Across the nine tested conditions, 20-37% of the subjects found the overall thermal environment to be not acceptable. The maximum percentage of dissatisfied people in international and European standards is 15% or less, depending on the indoor environmental category selected [15,16]. In the American standard, the percentage of those dissatisfied should be less than 20% [32]. Hence, the values obtained in these experiments are above the maximum limits proposed in these standards. In one case out of nine, the more lenient limit is just barely violated. However, it should be noted that those limits are given for a general population (e.g., considering both men and women). It is possible that the tested conditions would create a lower percentage of dissatisfied occupants in an environment with both male and female subjects and with some occupants having the lower leg covered. Nevertheless, even with an air temperature at the ankles of 21.7 °C and a moderate air speed of 0.16 m/s, 6 of 30 subjects (20%) expressed dissatisfaction with the overall thermal environment. For air distribution at the floor level, we suggest building HVAC designers and building managers to provide temperatures at the head and at the ankles higher than 24.1 °C and 21.7 °C, respectively, if women with uncovered legs are expected to be in the space. Air speed at the ankle should be less than 0.16 m/s. These suggestions are stricter than those given in existing guidelines [20].

The results show some potential for energy saving measures. When cooling is needed, increasing the temperature set point at the head level may have simultaneously energy and thermal comfort benefits. However, with available knowledge we cannot give a more complete and certain recommendation for floor-level air supply systems.

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4.2 Ankle air movement acceptability

Across the nine tested conditions, 23-57% of the subjects found the ankle air movement to be unacceptable. The maximum percentage of dissatisfied people owing to draft in international and European standards is 10%, 20% or 30% depending on the category of indoor environmental quality. The American standard [32] does not have either a maximum percentage of dissatisfied people limit or a draft risk model. It requires that for operative temperatures below 22.5 °C the average air speed caused by the building, its fenestration, and its HVAC system shall not exceed 0.15 m/s.

The dissatisfaction values for air movement obtained in these tests are above the maximum limit set by ISO 7730 [15] for indoor environmental categories A and B. For six out of nine tests, the proportion of dissatisfied subjects is above 30%, which is the maximum limit allowed for any of category A, B, or C. The proportion of dissatisfied subjects is higher than we expected. To have fewer than 10% of occupants dissatisfied, the air temperature should be higher and/or air speed should be lower than in the cases tested here. With an air temperature at the ankles of 21.7 °C and an air speed of 0.16 m/s, these experiments yielded 7 out of 30 (23%) dissatisfied subjects. Based on these experiments, to obtain below 30% dissatisfied with air movement, the following combinations of air temperature and air speed should be used (21 °C and 0.24 m/s; 21.6 °C and 0.32 m/s). Other combinations with higher temperatures and/or lower speeds could be employed.

4.3 Limitations

We selected the most sensitive group of subjects (young women) and therefore the results should not be directly applied for a general population. During the test, subjects were allowed to adapt their clothing level, but they were not allowed to cover their legs. Consequently, one of the adaptive mechanisms [47] was partially blocked. During the experiments the diffusers were visible and this may have influenced the subjects' perception. We did not ask about menstrual cycle and therefore we did not control for it.

5. CONCLUSIONS

We experimentally assessed the thermal comfort of thirty female subjects with uncovered lower legs, ankles and feet when they were exposed to nine indoor environmental conditions generated by cooled air supplied at the floor level. To our knowledge, this is the first study for displacement ventilation and underfloor air distribution done with women having uncovered lower legs, ankles and feet, despite the fact that such systems and attire are common.

By performing these experiments we have learned that an acclimatization period of 30 minutes before each test was sufficient for subjects to attain thermal neutrality. This step solves one of the main limitations of prior experiments that led to the development of the earlier draft risk model, i.e. that subjects who were cool or cold before starting a test might be more sensitive to draft than those who are thermally neutral. We also found that thermal comfort and thermal acceptability are highly correlated; therefore, future studies can rely on questions only about thermal acceptability. Thermal preference and air movement preference are significantly correlated: the cooler people feel, the less air movement they want.

The results show that subjects were more sensitive to ankle draft than expected. For the nine conditions tested, 20-37% of the subjects found the overall thermal environment to be not acceptable and, more specifically, 23-57% found the ankle air movement to be not acceptable. With an air temperature at head height of 24.1 °C, an air temperature at the ankles of 21.7 °C, and an air speed of

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0.16 m/s, 20-23% of occupants found the thermal environment and the ankle air movement to be unacceptable. This condition was expected to be the most favorable for comfort and yet it did not fully satisfy the requirements of thermal comfort standards for good indoor environmental quality.

The results show some potential for energy saving measures. Increasing the temperature set point at the head level may simultaneously yield energy and thermal comfort benefits. However, the study results also show that if designers follow the limited thermal comfort recommendations for spaces conditioned by displacement ventilation and underfloor air distribution, they may inadvertently create uncomfortable conditions for women. These findings are insufficient to develop guidelines on the design of such systems but revealed the need for performing human subject tests exploring combinations of ankle air temperatures, air speed, and thermal sensation for men and women with covered and uncovered lower legs to have a firm basis for more complete set of recommendations.

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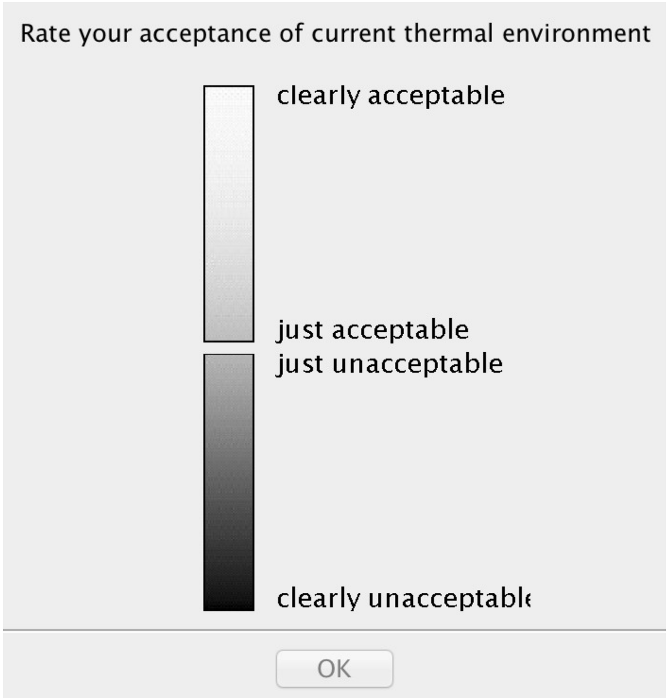
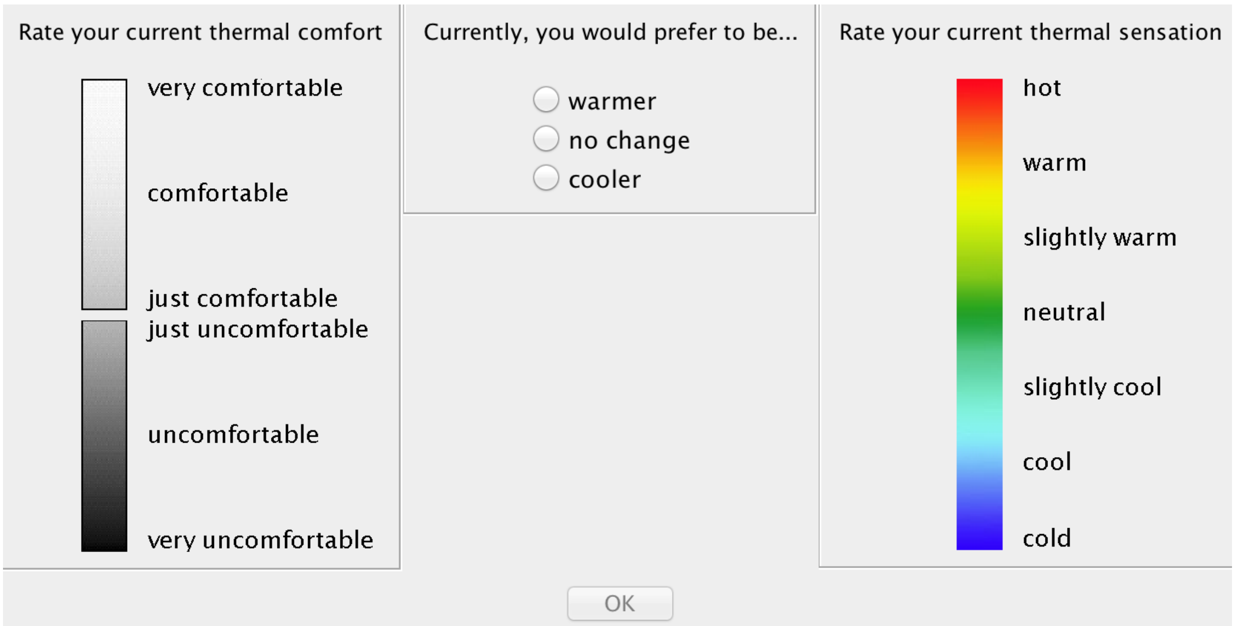
ON LINE SUPPORTING INFORMATION (this part is intended to be read in color)

Screenshots of the questionnaire are shown below.





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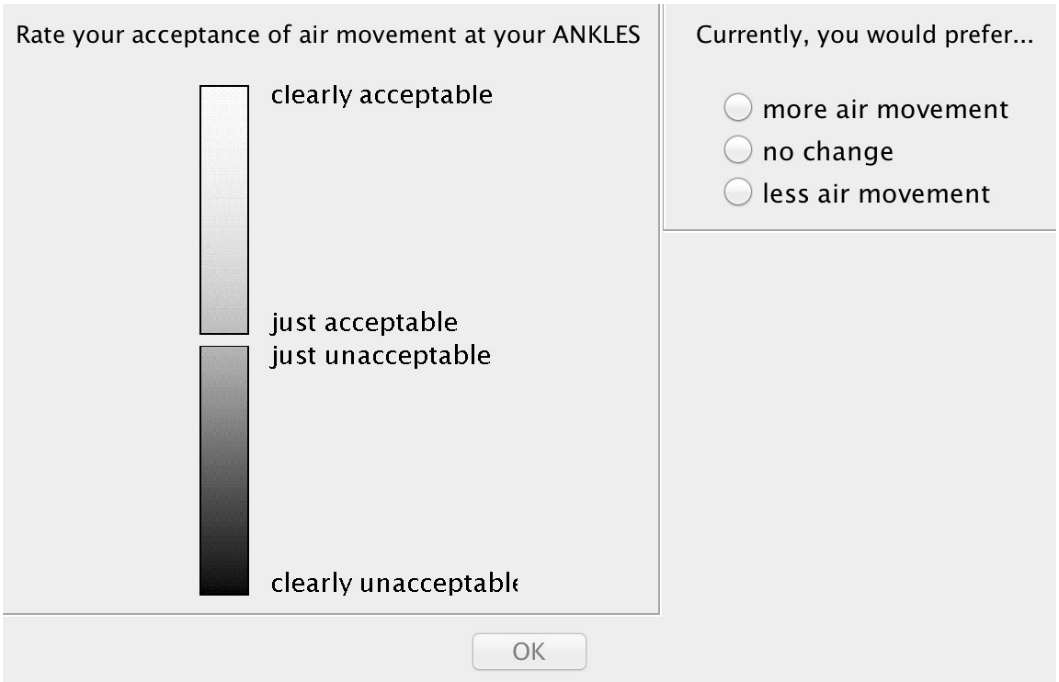

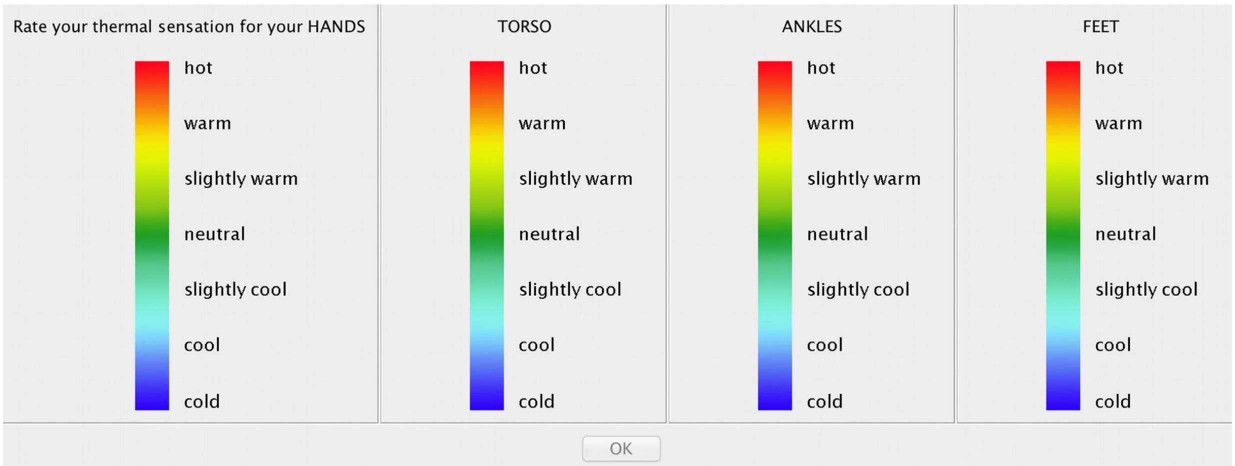

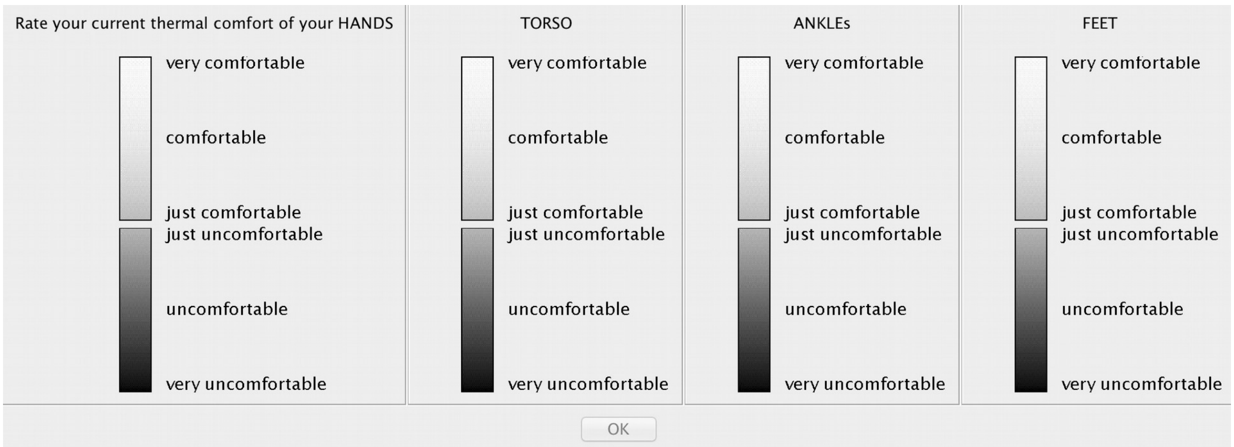

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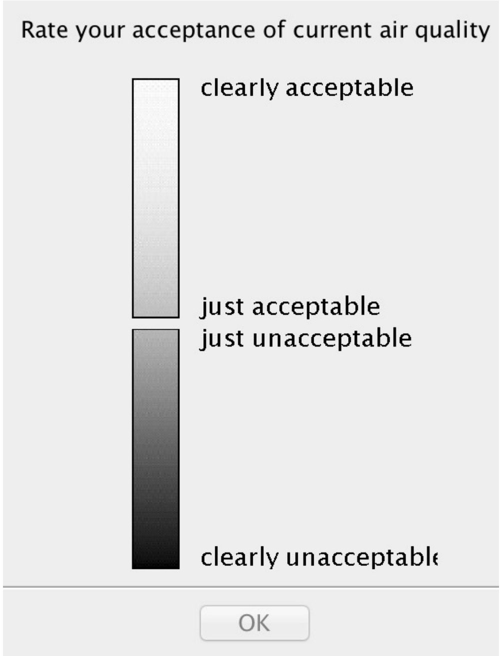

Figure S.1. Screenshots of the questionnaire.

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