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Effects of localized radiant heating on gender differences in skin temperature, thermal sensation, and comfort

Seyed Mohammad Hooshmand[1], Andreas Wagner[1] and Hui Zhang[2]

Abstract
Thermal conditions represent a key component of indoor environmental quality, influencing occupants' comfort, well-being, performance, and health. Thermal responses vary across body regions and between individuals, with gender differences being among the most widely reported. These differences often lead to discomfort. Localized heating devices have shown potential for improving comfort. In this study, gender-based differences in local and overall thermal sensation, thermal comfort, and skin temperature were examined under slightly cool indoor conditions using localized radiant heating. Custom radiant heating devices were used to conduct 270 controlled experiments. Skin temperature at multiple body regions was continuously recorded, and participants filled out questionnaires about their thermal sensation and comfort. Welch's *t*-test and Cohen's *d* were used to assess statistical and practical gender differences. Localized radiant heating substantially reduced gender differences in thermal responses. Most of the skin temperature differences between genders were not statistically significant. Effect sizes were negligible to small for most body parts, although moderate to large values remained for the chest, face, and upper leg. Across all body parts, both local and overall thermal sensation showed no significant gender differences, and effect sizes were small or negligible. Similar results were found for thermal comfort, with only the lower arm showing a moderate effect size in local thermal comfort. Applying localized

[1]Karlsruhe Institute of Technology, Germany
[2]Center for Environmental Design Research, U.C. Berkeley, CA, USA

Corresponding author:
Seyed Mohammad Hooshmand, Karlsruhe Institute of Technology, Englerstraße 7, Karlsruhe, Baden-Württemberg 76131, Germany.
Email: Hooshmand@kit.edu

heating to a single body part increased whole-body comfort levels for both genders. Among all tested body parts, heating the pelvis and chest produced the strongest improvements in whole-body sensation and comfort, and these regions also showed the lowest variability in comfort votes, identifying them as particularly influential targets for localized heating strategies. Overall, the findings demonstrate that localized radiant heating is an effective strategy for narrowing gender-based gaps in thermal responses, particularly under cooler conditions where women typically experience greater cool discomfort.

Keywords
gender differences, local heating, radiant heating, skin temperature, thermal comfort, thermal sensation, indoor climate, localized thermal perception

Introduction

Thermal conditions represent a fundamental aspect of indoor environmental quality, influencing occupants' comfort, well-being, performance, and their interaction with building thermal control systems. Each person could have a different thermal perception even under identical thermal conditions due to subjective and physiological factors (Humphreys and Fergus Nicol, 2002; Mountzouris et al., 2025; Wang et al., 2018).

Previous research has shown that different body parts respond differently to thermal conditions due to variations in their sensitivity to environmental temperature (Arens et al., 2006a; Nakamura et al., 2013; Zhang et al., 2004). Observations also highlight the importance of local thermal preferences and their role in determining overall comfort (Nakamura et al., 2006, 2008).

In addition to variations between body parts, individual differences between men and women also contribute to differences in thermal responses. Individual thermal perception is affected by physiological factors including body composition, fat distribution, blood flow, hormonal regulation, and metabolic rate (Ciuha and Mekjavic, 2016; Gagnon et al., 2013; Tikuisis et al., 2000; Wang et al., 2023; Yang et al., 2021). Several studies have investigated gender differences under various conditions. The studies reported significant gender differences in mean skin temperatures (Kwak et al., 2023), in thermal responses (Du et al., 2023; Zhang and Zhu, 2022), and in the relation between thermal comfort and skin temperature (Song et al., 2025). Parsons (2002) indicated that women tended to feel colder than men in cooler environments with the same activity level and clothing because women have a higher surface area to body mass ratio. Haselsteiner (2021) reported that the difference in preferred comfort temperature between genders could reach up to 3°C in office environments. Comparable findings have been reported before by Karjalainen (2007), Gerrett et al. (2014) emphasizing the importance of considering the gender specifications in thermal comfort modeling to improve performance and thermal comfort of occupants in indoor environments.

Despite the known local variations, most thermal comfort models, which are used widely, such as the Predicted Mean Vote (PMV) model by Fanger (1970), the KSU model by Azer and Hsu (1977), and the two-node model by Gagge et al. (1986) primarily address whole-body comfort and neglect the changes in local responses across the human body. These models rely on a single averaged or representative skin temperature and therefore do not capture regional variations or gender-related physiological differences. Obtaining local sensation and comfort is important because they decide, in some cases, even dictate the whole-body sensation and comfort (Zhang et al., 2010c). Achieving local and overall thermal comfort is not possible using a single skin temperature (Ciuha and Mekjavic, 2016). Models such as the Stolwijk (1971) model and the model by Fiala et al. (2001) simulate temperature distribution across multiple body parts, but they still depend on generalized physiological parameters. They consider fixed set points for each body part and gender-specific differences in local skin temperature and thermal perception are not explicitly incorporated.

Earlier findings have already shown that, in comparison with PMV model prediction, women tend to feel colder than men under the same environmental conditions and experience lower comfort and higher dissatisfaction (Schellen et al., 2012). HVAC systems are typically controlled based on these generalized models; and even with improved thermal comfort models, these systems are fundamentally limited because they condition entire rooms rather than individuals. As a result, achieving proper thermal comfort for all occupants simultaneously is not feasible without personalized or localized systems.

Recent work has focused specifically on local thermal responses. The studies indicated that gender differences existed in local skin temperature (Chen et al., 2025; Hashiguchi et al., 2010), local thermal sensation (Liu et al., 2018), and comfort (Ciuha and Mekjavic, 2017). Hooshmand et al. (2025) experimentally investigated the gender difference in skin temperature and local thermal comfort across multiple body parts under thermally neutral condition and found clear differences between males and females in both skin temperature and local thermal comfort. They suggested that improving comfort through personalized approaches such as localized radiant heating would be more effective than full-room temperature adjustments and could effectively help individuals to achieve proper thermal comfort.

Several studies have demonstrated the potential of personalized or localized heating methods to effectively enhance thermal comfort while reducing energy demand (Hooshmand et al., 2023a; Veselý et al., 2017). Personalized or task-based systems such as under-desk heaters (Nelson and Langness, 1992; Sørlie, 1993), radiant panels (Vissers, 2012; Wang et al., 2022), heated chairs (Madsen and Saxhof, 1977; Melikov et al., 1998; Pasut et al., 2015) or foot warmers (Oi et al., 2011; Zhang et al., 2015) have been shown to improve local and overall comfort, particularly in cool indoor environments. These findings suggest that localized heating not only improves individual comfort but also offers opportunities for energy-efficient conditioning by reducing reliance on full-room temperature adjustments and heating.

Although personalized environmental control systems (PECS) typically allow occupants to individually adjust local heating or cooling, the present study intentionally excluded user control. This approach was chosen allowing to investigate whether localized radiant heating systems can reduce gender-based differences in thermal perception and improve thermal comfort under cool indoor conditions. Previous studies have primarily focused on identifying gender differences in overall thermal sensation or comfort and often did not examine these differences across individual body parts. In addition, although some studies reported gender-related differences in local skin temperature at specific body regions, they did not investigate any methods to reduce or overcome these differences. As a result, it is still unknown whether applying localized thermal strategies to different body parts can close the comfort gap between males and females. Addressing this gender gap is essential, since unequal thermal comfort can affect well-being and productivity, and understanding how localized systems perform is necessary for ensuring that indoor environments provide proper comfort for both genders in an energy-efficient manner. Building upon these insights, the present study aims to investigate whether localized heating can mitigate or eliminate the gender-based differences in local and overall thermal comfort and sensation. To address this, we designed radiant local heating devices and conducted controlled experiments in which each body part was heated for 20 min following 30 min of recovery while local skin temperature and subjective thermal responses were recorded. These findings provide experimental evidence that can support future improvements of thermal comfort models.

Methods

Participants

Forty five participants (22 females and 23 males) participated in our experiments. All participants were within a healthy body mass index range (18.5–25) and between 18 and 35 years old. We advised them to avoid consuming alcohol, hot drinks, and high physical activity prior to the experiment. Instructions about the experimental process and information about it were explained to them when they arrived. The experimental process was approved by the Ethics Committee at the Karlsruhe Institute of Technology (KIT). The average values and standard deviations of participants' demographics are presented in Table 1.

Experimental facility

The study was conducted in the LOBSTER test facility at the Karlsruhe Institute of Technology. LOBSTER consists of two identical, fully controllable test rooms, each measuring 4 m × 6 m × 3 m. A separate adjacent area is used as an acclimation

Table 1. The average values and standard deviations of participants' demographics.

Participant group	Height (cm)	Weight (kg)	Age (years)
Male	178 ± 5.9	73.5 ± 9.1	23.1 ± 2.3
Female	166.4 ± 6.3	61.9 ± 8.6	22.3 ± 2.3
All	172 ± 8.5	67.5 ± 10.6	22.7 ± 2.3

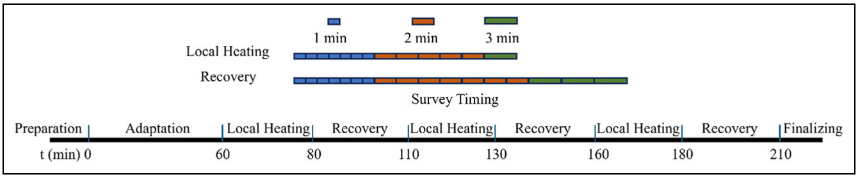

Figure 1. The test procedure of the local heating experiments.

space for participants before the experiments. All interior surface temperatures in each room can be individually heated and cooled through hydronic capillary tube systems, and each room has different ventilation options (manually, mechanical). The window façade was turned north to minimize the influence of solar radiation during experiments. Temperature, humidity, and air velocity were continuously monitored throughout all sessions. Detailed technical information about the LOBSTER facility is provided in Schweiker et al. (2014).

Experimental setup and test procedure

Upon arrival, participants were briefed on the experimental procedure. They first spent time in the acclimation area and then changed into the provided standardized clothing after all required sensors had been attached. The local heating experiment was carried out at an ambient temperature of 19.5°C, and the overall sequence is shown in Figure 1. This temperature represents the uniform background indoor condition of the climate chamber and served as the baseline environment, while localized radiant heating was applied independently to individual body parts. The ambient temperature of 19.5°C was selected to create a mildly cool indoor condition which, given the activity level and clothing insulation, results in slightly cool to cool thermal sensations prior to the application of local heating. Each test continued for 210 min: after a 60-min adaptation period, the session consisted of three heating and recovery cycles began. In each cycle, a different body part was heated for 20 min, followed by a 30 min recovery period before the next body part was heated. The 60-min adaptation period was implemented to allow participants' physiological and psychological responses to stabilize under uniform ambient

Table 2. Specifications and accuracy of physiological and environmental measurement instruments.

Parameter	Manufacturer	Model	Measurement range	Resolution	Accuracy
Skin temperature	iButton	DS1922L	−40 to +85°C	0.0625°C	±0.5°C
Air temperature	AHLBORN (ALMEMO®)	FHAD46C41A	−40 to +85°C	0.01°C	±0.1–0.2°C
Globe temperature	AHLBORN (ALMEMO®)	FPA805GTS	−50 to +200°C	0.1°C	±0.5°C
Relative humidity	AHLBORN (ALMEMO®)	FHAD46C41A	0%–100% RH	0.1% RH	±2% RH (10%–90%)
Air velocity	AHLBORN (ALMEMO®)	FVAD05TOK 300	0.05–1.0 m/s	0.01 m/s	±0.05 m/s

conditions, ensuring a reliable baseline for comparison before localized heating was introduced. The order of the body parts heated was arranged in a randomized manner. Participants took part in multiple sessions, so all investigated body parts were heated and assessed for each participant. Throughout the experiment, participants performed light office tasks such as reading and typing while seated (metabolic rate 1.1 met). During all experiments, participants wore a leotard, corresponding to an insulation level of approximately 0.32 clo. This clothing was selected to standardize clothing insulation across participants and to minimize the influence of clothing on local skin temperature and thermal perception. The use of a leotard was intentionally aligned with the experimental methodology reported by Zhang et al. (2010a), allowing direct comparison with previous results and supports future development of thermal sensation and comfort models. Skin temperatures at multiple body locations were continuously recorded using iButton sensors. Room air parameters were recorded using ALMEMO® 2690-8A and 2890-9 data loggers. The specifications, measurement ranges, resolutions, and accuracies of the measurement instruments used in this study are summarized in Table 2.

Local and overall thermal sensation and comfort were repeatedly assessed using survey questions administered during the session. The thermal sensation and thermal comfort scales are illustrated in Figure 2. Thermal comfort was evaluated on a continuous scale ranging from −4 (very uncomfortable) to +4 (very comfortable) proposed by Zhang et al. (2010b), where negative values indicate discomfort and positive values indicate comfort. Intermediate numerical values reflect gradual differences in perceived thermal comfort (e.g. −2 uncomfortable, +2 comfortable). At the midpoint, participants were required to indicate whether their condition was perceived as "just uncomfortable" (−0) or "just comfortable" (+0), allowing a distinction between marginal discomfort and marginal comfort. Thermal sensation was evaluated using an extended ASHRAE seven-point scale, expanded to nine points, ranging from −4 (very cold), −3 (cold), −2 (cool), −1 (slightly cool),

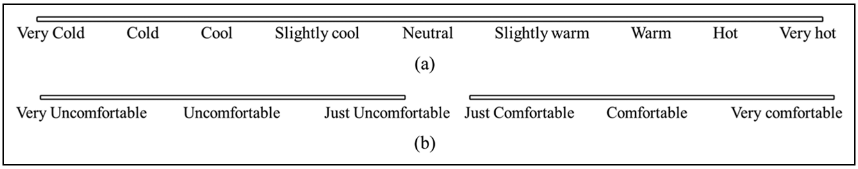

Figure 2. Scales for: (a) thermal sensation and (b) thermal comfort.

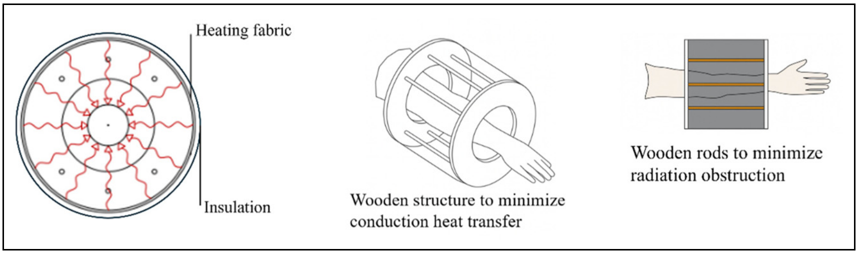

Figure 3. The schematic design of the arm local radiant heating device (Hooshmand et al., 2023b).

0 (neutral), +1 (slightly warm), +2 (warm), +3 (hot), to +4 (very hot). The survey frequencies are every 1, 2, 3 min, as shown in Figure 1.

For localized heating, several radiant heating devices were developed specifically for this study. Each device was built with a wooden frame to limit conductive heat transfer, and a flexible, insulated heating fabric was mounted inside the frame to provide uniform radiant heat across the targeted area. The devices used for the hand, foot, arm, and leg consisted of plywood rings connected by wooden rods, allowing the radiant heating fabric to emit heat with minimal obstruction. A spherical device was used for the head, and cylindrical frames were constructed for the arm and leg. The chest was heated using a radiant fabric positioned in front of the participant. The fabric was insulated on the rear side, to limit heat transfer to other body parts. The pelvis was heated using a radiant fabric mounted on a wooden chair to provide uniform radiant heating while participants remained seated. To ensure comparable heating conditions across body parts, each device was calibrated to achieve an internal radiant temperature of approximately 35°C under the ambient temperature of 19.5°C. The schematic design of the local radiant heating device for arm is shown in Figure 3. Figure 4 presents the designed local radiant heating devices used for the different body parts. Further details regarding the design and fabrication of the heating devices are available in Hooshmand et al. (2023b).

Statistical approach

All statistical analyses were carried out using R (version 4.3.2). Data normality for each body region and gender group was assessed using the Shapiro–Wilk test, which evaluates whether the dataset follows a normal distribution or deviates significantly from it. Homogeneity of variances between male and female groups was examined using Levene's test. Differences between male and female participants were analyzed using Welch's t-test, which compares the means of two independent samples and does not assume equal variances. To assess the magnitude of these differences, effect sizes were calculated using Cohen's d, which expresses the standardized difference between two group means independently of sample size. Interpretation of effect size followed commonly used thresholds proposed by Cohen (1988), where values of approximately 0.2 indicate a small effect, 0.5 a moderate effect, and 0.8 or higher a large effect. While p-values identify whether differences reach statistical significance, Cohen's d provides an indication of their practical or physiological relevance.

Results and discussion

Previous research has reported clear gender differences in skin temperature, local thermal sensation, and thermal comfort, especially in cooler environments (Haselsteiner, 2021; Karjalainen, 2007; Parsons, 2002; Schellen et al., 2012). The goal of the present study was to determine whether localized radiant heating can reduce or eliminate these differences.

Before the application of localized heating, local skin temperature data were evaluated at the end of the 60-min adaptation period to establish baseline gender differences under uniform ambient conditions (19.5°C). At this stage, several body parts exhibited statistically significant gender differences with moderate to large effect sizes, particularly at the chest ($p < 0.001$, $d = -1.32$), head ($p = 0.002$, $d = 0.99$), pelvis ($p = 0.013$, $d = -0.79$), and upper leg ($p = 0.007$, $d = 0.85$). These baseline differences are consistent with previous findings reported under cool or neutral indoor conditions and provide a reference for assessing the effect of localized radiant heating in the subsequent analysis (Chudecka and Lubkowska, 2015; Ciuha and Mekjavic, 2016; Hooshmand et al., 2025).

Boxplots in Figures 5–9 show the results at end of each local heating application, while the radiation devices were still on. In all boxplots, the box represents the interquartile range (25th–75th percentile), the central line indicates the median, and the whiskers indicate the data range. Figure 5 illustrates the distribution of local skin temperatures at the end of the heating period. At the chest, female participants showed higher temperatures than males. A similar pattern was reported by Chudecka and Lubkowska (2015), who found that women tend to exhibit warmer chest temperatures. This difference may be related to the chest's proximity to core organs as well as gender-related differences in fat distribution and metabolic processes. In our experiment, the highest temperatures occurred at the chest, neck,

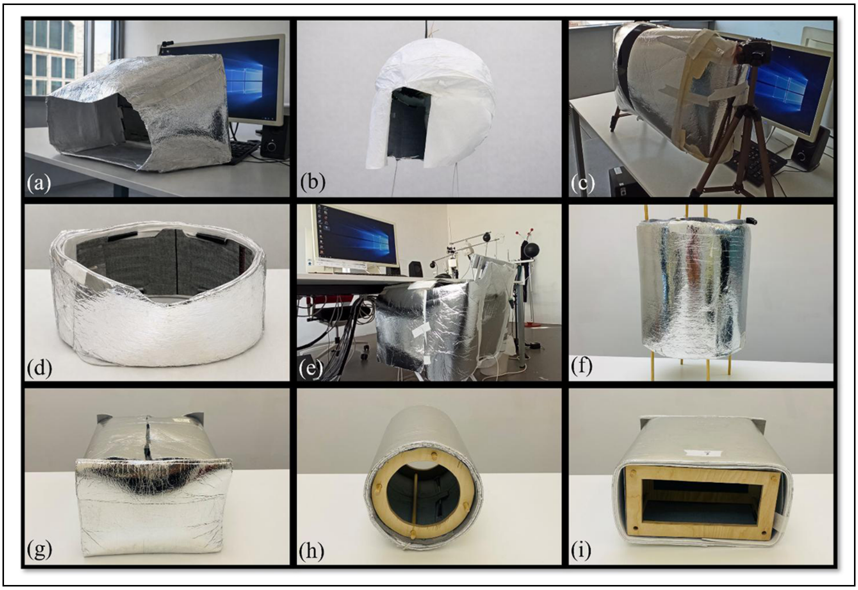

Figure 4. Designed local radiant heating devices: (a) chest, (b) head, (c) face, (d) neck, (e) pelvis, (f) upper and lower leg, (g) foot, (h) upper and lower arm, and (i) hand (Hooshmand et al., 2023b).

and face. Elevated temperature at the chest is consistent with its anatomical closeness to central organs that produce metabolic heat. Higher temperatures at the face and neck are likely related to their high blood perfusion, proximity to major blood vessels, and their role in thermoregulation. The lowest temperatures were recorded at the foot and hand. This temperature pattern aligns with findings that skin temperature decreases in cool environments as body regions become more distant from the core (Nakamura et al., 2013; Niu et al., 2001).

Extremities such as the hands, feet, and lower legs are more exposed to the environment and contain vascular structures that allow rapid modulation of blood flow for thermal regulation. As a result, these regions exhibited wider temperature distributions, reflected by larger interquartile ranges and longer whiskers in Figure 5, indicating greater variability and sensitivity compared with more central body parts.

When comparing genders for each body part, most body parts showed small gender differences or nearly identical distributions, likely due to the effect of localized heating, which minimizes gender-related variability in those areas. Males displayed slightly higher temperatures at the head, face, hand, leg, and arm, which agrees with earlier findings in mildly cool environments (Chudecka and Lubkowska, 2015). These patterns may also be influenced by body-composition differences: men typically have more muscle mass, which produces heat, and less subcutaneous fat, while women usually have a thicker layer of body fat that

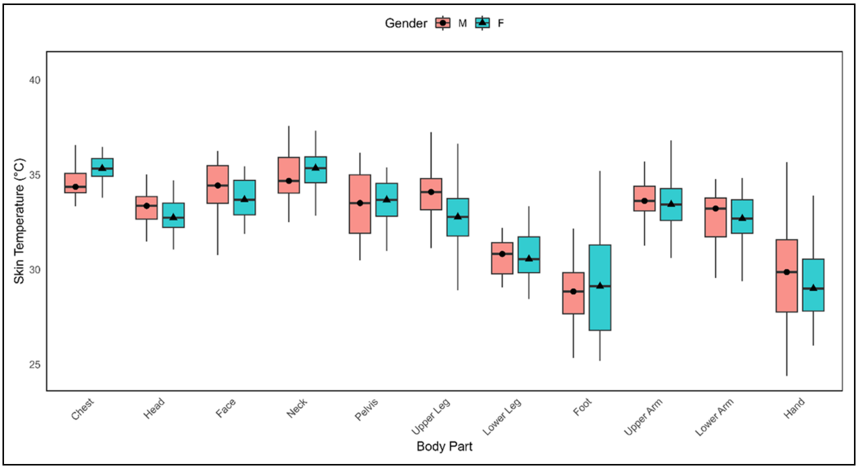

Figure 5. Local skin temperatures for male and female participants measured at the locally heated body part at the end of the heating period.

Table 3. Statistical results and effect sizes for gender-related differences in local skin temperature.

Body part	*p*-Value	Effect size
Chest	0.06	−0.85/Large
Head	0.16	0.47/Small
Face	0.11	0.51/Moderate
Neck	0.41	−0.31/Small
Pelvis	0.91	−0.04/Negligible
Upper leg	0.03	0.98/Large
Lower leg	0.77	−0.10/Negligible
Foot	0.71	−0.10/Negligible
Upper arm	0.49	0.20/Small
Lower arm	0.63	−0.14/Negligible
Hand	0.46	0.21/Small

provides insulation. Additionally, women's heat dissipation may differ due to factors such as a higher surface area to mass ratio, greater body fat percentage, and lower blood volume relative to lean body mass, all of which reduce heat exchange efficiency (Kaciuba-Uscilko and Grucza, 2001).

Table 3 summarizes the statistical comparisons and corresponding effect sizes. Although all *p*-values were not statistically significant except upper leg, effect sizes allow a clearer interpretation of the magnitude of differences. Large effect sizes were found for the chest and upper leg, and a moderate effect was observed for the

Table 4. Statistical results and effect sizes for gender-related differences in local thermal sensation.

Body part	p-Value	Effect size
Chest	0.22	−0.37/Small
Head	0.70	−0.12/Negligible
Face	0.95	0.02/Negligible
Neck	0.24	0.32/Small
Pelvis	0.40	−0.26/Small
Upper leg	0.65	−0.13/Negligible
Lower leg	0.94	−0.02/Negligible
Foot	0.54	0.17/Negligible
Upper arm	0.79	−0.08/Negligible
Lower arm	0.99	−0.01/Negligible
Hand	0.54	0.17/Negligible

face, indicating meaningful gender differences in these regions despite nonsignificant p-values. Chest and upper leg have gender-related differences in subcutaneous fat thickness, muscle composition, and blood flow regulation. Such physiological differences may contribute to the larger effect sizes observed in these areas. In contrast, all remaining locations showed small or negligible effect sizes, suggesting that localized radiant heating substantially reduced gender differences for most body parts. Compared with our previous study (Hooshmand et al., 2025), in which nearly all regions (except the lower arm) showed moderate or large gender differences under neutral conditions, the present results demonstrate that radiant local heating effectively narrows these differences across the majority of body parts.

After assessing local skin temperature, the next step is to examine local thermal sensation and comfort. This allows us to evaluate whether localized radiant heating influences local thermal responses and whether it can compensate for the gender-related skin temperature differences observed in some body parts.

At the end of the 60-min adaptation period, before the application of localized heating, gender-related differences in local thermal sensation were observed for several body parts. Although most comparisons did not reach statistical significance, effect size analysis revealed meaningful differences in distal and limb regions. Moderate effect sizes were found for the foot ($d = 0.73$), hand ($d = 0.55$), lower arm ($d = 0.51$), lower leg ($d = 0.60$), pelvis ($d = 0.54$), and upper arm ($d = 0.59$), indicating that women generally reported cooler local sensations than men at baseline under cool ambient conditions. These baseline findings are consistent with previous observations that gender differences in thermal sensation are more pronounced in peripheral body parts under cool or neutral conditions and provide an important reference for evaluating the effect of localized radiant heating in reducing these differences (Liu et al., 2018; Parsons, 2002).

Figure 6 illustrates the distribution of local thermal sensation and Table 4 presents the statistical comparisons and effect sizes for male and female participants

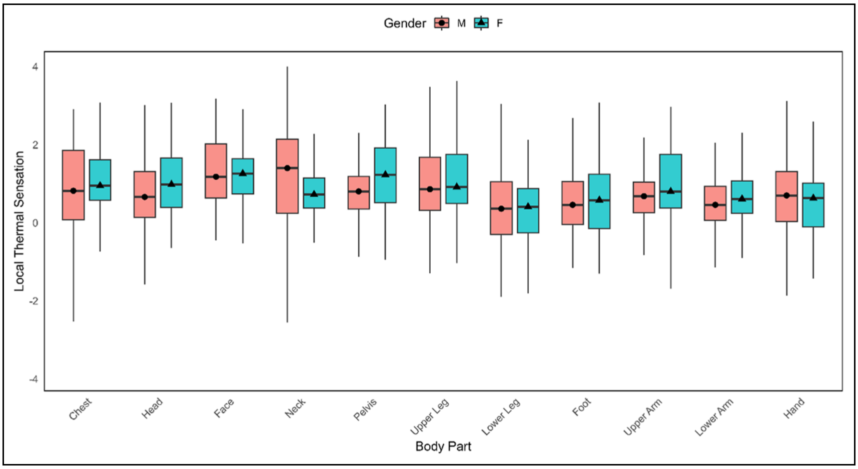

Figure 6. Local thermal sensation for male and female participants at the end of the heating period.

at the end of the heating period. As expected, the use of localized radiant heating shifted the thermal sensation of both genders toward the "slightly warm" range, indicating that the devices successfully improved local thermal perception across all body parts. Comparing the median values reveals that sensations were nearly identical between genders for most body parts. For example, for foot, the effect sizes between genders reduced from $d = 0.73$ (before local heating application) to $d = 0.17$ (negligible after local heating application). The only noticeable difference appears at the neck, where the median values diverge slightly. However, Table 4 shows that the effect size at the neck (Cohen's $d = 0.32$) remains within the small range.

In contrast to previous findings such as those reported by Liu et al. (2018), who observed that women tended to feel cooler than men in hands, feet, and lower body regions under cold conditions, the present results show no statistically significant differences between genders with local heating. All p-values exceed 0.05, and effect sizes are small or negligible across all body parts. These outcomes suggest that localized radiant heating effectively minimizes the gender gap in local thermal sensation. Body parts that previously exhibited significant gender differences in colder environments now show comparable sensation levels between males and females. Thus, radiant local heating appears to mitigate the cooler sensation typically experienced by women, contributing to more uniform thermal perceptions across genders.

Comparing these results with the skin temperature findings show that, although noticeable physiological differences (skin temperatures) remained at the chest and upper leg, participants reported similar thermal sensations across all body parts.

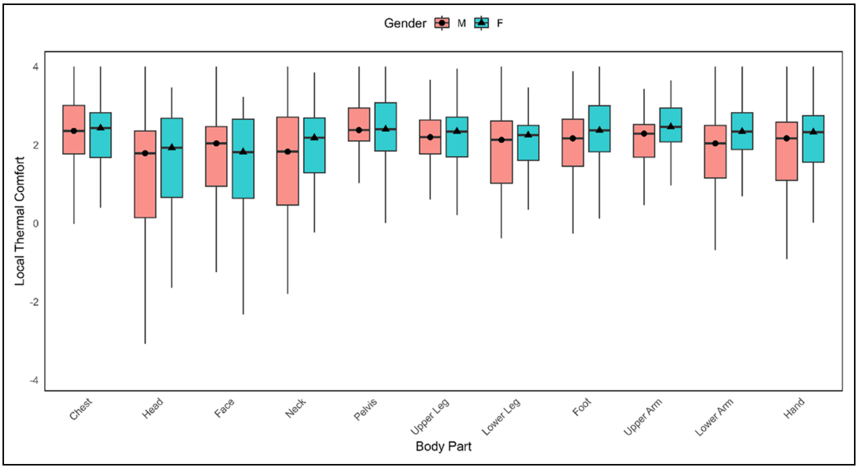

Figure 7. Local thermal comfort for male and female participants at the end of the heating period.

This indicates that localized radiant heating was able to override the natural gender-related variations in skin temperature with respect to local sensation. However, identical sensation does not necessarily translate into identical comfort, particularly between genders. Therefore, it is essential to also analyze local thermal comfort to determine whether the reduction in gender differences extends beyond sensation and results in comparable comfort levels.

At the end of the adaptation period, gender differences in local thermal comfort were generally small across most body parts. However, extremities showed comparatively larger differences. In particular, the foot exhibited a moderate gender effect size ($d = 0.71$), while the hand ($d = 0.44$) and lower leg ($d = 0.44$) showed small to moderate effect sizes, indicating higher sensitivity and variability in distal regions. After applying localized radiant heating, these differences were reduced.

Figure 7 presents the distribution of local thermal comfort for male and female participants at the end of the heating period. For all body parts except face, females' comfort is higher than males, indicating that local heating is more welcome by female than male. Most responses fall on the positive side of the scale, indicating that the localized heating created comfortable conditions across all body parts. The head, face, and neck show a wider spread of votes compared with other body parts. This observation is consistent with previous findings showing that occupants are generally less tolerant of heating in the head region and tend to prefer lower thermal stimulation there (Arens et al., 2006b). In addition, the neck had some of the highest skin temperatures, which can reduce comfort. Despite this wider variability, the median comfort vote for every body part and both genders is around +2, meaning participants were comfortable.

Table 5. Statistical results and effect sizes for gender-related differences in local thermal comfort.

Body part	*p*-Value	Effect size
Chest	0.62	−0.15/Negligible
Head	0.96	0.02/Negligible
Face	0.48	0.22/Small
Neck	0.84	−0.06/Negligible
Pelvis	0.86	0.05/Negligible
Upper leg	0.81	−0.07/Negligible
Lower leg	0.43	−0.23/Small
Foot	0.46	−0.20/Small
Upper arm	0.62	−0.15/Negligible
Lower arm	0.33	−0.64/Moderate
Hand	0.45	−0.20/Small

Table 5 summarizes the statistical results and effect sizes for gender-related differences in local thermal comfort. All p-values exceed 0.05, and effect sizes are small or negligible for every body part except the lower arm, where a moderate effect size suggests a minor remaining difference between genders. These findings contrast with earlier research; for example, in Hooshmand et al. (2025) study, most body regions showed moderate or large gender differences in comfort under neutral conditions. Also, Hashiguchi et al. (2010) reported significant gender differences in thermal comfort under cool conditions near the floor (16°C–19°C), with women experiencing greater discomfort. The present results demonstrate that localized radiant heating substantially reduces these differences and leads to more uniform comfort levels between male and female participants across nearly all body parts.

Since local thermal sensation and comfort at individual body regions can influence whole-body perception, the next step is to evaluate overall thermal sensation and comfort. This allows us to determine whether the reduction in local gender differences also translates into comparable whole-body thermal experience.

At the end of the 60-min adaptation period, clear gender differences in overall thermal sensation were observed across all investigated body parts. All body parts exhibited statistically significant gender differences ($p < 0.05$) with moderate effect sizes (Cohen's $d \approx 0.57$–0.74). Female participants consistently reported cooler overall sensations than male participants, indicating both physiologically and psychologically gender differences under uniform ambient conditions prior to the application of localized heating.

Figure 8 shows the distribution of overall thermal sensation when one body part was heated, and Table 6 summarizes the corresponding statistical results. For both genders, the median is close or higher than -1 across all body parts, indicating that participants generally perceived the environment as slightly cool. Only small visual gender differences appear at the head and pelvis. In general, except chest, women

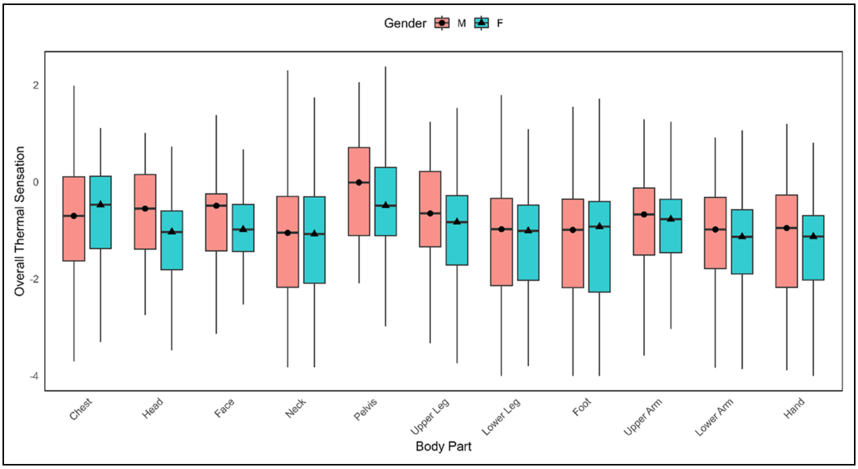

Figure 8. Overall thermal sensation for male and female participants at the end of the heating period.

felt slightly cooler or equal than male thermal sensation. The effect size for the head is 0.56 (moderate), while the pelvis shows a small effect size of 0.26. Male participants also reported slightly warmer overall sensations than women when certain local regions were heated, similar to the pattern seen in the local thermal sensation results.

Figure 8 also reveals that heating the pelvis shifted the median overall sensation for male participants close to neutral level, suggesting that heating this region contributed most strongly to improving overall sensation in men. For women, heating the pelvis and chest produced the warmest overall sensations, indicating that heating these areas had the strongest influence on whole-body thermal sensation.

Overall, Table 6 confirms that gender differences were small or negligible for all body parts except the head. These results show that localized radiant heating substantially reduced gender differences in whole-body thermal sensation. Earlier studies reported that women tended to feel noticeably cooler under cold conditions, but here the local heating strategy minimized these differences and produced comparable overall sensations between genders (Karjalainen, 2007; Parsons, 2002; Schellen et al., 2012).

However, reducing gender differences in overall thermal sensation does not guarantee an equivalent response in overall thermal comfort. Therefore, it is necessary to examine overall comfort to determine whether localized heating also equalizes the broader comfort experience between genders. In addition, analyzing overall thermal comfort helps identify which body parts contribute most effectively to improving whole-body comfort, providing insight into the regions where localized heating yields the strongest overall benefit.

Table 6. Statistical results and effect sizes for gender-related differences in overall thermal sensation.

Body part	*p*-Value	Effect size
Chest	0.99	0.01/Negligible
Head	0.07	0.56/Moderate
Face	0.45	0.23/Small
Neck	0.82	−0.06/Negligible
Pelvis	0.39	0.26/Small
Upper leg	0.31	0.30/Small
Lower leg	0.74	0.1/Negligible
Foot	0.81	−0.06/Negligible
Upper arm	0.88	0.04/Negligible
Lower arm	0.35	0.27/Small
Hand	0.74	0.09/Negligible

At the end of the 60-min adaptation period, moderate gender differences in overall thermal comfort were observed for several body parts, including the head ($d = 0.62$), lower arm ($d = 0.55$), lower leg ($d = 0.56$), pelvis ($d = 0.60$), upper arm ($d = 0.56$), face ($d = 0.50$), and upper leg ($d = 0.53$). Effect sizes for the remaining body parts, foot ($d = 0.48$), hand ($d = 0.45$), chest ($d = 0.42$), and neck ($d = 0.38$), were also close to the moderate range, indicating differences in overall thermal comfort between men and women.

Figure 9 presents the distribution of overall thermal comfort for male and female participants at the end of the heating period. For both genders, the median comfort for all body parts is in the positive side and most have overall thermal comfort around +1 to +2, indicating that most participants experienced a clearly comfortable overall state. Neck shows wider spreads, suggesting that this area is more sensitive to heating intensity and individual preference. In contrast, the pelvis shows the smallest variation, indicating that heating this region produced the most stable comfort response across participants. The comparison between genders shows no meaningful visual differences in overall comfort, but it did show a trend that female overall comfort is slightly lower than male, which is different from local comfort, where females local comfort levels are slightly higher than males for most body parts. Table 7 confirms this: all *p*-values are non-significant, and all effect sizes are small or negligible. This means that any remaining gender related variation is minimal. These results indicate that localized radiant heating effectively reduces the gender gap in overall thermal comfort, even at an ambient temperature of about 19.5°C, where women typically report lower comfort in the absence of heating (Haselsteiner, 2021; Parsons, 2002; Schellen et al., 2012).

Although the overall thermal sensation results showed a moderate gender difference at the head, this difference did not translate into overall comfort. The comfort data were more stable and showed no significant gender differences for any body

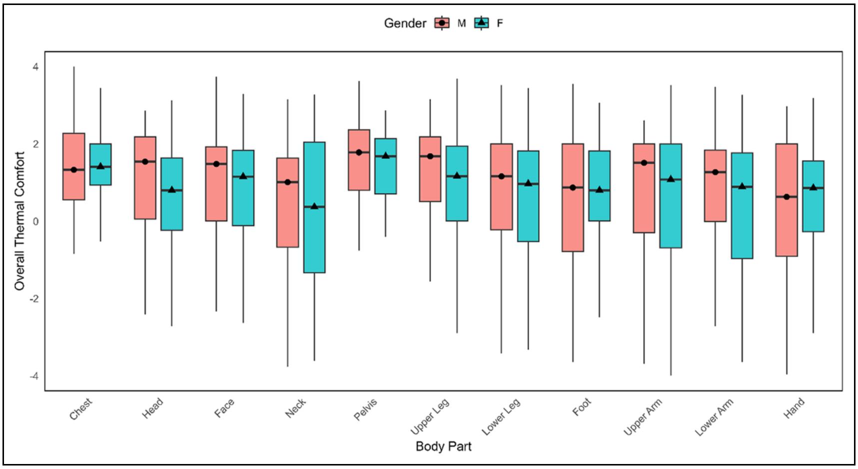

Figure 9. Overall thermal comfort for male and female participants at the end of the heating period.

Table 7. Statistical results and effect sizes for gender-related differences in overall thermal comfort.

Body part	*p*-Value	Effect size
Chest	0.65	−0.14/Negligible
Head	0.13	0.46/Small
Face	0.89	0.04/Negligible
Neck	0.82	0.06/Negligible
Pelvis	0.24	0.35/Small
Upper leg	0.38	0.26/Small
Lower leg	0.65	0.13/Negligible
Foot	0.52	−0.17/Negligible
Upper arm	0.80	0.07/Negligible
Lower arm	0.36	0.27/Small
Hand	0.90	−0.03/Negligible

part. This indicates that localized radiant heating can equalize comfort even when small differences in sensation remain.

These findings also help identify which body parts have the strongest influence on whole-body comfort. Regions such as the pelvis and chest, which showed both high comfort ratings and low variability, appear to be particularly effective targets for improving overall comfort with minimal energy input.

Conclusion

This study examined whether localized radiant heating could mitigate the gender-based differences in skin temperature, local and overall thermal sensation, and thermal comfort under cool indoor conditions. More than 270 controlled experiments were conducted using a set of newly developed radiant heating devices designed to heat specific body parts.

Consistent with previous literature, baseline measurements showed meaningful gender differences, particularly in distal regions such as the hands, feet, and lower legs. However, once localized heating was applied, these disparities were substantially reduced. For nearly all body regions, males and females reported comparable local and overall thermal sensations, and no statistically significant differences were observed. Local thermal comfort ratings also converged between genders, with all median values falling within the comfortable range. Although physiological skin temperature differences persisted in a few regions, most notably the chest and upper leg, these did not translate into meaningful differences in whole-body thermal sensation or comfort.

Overall, the results demonstrate that targeted radiant heating is an effective strategy for narrowing the thermal response gap between genders, particularly in cooler environments where women typically experience greater discomfort. These findings support the broader use of personalized thermal control systems such as radiant heating panels, heated seats, or task-based microclimate technologies as an alternative to conventional whole-room HVAC adjustments. Such systems offer a practical pathway toward more inclusive indoor environments, providing comfort without requiring substantial increases in ambient temperature. The evidence presented here provides a foundation for incorporating localized thermal strategies into future comfort models and building design practices aimed at achieving both equity and energy efficiency.

In addition, the results indicate that certain body parts have a stronger influence on whole-body responses. Heating the pelvis produced the largest increase in overall thermal sensation for male participants and brought their median sensation close to neutral. For female participants, heating the pelvis and chest led to the highest overall sensation values. These two regions also showed high overall comfort ratings with relatively low variability for both genders. Therefore, the pelvis and chest appear to be particularly effective targets for task-based heating strategies aimed at improving whole-body comfort with minimal energy input.

The findings could be helpful for building designers and HVAC engineers and suggest that task-based heating systems can provide comfortable conditions while reducing energy demand. Integrating such systems into spaces like workplaces may help address comfort differences across occupants without relying solely on central heating adjustments. Future research should explore the integration of localized heating into smart HVAC systems, evaluate long-term comfort and energy impacts in field studies. Additional work is also needed to incorporate gender-specific insights into thermal comfort models to improve prediction accuracy and design guidance.

Limitations

Several limitations should be acknowledged. The experiment was conducted under a single controlled ambient temperature (≈19.5°C), and responses may differ under warmer or more variable conditions. All participants were young adults within a healthy BMI range; broader demographic diversity could yield different responses. Localized heating was applied to one body region at a time; combined or adaptive multi-region heating strategies may produce stronger or more efficient effects.

ORCID iDs

Seyed Mohammad Hooshmand https://orcid.org/0000-0002-2631-3801
Andreas Wagner https://orcid.org/0000-0003-4015-236X

Ethical considerations

The experimental process was approved by the Ethics Committee at the Karlsruhe Institute of Technology (KIT) on 25.07.2022.

Consent to participate

Participants gave written consent for review and signature before starting the experiments.

Consent for publication

Not applicable.

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