# Experimental investigation of the effect of local radiant asymmetry on thermal comfort

Stijn Van Craenendonck[1,*], Leen Lauriks[1], Cedric Vuye[1]

[1]EMIB Research group, University of Antwerp, Belgium

[*]*Corresponding email: Stijn.vancraenendonck@uantwerpen.be*

## ABSTRACT

In cold and moderate climates, poorly designed construction joints can lead to local low surface temperatures, which entails local radiant asymmetry. An experiment was set up to test the hypothesis that overall and local thermal sensation is influenced by local radiant asymmetry. Another hypothesis under investigation was that local cooling of the body is sometimes misidentified as draft.

In the experiment, 16 subjects were introduced in a room between 22°C and 24°C and between 30% and 50% relative humidity. The subjects were exposed to local radiant asymmetry created by a cooling plate. This plate was positioned at three different heights, and controlled for temperatures at 3, 6 or 10°C below room air temperature. Subjects were asked to rate overall thermal sensation, comfort acceptability and draft sensation. Local thermal sensation and draft at 9 different body parts were also rated. Mixed linear modelling and repeated measures ANOVA was used to statistically analyze the survey and measured environmental conditions.

The analysis showed that local thermal sensation is indeed influenced by local radiant asymmetry. The effect was most noticeable in the bodies' extremities, with statistically significant linear relationships between thermal sensation in the feet and temperature of the bottom plate. Similar relationships were also found for upper arm, lower arm and hand thermal sensation and top plate temperature. Head, neck and chest thermal sensation were not affected by local radiant asymmetry. The results also showed significant indications that local cooling of body parts might be mistaken for draft in the bodies' extremities.

## KEYWORDS

Thermal sensation, radiant asymmetry, draft

## INTRODUCTION

While renovating existing buildings, planar parts of the building shell are often insulated without proper care for the joints connecting these parts. In cold and moderate climates, poorly designed construction joints can lead to local wall areas with a low surface temperature. These local colder areas lead, next to a higher risk for surface condensation, to radiant temperature asymmetry and can influence thermal comfort of the residents.

Research into radiant temperature asymmetry was first conducted by McNall and Biddison in 1970. [1] They placed subjects in a test chamber of which they cooled and heated one wall or the ceiling. Subjects were asked to rate their thermal comfort on a ballot. They concluded that no significant discomfort could be attributed to radiant temperature asymmetry due to a wall with view factor 0.2 at 11°C colder than the environment. Olesen et al. investigated the maximum radiant temperature asymmetry that could be endured while still remaining thermally neutral in 1972. [2] They discovered that subjects could sense small degrees of radiant temperature asymmetry, but much

*Corresponding Author: f.author@affiliation.com

larger asymmetry was needed to cause discomfort. Cooling the front of a person was found to have the smallest effect on thermal comfort.
Research by Fanger et al. [3] in 1985 found that among warm walls, cool walls and cool ceilings, the cool walls have the largest influence on thermal comfort. This influence however was relatively limited: if the surface temperature of the cool wall was less than 10 °C under average air temperature, the percentage of people dissatisfied with the environments was less than 5%.
More recently, Sakoi et al studied thermal comfort, skin temperature and sensible heat loss in asymmetric environments. [4] It was found that local cold discomfort in the foot depends mainly on skin temperature and not on sensible heat loss.
However, in all these experiments, the asymmetric environment was realized cooling entire walls of a chamber. When looking at the construction joints, the lower surface temperature is only a local effect.

In 2006, Arens et al demonstrated in a series of experiments that cooling of the trunk areas of the body (chest, back) strongly affects overall thermal sensation, while the effect is much less noticeable in the bodies' extremities (hands, feet). [5] Nakamura et al showed that different parts of the body not only have different thermal sensation, but also have different influences on overall thermal comfort. [6] Local radiant temperature asymmetry can lead to cooling of local areas of the body and therefore has the possibility to negatively affect thermal comfort.

In this paper, a thermal comfort experiment in a semi-controlled environment is reported to test two hypotheses:

- Overall and local thermal sensation are influenced by local radiant cooling
- Local radiant cooling of the body can be mistaken as draft

## EXPERIMENTAL SETUP

**Subjects**
21 Subjects participated in the experiment. With 5 test subjects, the imposed conditions were not met, thus these results were excluded from further analysis. The remaining 16 subjects were 4 male and 12 female. The average (± standard deviation) age of the subjects was 27.1 ± 10.9 years.
All subjects wore clothes for an overall clothing value of 0.76 clo (underwear, long non-ripped pants, T-shirt, sweater, socks and closed shoes) according to NBN EN ISO 9920 [7]. All subjects were seated on a standard office chair raising clothing insulation to 0.93. [8]

**Conditions**
The experiments took place in the University of Antwerp, Belgium, where a 6.4 m x 4.7 m x 4.1 m office was converted into a test room. Temperature was controlled by the building management system between 22 and 24°C. Adjacent rooms were kept at the same temperature. All conditions were imposed for at least 48h before each test to assure that mean radiant temperature was equal to air temperature. It should be noted that a computer was present, producing heat at participants' feet level. Relative humidity was not controlled but monitored and remained between 30 and 50%.
Despite a ventilation outlet being present over the subjects' workplace, air velocity at the workstation remained below 0.1 m/s. Air temperature was also not affected by the outlet.
To simulate the cold spots caused by construction joints, a setup was built employing three cooling plates, as seen in Fig. 1.

Three temperature points for the plates, as well as the size of the plates, were chosen based on simulation of common Belgian construction joints: 3, 6 and 10°C below ambient air temperature of the room.


**Fig. 1:** Experimental setup

**Experimental procedure**

All experiments were performed in April and May 2017.
Before entering the test room, subjects stayed in an antechamber for 15 minutes during which they prepared for the experiment and filled out a preliminary questionnaire. Subjects were then asked to sit in the test room for 2 hours. These 2 hours consisted of a 30-minute acclimatization period, after which 3 different test conditions were applied to the room, each lasting 30 minutes. After 1 hour in the room, all subjects took a sanitary brake of 5 minutes. After the 2 hours in the test room, subjects again spent 10 minutes in the antechamber to debrief.
During the experiment, subjects were instructed to sit and work on a computer present in the test chamber, ensuring an activity level of 1.5 met according to NBN EN ISO 8996 [9].

**Questionnaire**

A preliminary survey was taken before the subject entered the test room. This survey consisted of questions on general health, sleep quality, caffeine and alcohol consumption, hunger and general thermal sensation.
During the test, subjects had to fill out a questionnaire 5, 15 and 25 minutes into each test condition. A bipolar 7-point scale was used to rate overall and local (head, neck, chest, upper arm, lower arm, hand, upper leg, lower leg and foot) thermal sensation (TSV), overall thermal comfort (TCV) and change preference. A Boolean option was used to indicate overall and local draft perception and overall acceptability of the environment.

**Analysis Methods**

Before analysis began, outliers were removed. Univariate outliers of TSV-scores were removed based on Z-scores, with all entries with a score lower than -3 or higher than +3 removed. Pairwise removal of bivariate outliers of TSV-temperature pairs was performed based on Mahalanobis distance. [10] Due to the way the response slider worked in the survey, it was impossible to put the slider in the exact same place two times, even if that was the intention of the subject. To account for small inaccuracies in the responses, all responses for the TSV-scores were thus binned into 0.4-wide intervals (e.g. all TSV-scores between -3.0 and -2.6 were recoded to -2.8).

The relation between temperature of the cooling plates and local TSV-scores of the subjects was examined using linear mixed modelling. Plate temperature and 5-minute average of the ambient temperature were used as fixed parameters. A random intercept model was used to account for possible differences in base comfort levels of the subjects, i.e. subjects placed in the same environment can still have different comfort experiences. Models with and without plate temperature were used in a likelihood ratio test to calculate the p-value of the plate temperature as predictor. [11] Plate temperature was checked for its statistical significance as a predictor in the models, based on the p-value ( $< 0.05$ to be significant). Goodness of fit of the model was estimated using $R^2_{GLMM(m)}$ as proposed by Nakagawa & Schielzeth. [12] Modelling was performed in R version 3.4.3 with lme4 package. [13], [14]

The relationship between categorical variables, such as draft perception and whether or not a cooling plate was active, was investigated using Chi-square test [15, pp. 45–52]. Post-hoc analysis of the standard residuals as proposed by Sharpe [16] was employed when the Chi-square test yielded significant results.

This analysis was performed in SPSS version 24 [17].

## THERMAL SENSATION

Analysis showed that the temperature of the top plate is a significant predictor for local TSV in the upper legs of the subjects, as well as in all arm regions (upper arm, lower arm, hand). The scatter plots of binned local TSV-scores and corresponding top plate temperature are shown in Fig. 2. Model equations itself are given in equations (1) to (3).

The three significant results are unexpected, as these areas are not the ones with the highest view factor from the upper plate. When looking at the $R^2_{GLMM(m)}$-values in Table 1, we notice that $R^2_{GLMM(m)}$ is lowest for the upper leg, meaning that less of the variation in TSV can be explained by variation in plate temperature. This can be explained by the lower view factor for this body region to the upper plate. Overall, temperature of the upper plate is a good predictor of thermal sensation in the arm region.

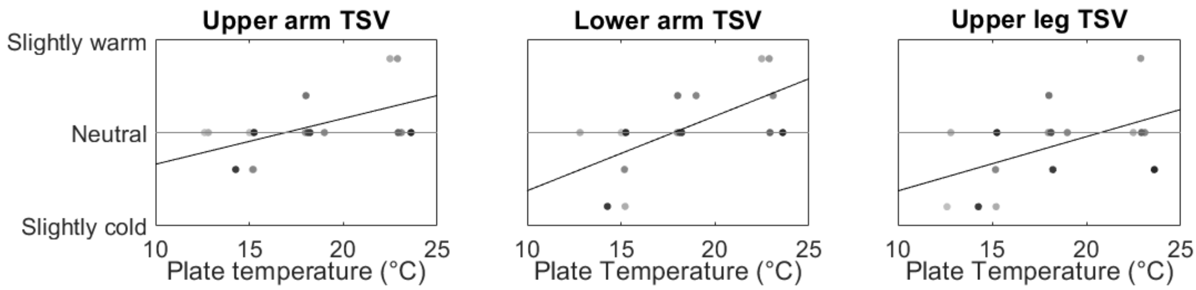


**Fig. 2:** Local TSV scores vs. temperature of the top plate

$$TSV_{UpperArm} = 0.04959 \cdot PlateTemp_{Upper} - 0.22680 \cdot T_{avg,5\min} + 4.59175 + \varepsilon \quad (1)$$

$$TSV_{LowerArm} = 0.08088 \cdot PlateTemp_{Upper} + 0.06907 \cdot T_{avg,5\min} - 3.09291 + \varepsilon \quad (2)$$

$$TSV_{UpperLeg} = 0.05854 \cdot PlateTemp_{Upper} - 0.05548 \cdot T_{avg,5\min} + 0.11374 + \varepsilon \quad (3)$$

Bottom plate temperature was also a significant predictor for thermal sensation in the lower leg and foot (scatter plots Fig. 3 and model equations in equations (4) and (5)).
No significant covariance between overall or local TSV and middle plate temperature was found. In Table 1, p-values of plate temperature as a predictor of TSV and $R^2_{GLMM(m)}$-values for all statistically significant models are given.
There was one data point (14.4°C TSV 2.0), not pictured in Fig. 3 that seemed to be an outlying value although it was not marked as such during the data pre-processing. This value stems from a survey where the subject at one point during the experiments felt warm. Further testing with more subjects is needed to take conclusive actions regarding this data-point.

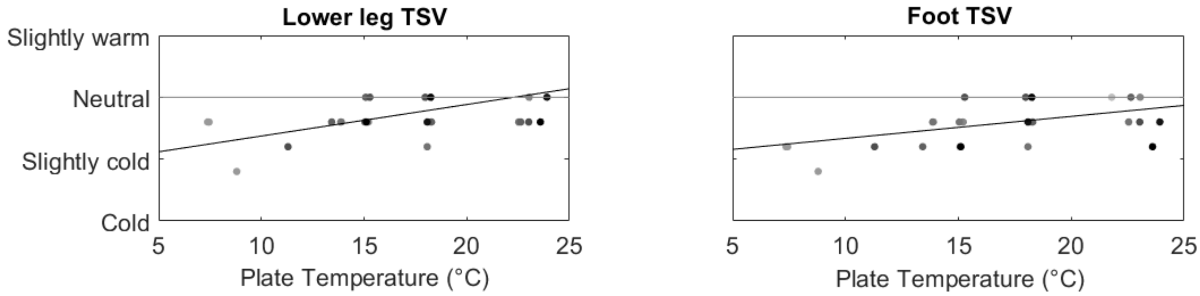


**Fig. 3:** Lower leg and foot TSV vs temperature of the bottom plate

$$TSV_{LowerLeg} = 0.05088 \cdot PlateTemp_{Bottom} - 0.67056 \cdot T_{avg,5\min} + 14.11548 + \varepsilon \quad (4)$$

$$TSV_{Foot} = 0.03557 \cdot PlateTemp_{Bottom} - 0.25548 \cdot T_{avg,5\min} + 4.78984 + \varepsilon \quad (5)$$

**Table 1: p-values of plate temperature as a predictor of TSV and $R^2_{GLMM(m)}$ of all significant models**

| | p | $R^2_{GLMM(m)}$ |
|---|---|---|
| Upper arm TSV – Upper plate temperature | 0.0128 | 0.335 |
| Lower arm TSV – Upper plate temperature | 0.0037 | 0.426 |
| Upper leg TSV – Upper plate temperature | 0.0276 | 0.276 |
| Lower leg TSV – Bottom plate temperature | 0.0073 | 0.576 |
| Foot TSV – Bottom plate temperature | 0.0356 | 0.286 |

## DRAFT PERCEPTION

Draft perception was rated with the question: “Do you experience draft?” Subjects could answer “Yes” or “No” for the whole-body and 9 different body regions. In 76,7% of the cases, if subjects

indicated that draft was felt, it was in the leg region (upper legs, lower legs or feet), compared to only 15,0 % in the arms region (upper arms, lower arms or hands) and 8,3% in the head region (head or neck). No subject ever indicated to experience draft at the chest.
Analysis showed that a significant majority of people indicated to experience draft overall ($p = 0.023$) and at their lower leg ($p = 0.017$) when the bottom plate was set at the coldest setting: 10°C below ambient temperature. In that case, 83% of people indicated they felt draft in general, with 67% and 50% of subjects experiencing draft at lower legs and feet respectively.
These results show that local cooling of the lower legs is often mistaken for draft. As expected, sensation of draft is strongest in the bodies' extremities, such as the arms and legs, and almost none–existent in the bodies' core and head region. This further strengthens the hypothesis that local radiative cooling can be mistaken for draft in the bodies' extremities.

## CONCLUSIONS

Local radiant asymmetry does influence local thermal sensation, but not overall thermal sensation. The effect is relatively small and can make local thermal sensation in the bodies' extremities, especially the arms, variate between "slightly cold" and "slightly warm".
This effect can influence the comfort of people residing in renovated buildings. When not enough attention is paid to construction joints during renovation, local cold spots can arise on walls. Local radiant asymmetry due to these local cold spots influence thermal sensation.
Local radiant cooling of body regions is often mistaken as draft by people, especially in the bodies' extremities. This is probably due to people feeling the local cooling effect, but identifying it as draft because they are more familiar with it. In further research into small local cooling effects, it is therefore important to not only ask subjects whether body regions are warm or cold, but also whether they experience draft. When trying to solve draft problems in existing buildings, it may also be a point of interest. Complaints about draft may not always be due to air movement, but may also stem from local radiant cooling. This can help identify and resolve the source of local thermal discomfort.

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