# The influence of colliding supply jets on predicted and perceived thermal comfort

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**Abstract.** The aim of this study was to examine the effect of draught caused by colliding supply jets from above the occupant on thermal comfort in laboratory conditions. The study had a repeated measures design with two conditions: A) temperature T=23.2 °C, air speed v<0.1 m/s, draught rate DR < 10 %, supply airflow Q= 30 l/s, and B) T=22.8 °C, v<0.4 m/s, DR < 30 %, Q= 70 l/s. Thirty-six volunteer university students participated in the experiment. Participants' clothing insulation was estimated to correspond 0.71 clo and the main task was typing (activity level 1.1 met). The session lasted altogether 2.5 hours including a preparation phase and both test condition phases. Overall thermal comfort, local thermal comfort, and sensation of draught were assessed with questionnaires. The difference between conditions was mainly seen in subjective measures, but small difference was also observed in the work performance. The study highlights the importance of airflow patterns in the occupied zone of an office. The results can be used in the planning and product development of air conditioning and supply air distribution in offices.

**Keywords.** Draught, thermal comfort, test chamber, PMV, perception

## 1. Introduction

Thermal environment affects occupants' thermal sensation and comfort (Parsons 2003; De Dear et al., 2013; Maula et al., 2016a). Thermal environment includes air temperature, air relative humidity, and air speed. The effect of thermal environment on occupants can be studied with thermal sensation vote (TSV).

The mean value of thermal sensation votes of a large group of people can be estimated with PMV model (ISO 7730, 2005). The model is based on the heat balance of the human body. It uses the 7-point thermal sensation scale: Cold (-3), Cool (-2), Slightly cool (-1), Neutral (0), Slightly warm (1), Warm (2), and Hot (3). The PMV model considers people as a group and does not take into account individual factors such as age, body mass index or gender. For example, females have been found to be more dissatisfied than males, especially in cooler conditions (Karjalainen, 2011; Schellen et al., 2012).

People are more sensitive to draught when their thermal sensation is Neutral or cooler. Draught is defined as unwanted local cooling of the body caused by air movement (ISO 7730, 2005). Draught rate (*DR*) is the percentage of people predicted to be bothered by draught. The DR model applies to people, such as office occupants, having a light activity with thermal sensation close to Neutral. The draught rate can be calculated with **equation 1**:

$$DR = (34 - t_{a,l})(\bar{v}_{a,l} - 0{,}05)^{0{,}62} \times (0{,}37 \times \bar{v}_{a,l} \times Tu + 3{,}14) \quad (1)$$

where $t_{a,l}$ is the local air temperature (°C), $\bar{v}_{a,l}$ is the local mean air velocity (m/s), and $Tu$ is the local turbulence intensity (%). Draught rate should be < 10 % in thermal environment category A and < 30 % in category C (ISO 7730, 2005).

Complaints regarding thermal discomfort in offices are often related draught, especially in cold or temperate climate regions. Space efficiency demands have increased the heat load in offices, and increased cooling is needed to control the room air temperature. Draught problems can occur in these situations when the workstation is located in the downfall area of the inlet jet. Koskela et al (2010) confirmed this phenomenon in a study of airflow patterns and mean air speeds in a full-scale open-plan office laboratory. They found that one of the main cause of draught risk is downfall of colliding supply jets.

There are many studies in literature about the effect of too warm environment, too cold environment, or locally increased air movement, for example using table fans, on thermal comfort and perception (Parsons, 2003; De Dear et al, 2013, Maula et al., 2016b). However, the literature is lacking variety of studies with human subjects, where the draught is caused by different HVAC solutions (De Dear et al., 2013). These include above-mentioned case with workstation in the downfall area of the collided inlet jets. More knowledge is needed about the comfort and perception effects of real-life draught situation where draught is generated from increased heat loads and cooling with HVAC solution, while room temperature itself is kept at good level. In addition, many studies related to draught have used set-up of supply air terminals, where participants can easily guess that the research question is related to air movement. More research is needed in a realistic office environment with subjects that are unaware that the research question is related to air movement and do not have expectations towards the test objectives.

The aim is to examine the effect of increased air movement on occupants' perception in an office laboratory simulating a draught situation caused by downfall of colliding supply jets. The mean thermal sensation vote is compared to the predicted mean thermal sensation vote gained from the PMV model.

# 2. Methods

## 2.1 Participants

Thirty-six volunteer university students participated in the experiment (16 males, mean age 26 years, range 19-43 years). The participants were advised beforehand to wear t-shirt, trousers, and ankle-length shoes (0.71 clo including office chair; ISO 7730). The main activity was working with the computer (1.1 met; ISO 7730). The participants were compensated for their effort and time with a gift voucher worth 30 euros. The participants were not told about the purpose of the study.

## 2.2 Experimental design and procedure

The experiment was carried out in spring 2022 in the environmental chamber at the psychophysics laboratory, Turku University of Applied Sciences, Finland (**Figure 1**). The chamber has two similar test rooms, 1 and 2, where indoor air quality, thermal environment, lighting, and acoustics can be controlled. Test rooms represents typical office rooms with commercially available products. Active chilled beams were used as supply air terminal devices.

The study had a repeated measures design, where each participant was exposed to both conditions one after the other. The two conditions were:

A. room air temperature $T$=23.2 °C, air speed $v$<0.10 m/s, draught rate $DR$ < 10 %, supply airflow $Q$= 30 l/s, and

B. room air temperature $T$=22.8 °C, air speed $v$<0.40 m/s, draught rate $DR$ < 30 %, supply airflow $Q$= 70 l/s.

Conditions A was B were implemented in rooms 1 and 2, respectively. The order of conditions was counterbalanced. The test conditions were planned and implemented by taking into account the PMV model and the draught classifications of the ISO 7730 standard (2005). First, the condition A was planned so that the predicted mean vote (*PMV*) is close to Neutral and the draught risk is less than 10% (class A in ISO 7730). Second, the condition B was implemented by increasing the heat loads, in which case greater cooling power was needed to maintain the desired temperature. The higher cooling power increased the air speeds and draught in the occupied zones. The condition B was planned so that it the draught risk felled into class C ($DR$ < 30 %, ISO 7730).

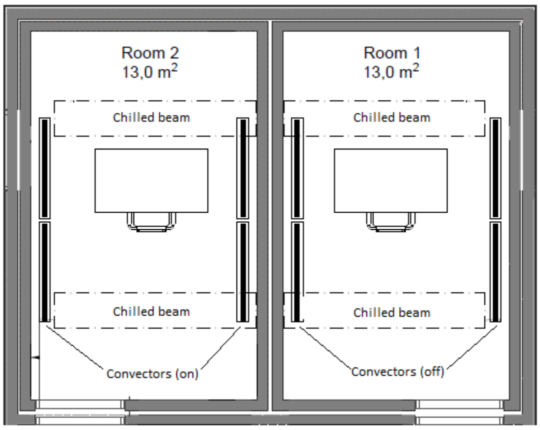
According to the PMV model, the predicted thermal sensation vote is -0.46 in the condition A, and -1.10 in the condition B. Similarly, in the condition A, the predicted percentage of dissatisfied (PPD) is 9 % in the condition A, and 30% in the condition (ISO 7730, 2005). In addition of before-mentioned parameters, relative humidity of $RH$=21 % (in both conditions) and air speed $v$=0.10 m/s (condition A) and $v$=0.35 m/s (condition B; Sivula et al., 2023) was used in PMV-PPD calculations.

Air speeds were measured from horizontal plane above participant (1.5m from the floor, 10 cm * 10 cm measurement grid). The mean air speeds were sampled for 3 min with hot-sphere anemometers (Dantec Dynamics A/S, Denmark, accuracy of 5% of reading ±0.01 m/s). The airflow patterns, local air speeds and draught risks in the test condition B are explain in detail by Sivula et al. (2023).

The condition B was built with 1300 W higher heat load (convectors in **Figure 1**). Therefore, 1300W higher cooling power was needed than in the condition A. Convectors were used instead of radiators to avoid differences in thermal radiation between the conditions. Both rooms had similar visual appearance, so that the participants did not see the difference between the two conditions while entering the room. Both rooms included also convectors. However, they were not heated in room 1. Fresh outdoor air was supplied with two chilled beams in both rooms.

**Figure 1**

*The layout of the environmental chambers. The room height is 2.8 m. Chilled beams are installed into suspended ceiling with exposed installation.*




The session lasted altogether 2.5 hours including a 30 min preparation phase and first experimental phase (60 min), and second experimental phase (60 min). Participants read and signed the informed consent form and worked with the computer (activity of 1.1 met; ISO 7730) during the preparation phase. Both experimental phase involved questionnaires at the beginning, in the middle, and at the end.

### 2.3 Questionnaires

The thermal comfort and the perception of air movement were assessed with questionnaires (MATLAB R2018a). Overall thermal sensation was asked using a seven-point response scale (3 Hot, 2 Warm, 1 Slightly warm, 0 Neutral, -1 Slightly cool, -2 Cool, and -3 Cold, ISO 7730). Local thermal comfort were assessed by asking participants to list body parts where they felt "specially cold" and body parts where they felt "specially warm".

All participants were asked whether they feel air movement or not, and further questions were presented if they replied "yes". The pleasantness of the air movement was inquired with a five-point response scale (-2 Very unpleasant, -1 Slightly unpleasant, 0 Not pleasant or unpleasant, 1 Slightly pleasant, and 2 Very pleasant). The air movement preference was asked with a three-point response scale (1 Less, 2 More, and 3 No change). The local sensation of air movement, the body parts where air movement is felt as pleasant and the body parts where air movement is felt as unpleasant were asked. The annoyance of the air movement was assessed with a question: "How much does the air movement disturb, annoy or bother you?" Participants replied with an 11-point response scale form 0 (Not at all) to 10 (Extremely). Participants responding 5 or more was considered as annoyed due to the air movement.

### 2.4 Analysis

Statistical analyses were conducted with IBM SPSS Statistics for Windows, Version 26.0 (Armonk, NY: IBM Corp.). The normality of the data was tested with Shapiro-Wilk test. A repeated-measures ANOVA was used for the normally distributed or similarly skewed data. The Greenhouse-Geisser correction was applied when Mauchly's test indicated violation of sphericity, and the corresponding p-values are reported. Wilcoxon's test was used for variables that were not normally distributed or similarly skewed. A p-value of 0.05 or less is considered as statistically significant.

## 3. Results

### 3.1 Thermal comfort

Condition had a significant effect on the mean thermal sensation vote ($p<0.001$, **Table 1**). The percentage of dissatisfied was higher in the condition B (**Table 1**). Females felt cooler than males despite similar clothing (**Table 1** and **Figure 2**) and statistically significant difference between genders was seen on thermal sensation vote at the end of the condition B (**Figure 2**).

Hands and feet receive inconsistent responses in open questions. Part of the participants reported hands and feet to be felt as specially cold and part of the participants reported them as specially warm (**Tables 2 and 3**). Other body parts, such as the face, head, neck, torso, back and thighs, were mentioned in less than 3 % of responses.

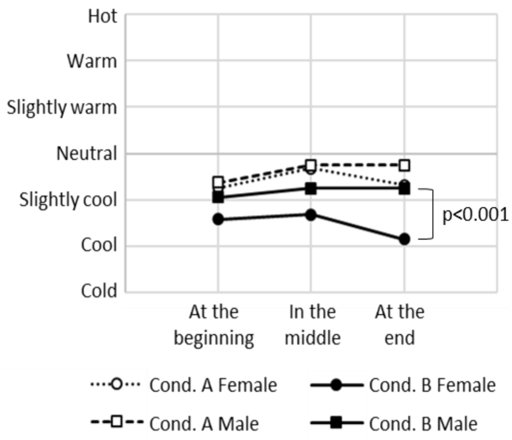
**Table 1**

*The mean thermal sensation vote (TSV), standard deviation (in brackets) and the percentage of dissatisfied (PD, %) in both conditions. The response scale for TSV is 3 Hot, 2 Warm, 1 Slightly warm, 0 Neutral, -1 Slightly cool, -2 Cool, and -3 Cold.*

| | Condition A | | Condition B | |
|---|---|---|---|---|
| | TSV | PD | TSV | PD |
| All | -0.5 (0.9) | 24 | -1.2 (0.9) | 60 |
| Female | -0.6 (0.9) | 33 | -1.5 (0.9) | 68 |
| Male | -0.4 (1.0) | 15 | -0.8 (0.9) | 52 |

**Figure 2**

*The mean thermal sensation vote at different exposure times in both conditions classified by gender.*




### *3.2 The perception of air movement*

The participants were not told about the higher air speeds in the condition B, which had a visually similar appearance as the condition A. The participants reported that they felt air movement in 90 % of responses in the condition B. Among those responses, 64 % reported that the air movement was unpleasant and 80 % would have preferred less air movement. **Figure 3** shows the body parts where air movement was felt and the percentage of responses reporting to feel air movement in that body part. The percentage of responses reporting air movement to be pleasant or unpleasant in different body parts is presented in **Table 4**. More participants were annoyed by draught in the condition B than in the condition A ($p<0.001$).

**Table 2**

*The percentage of responses [%] reporting body parts to feel as "especially cold" or "especially warm" in the condition A. Other body parts were mentioned in less than 3 % of responses.*

| | Hands | feet |
|---|---|---|
| Specially cold | 30 | 5 |
| Specially warm | 4 | 17 |

**Table 3**

*The percentage of responses [%] reporting body parts to feel as "especially cold" or "especially warm" in the condition B. Other body parts were mentioned in less than 3 % of responses.*

| | Hands | feet |
|---|---|---|
| Specially cold | 47 | 5 |
| Specially warm | 0 | 16 |

**Figure 3**

*The body parts where the air movement was felt in the condition B, and the percentage of responses [%] reporting to feel air movement in that body part. Only participants reporting to feel air movement is included (N=36 at the beginning, N=29 in the middle and N=32 at the end).*

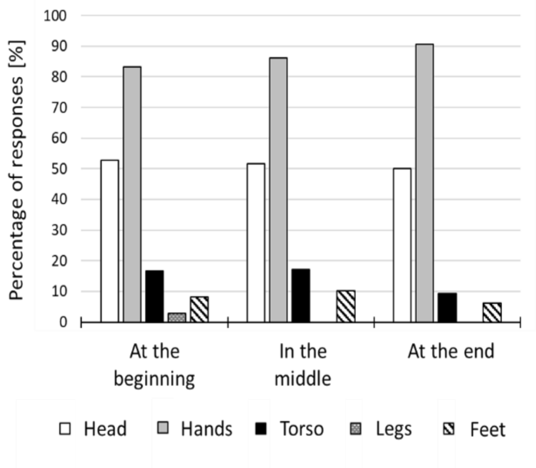



**Table 4**

*The percentage of responses [%] reporting the air movement to be pleasant or unpleasant in different body parts in the condition B. Only participants reporting to feel air movement is included (N=36 at the beginning, N=29 in the middle and N=32 at the end).*

| | Head | Hands | Torso | feet |
|---|---|---|---|---|
| Pleasant | 4 | 8 | 0 | 1 |
| Unpleasant | 19 | 45 | 3 | 3 |

## 4. Discussion

The mean thermal sensation vote in the condition A was near "Neutral" which is in line with previous study by Maula et al. (2016a) having similar activity levels and nearly the same temperature (23.5 °C), but higher clothing value of 0.83 clo.

A gender difference was found, indicating that females feel cooler than males when temperature is near optimal. Similar findings have been seen in previous studies (Maula et al., 2016a; Schellen et al., 2012). A review by Karjalainen (2011) showed that females are more sensitive to deviations from an optimal temperature and express more dissatisfaction than males, especially in cooler conditions. In our study, a statistically significant difference between genders was seen on thermal sensation vote at the end of the condition B. In a previous study of Maula et al. (2016b), no gender difference was seen with higher air speed of 0.8 m/s when room temperature was moderately warm, which conforms the findings by Karjalainen (2011) regarding females sensitiveness to dissatisfaction specially in cooler conditions.

The predicted mean vote (*PMV*) model was able to predict rather well the mean thermal sensation vote for all participants in both conditions but the predicted percentage dissatisfied (*PPD*) model underestimated the percentage dissatisfied (**Table 1**). The PMV was close to the TSV for both genders in the condition A, but underestimated the cooler thermal sensation among females and overestimated the cooler thermal sensation among males in the condition B. In a study by Schellen et al., (2012), both genders were feeling significantly colder than predicted by the PMV during convective cooling in 25 °C.

The perception of air movement was in a contradiction (**Table 4**). The air movement was reported to feel as unpleasant especially in hands and head. However, part of the participants reported the air movement to feel as pleasant in those body parts. Similar findings regarding the local sensation in head region has been seen when participants' perception of the air movement is studied in moderately warm conditions (Maula et al., 2016b).

There are limitations why these results shall be cautiously applied in practice. All of the participants were healthy young adults. Participants' clothing insulation and activity level were not measured. The participants were exposed to the increased air movement for a shorter time than a normal 8-h workday. Different results might be possible with elderly or unhealthy participants and with longer exposure time. Given clothing and activity level values are estimations based on the standard ISO 7730 (2005). The experiment was conducted in the springtime. Different results may be gained during summer or winter. There are numerous ways of producing increased air movement at workstation. Only one type of HVAC system was studied with a fixed room temperature, relative humidity, subjects' clothing insulation and activity level.

This study responses to the lack in the literature highlighted by de Dear et al. (2013) about the variety of studies with human subjects, where the draught is caused by different HVAC solutions in a realistic office environment. However, due to the diversity of physical parameters affecting to airflow characteristics and thermal comfort, there is still a need for more studies related to this topic. Also, the array of HVAC solutions is so wide that a single study is not enough to cover the lack found in the literature. More human subject experiments with different HVAC solutions in a realistic office environment is needed.

## 5. Conclusion

The PMV model was able to predict rather well the mean thermal sensation vote for all participants in both conditions, but the PPD model underestimated the percentage dissatisfied.

This study responses to the lack in the literature of the variety of studies with human subjects, where the draught is caused by different HVAC solutions in a realistic office environment. It highlights the importance of airflow patterns in the occupied zone of an office. The results can be used in the planning and product development of air conditioning and supply air distribution in offices. Due to the diversity of affecting physical parameters related to the airflow characteristics, and array of HVAC solutions, more research in this topic is needed.

## 6. Acknowledgements

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