



Assessment of Thermal Comfort in the Intelligent Building – Differences in Room Users' Perceptions

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Abstract: The article discusses possible differences in subjective assessment of thermal sensations of people in the intelligent building "Energis" of Kielce University of Technology with a focus on the impact of gender. The measurements took place in 52 educational rooms, during which 1143 questionnaire forms were collected from the respondents. Thermal sensation, acceptability, and preference votes were analyzed. The results indicate that women and men might perceive the indoor environment differently. Generally speaking, men seemed to rate colder environments as warmer, while hotter environments as cooler than female responses. However, the dependence of thermal preference vs. thermal sensation votes was almost identical for both genders, indicating the same character of perception of both parameters when they are considered together. Similarly, the highest thermal acceptability rating was recorded for the same range of thermal sensation votes from about -0.25 to +0.25 for both women and men.

Keywords: thermal comfort, thermal sensation, acceptability, preferences

1. Introduction

Thermal comfort research has been going on continuously for about 100 years. Over the last dozen or so years, there has been an increase in publications on the microclimate and thermal comfort in buildings. Many experimental studies are carried out in lecture halls at universities and school halls. Such studies are the most reliable for determining the average assessment of thermal sensations. Thermal comfort assessment in buildings is one of the key issues in the design of indoor environments aimed at ensuring optimal conditions for users. Thermal comfort refers to the subjective satisfaction with thermal conditions and depends on many factors, mainly the surroundings and indoor environment. Individual differences, including biological and social differences, can affect the perception of thermal conditions. One important aspect in this field is the influence of personal identity – namely gender – on the sensation of thermal comfort. This impact has recently been recognized in other areas (Szadvári et al. 2023). Thus, physiological differences, such as metabolic rate, body weight composition, or endocrine system, can significantly affect the body's response to ambient temperature. In addition, cultural and social differences related to clothing choices or space use can further shape subjective feelings of thermal comfort by gender.

The study (Rupp et al. 2018) took place in four office buildings situated in a humid subtropical climate zone of Brazil and examined the influence of weight, type of ventilation, and gender on thermal sensations. The authors noticed that men, overweight people, and people who spend more time in air-conditioned rooms experience thermal discomfort compared to people with a lower BMI (body mass index), women, and people who use air conditioning less often. Moreover, women were more likely to declare 'cold' discomfort. According to the research (Maycot et al. 2018) conducted on 584 participants in two Brazilian office buildings, women prefer higher air temperatures in air-conditioned and mixed-mode buildings - naturally ventilated or air-conditioned. Generally speaking, the comfort temperature was 23.2°C for men and 24.0°C for women.

The article (Asif et al. 2022) describes the study of the influence of gender on the perception of indoor thermal comfort in summer and winter. It compares the methods of predicting comfort temperature. The study was conducted in Pakistan and included 971 participants (526 women and 445 men) of different age groups living in dormitories. The study aimed to understand whether gender has different requirements for comfort temperature in different seasons and which temperature prediction methods are best for assessing



thermal comfort. The study results showed that women had higher comfort temperature requirements than men in both summer and winter. Even though the thermal sensation of both genders was statistically different, no statistically significant difference in indoor comfort temperature was observed. The values of comfort temperatures were 26.4°C and 27.8°C (for summer) and 22.7°C and 22.4°C (for winter) for women and men, respectively. However, it needs to be noted that according to the study (Cao et al. 2016) conducted in three climatic zones in China, people living in the warmest environment adapt better to the cold environment. This fact might also, to some extent, influence the thermal sensation of the individuals taking part in the questionnaire studies.

According to the paper (Hwang et al. 2006), where test results of measurements in ten naturally ventilated and twenty six air-conditioned campus classrooms were presented, women had a narrower neutral temperature range and adjusted their clothing level more swiftly as the temperature changed. Concerning thermal preference, the share of females who were satisfied with their thermal environment was lower than that of males in the same room. In the study (Indraganti et al. 2015) of thermal comfort in twenty eight office buildings in India, statistically significant gender differences were confirmed regarding comfort temperature, thermal acceptability, and the use of controls such as windows. It turned out that thermal acceptability and comfort temperature in the female group were considerably larger than in the male group. Additionally, the average clothing insulation of females was 0.1 clo higher than that of males. The authors also concluded that it would be welcome to be sensitive to gender issues in the design of indoor environments to increase women's participation in the labor force in India (which is much less than men's). According to (Indraganti & Rao 2010), women expressed slightly higher thermal sensations, preferring warmer environments. Moreover, their thermal acceptance was higher than men's (88% for women vs. 83% for men). At the same, a larger percentage of females (74%) were satisfied with the thermal conditions, whereas only 69% of the males considered the same conditions comfortable. The tests (Karjalainen 2007) conducted in homes and offices in Finland generally showed that women were less satisfied with thermal environments than men and felt cold and hot more often than men. In residential buildings, females preferred higher temperatures than males (although men tended to use thermostats more often). The results also suggest that women are more critical of their thermal environments. It needs to be added that women in the offices were less satisfied with room temperatures during the winter and summer seasons and felt hot more often during the summer. A study conducted by (Parsons 2002) of two groups of sixteen persons indicated that differences in thermal responses for identical clothing and activity for both genders could be found. The author concluded that women tend to be cooler than men in cool conditions. Moreover, the author indicated that changes in thermal responses in neutral and slightly warm indoor environments due to heat acclimation were small. Moreover, the review paper by (Luo et al. 2018) indicates that pregnancy and menopause status could influence thermal sensations in rooms.

As can be seen, the person's individual features can have an impact on the thermal sensations experienced by the respondents during the tests. Naturally, other aspects of the indoor environment are important, such as ventilation (Telejko & Zender-Świercz 2017, Zender-Świercz 2021) and heating systems (Nogaj et al. 2017, Nogaj et al. 2018, Stokowiec et al. 2023). In fact, the impact of gender has also been observed concerning the sick-building syndrome symptoms. According to (Krawczyk et al. 2023), men and women experienced those symptoms differently, especially dizziness and nausea.

Since the beginning of the 21st century, there has been noticeable technological progress in areas such as computer science, electronics, and telecommunications, as well as automation and robotics, which has led to a different approach to solving issues of control and supervision of building installations than those in force several decades earlier. Also, for several years, there has been noticeable progress in the field of artificial intelligence, including in the field of intelligent buildings. However, the term "intelligent building" appeared in the early eighties of the last century. Initially, it only covered buildings equipped with advanced automation of installations and systems. The correctness of this term raised doubts. The "intelligence" of such buildings was questioned, and it was claimed that it would be more appropriate to talk about the "instinct" of the building (Duszczyk et al. 2019). Information technology is included in the definition and is important for an intelligent building, but it is insufficient to present a complete picture of such a facility. This is reflected in the definition proposed by P. Robathan in 1989: "An intelligent building creates conditions that maximize the efficiency of the building user and at the same time allow for the efficient management of resources with minimal operating costs" (Robathan P 1989). An intelligent building is therefore characterized not only by high technical quality but must be characterized by broadly understood quality to meet users' requirements. However, whether a building is intelligent is determined by the presence of a single management system for all installations, the so-called BMS (Building Management System) system (Biskupski 2009).

The literature provides some experimental data on the impact of gender on thermal comfort. However, the results reported by various researchers are often contradictory, and the widely accepted view on the influence of gender does not exist. Moreover, the studies are typically conducted in traditional buildings, and the analysis of the impact of gender in intelligent buildings has not been found in the literature, especially in the case of Central Europe, where limited experimental datasets and scientific reports on this issue can be found. The present paper aims to bridge this research gap and consider a large experimental database of over one thousand questionnaires.

2. Subject and Methods of the Study

Research on thermal comfort was carried out in an intelligent building, "Energis" at the Faculty of Environmental Engineering, Geodesy, and Renewable Energy. It was developed using modern building technologies (Kosiń et al. 2020) and is currently equipped with several renewable energy sources such as solar collectors, photovoltaic panels, heat pumps, and a wind turbine. The application of environmentally friendly technologies is widespread these days (Kowalik et al. 2021, Nešović et al. 2024, Patsch & Pilát 2018, Pilát et al. 2014) however, integration of renewable energy systems into a large educational building might be a challenge. Thus, the building is equipped with Building Management Systems. The software enables efficient use of the available systems and data from the sensors, which can also be used for modeling purposes (Major & Major 2014).

The study took place in the building presented in Figure 1a, while Figure 1b shows the largest lecture hall there, located on the 4th floor. The photo was taken during the measurements, which utilized the microclimate meter BABUC/A with attached probes.



Fig. 1a. Intelligent building "Energis": North - Western side



Fig. 1b. Measuring set-up in a lecture hall

The measurements covered all the indoor environment parameters (air and globe temperature, relative humidity, airflow velocity, and carbon dioxide level) – the LCD display of the microclimate meter presented in Figure 1b shows the recorded parameters in real-time. The respondents were asked to complete a questionnaire survey that contained questions about their thermal sensation, acceptability level, and preferences regarding the temperature within rooms. The questionnaire was anonymous and took several minutes to complete. The study took place in 52 rooms of the building (some rooms were used more than once) and was based on the analysis of 1143 questionnaire forms (with an almost equal share of females: 593 and males: 550) filled in mainly by students, whose average age was 21.9 years old. The standard deviation of the age of the surveyed persons was 2.94. Figure 2 presents the BMI (body mass index) histograms for the women and men who took part in the present study. The BMI index was calculated as the ratio of the mass over height squared. The value of this index was typically lower for women and amounted to 17.5-24 kg/m², while for men, it was typically 20-26 kg/m². The mean value of BMI was 22.5 kg/m² (standard deviation: 4.1 kg/m²). The weight of the respondents was, on average, 68.9 kg (standard deviation 14.8 kg), while their height was 1.73 m (standard deviation 0.09 m).

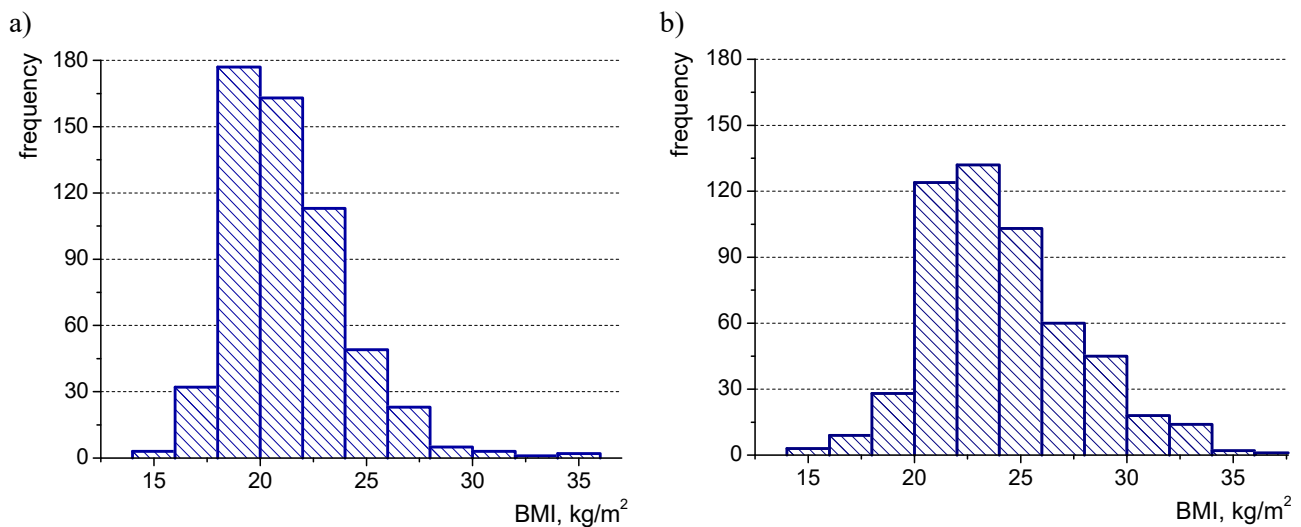


Fig. 2. Histograms of the BMI index of female (a) and male (b) respondents

Before the study, the building was analysed with an infrared camera to check if there are any thermal bridges or other problems that could affect the thermal sensation of the people within the rooms. Figure 3 presents the results of the infrared tests carried out during winter conditions from the outside (a, b) and inside (c) of the "Energis" building. No problems were detected that could influence the volunteers' responses. Moreover, the quality of thermal insulation materials is high enough, and the building is close to the passive building standard. This can be obtained with proper thermal insulation (Pavlenko & Szkarowski 2018).

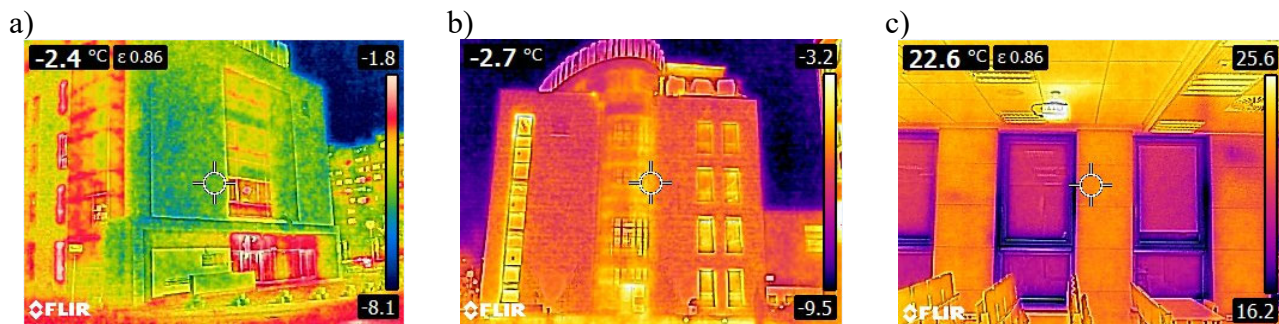


Fig. 3. Thermographs of the intelligent building from the outside: North (a), South (b), and inside: lecture room on the first floor (c)

The thermal imaging results indicate increased heat losses at the entrance to the building (Fig. 3a), which is made of glass. Similarly, the staircase on the right side of this image also shows increased heat losses, as well as the window just above the entrance. The same phenomenon can be observed in Fig. 3b, with hotter glass partition in the central part. The window areas in Fig 3c are also responsible for elevated heat losses. These locations are typical sites where thermal losses are found in buildings, thus, they should not be considered sources of problems regarding the thermal performance of the "Energis" building.

3. Results and Discussion

The results obtained from the survey allowed the respondents to assess their thermal sensations in the tested rooms. First, the respondents were asked about their sensations (TSV – Thermal Sensation Vote), which are on a seven-point scale following (ASHRAE Standard 55 2017) and the international standard (ISO Standard 7730 2005). On the x-axis, these values mean: 3 – too hot, 2 – too warm, 0 – pleasant, 1 – pleasantly warm, -1 – pleasantly cool, -2 – too cool and -3 – too cold. The question was: "How do you rate your thermal sensations at the moment?". Figure 2 below shows a graph showing the average thermal sensations felt by women and men in each room (each dot represents one room, where two values of TSV were calculated – separately for women and men sitting there).

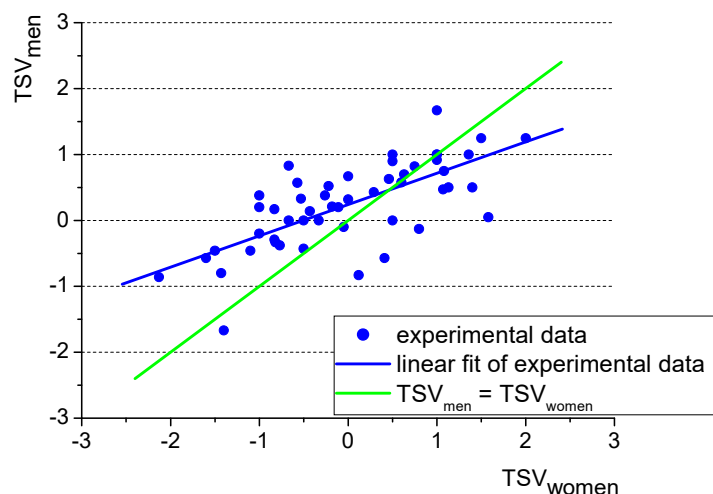


Fig. 4. Mean thermal sensation ratings for women and men in 52 rooms

The above graph shows the relationship between sensations experienced by women and men. The straight blue line represents the linear fit of the data (the regression coefficient was $R^2 = 0.5$, which can be considered relatively good for the survey type of measurements). The resulting relationship is of the form:

$$TSV_{men} = 0.4752TSV_{women} + 0.2412 \quad (1)$$

The experimental points indicate a difference concerning the sensations of both genders. If the sensations were the same, the linear fit would be like the green line in Figure 2 (which represents the same values of TSV for both genders; for example, if thermal sensations of women equaled "-2", the same value "-2" would be obtained in the responses from men). However, here, discrepancies occur. Men seem to rate colder environments ($TSV < 0$) as warmer, while hotter environments ($TSV > 0$) as cooler in comparison to the female sensations. This fact should be problematic, especially during the transition periods of the year, when the heating systems are off, and the room air temperature might be low, but also during the summer when high temperatures are common. Naturally, intelligent buildings are equipped with air conditioning systems and can provide cooling and heating on demand, but in the case of traditional buildings or any malfunction in smart buildings, problems with thermal comfort can occur.

The next graph shows the temperature acceptability using the TAV (temperature acceptability vote) indicator. It represents the mean value of the answers given by the respondents to the question: "How do you feel the temperature?" for each room. The respondents could choose from the following answers in the questionnaire form: +2 – definitely acceptable, +1 – still acceptable, -1 – no longer acceptable, -2 – definitely unacceptable. Figure 5 presents the results for the pairs of the average values of TSV for each room, depending on gender.

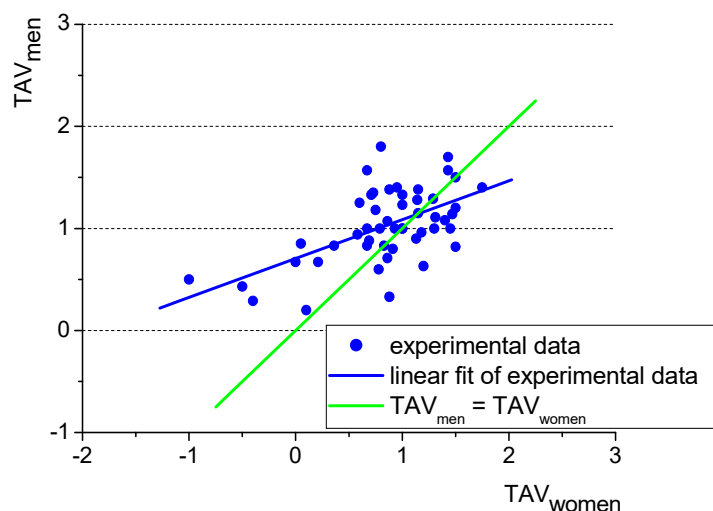


Fig. 5. Mean thermal acceptability ratings for women and men in 52 rooms

In the case of thermal acceptability, differences depending on gender also occur, as evidenced in the figure above. The fitting line for the experimental data does not match the anticipated (green) line of the same responses from men and women. Generally speaking, men were more accepting of the environment than women. For example, when women assessed their surroundings negatively ($TAV < 0$), the responses from men were positive – in the range 0-1. At the same time, a larger share of women considered the environment as very acceptable ($TAV > 1.4$), as opposed to men (about 30% fewer such answers). The linear relationship in Figure 5 takes the following form (with the value of $R^2 = 0.33$):

$$TAV_{men} = 0.3809TAV_{women} + 0.7052 \quad (2)$$

When the students were asked about a possible change in air temperature, they could choose from the following answers: +2 – definitely warmer, +1 – warmer, 0 – no change, -1 – colder, -2 – definitely colder. The results, as the mean value of the responses given in the questionnaire (called Thermal Preferences Vote) in each room for both genders, are shown in Figure 6.

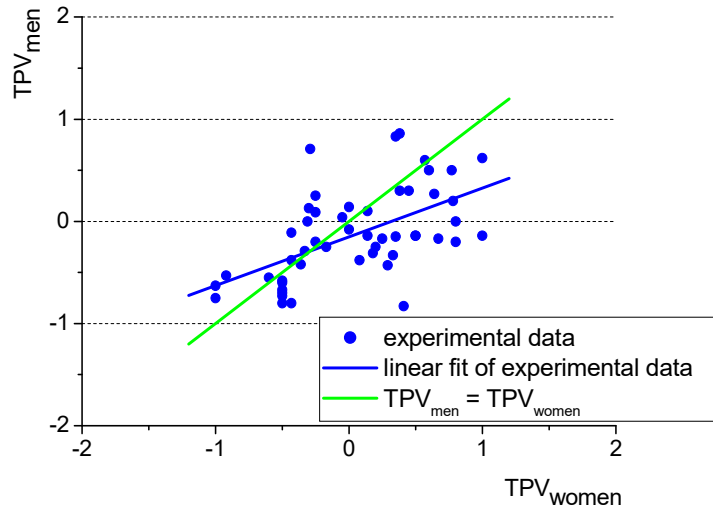


Fig. 6. Mean preference ratings for women and men in 52 rooms

As can be seen, the preferences regarding air temperature also differ, but it could be anticipated because thermal sensations were different for both genders. Women typically opted for warmer environments ($TPV > 0$) than men. A share of women who wanted the air temperature to be higher was larger (56%) than the male voices (37%). The linear fit of the experimental data and the ideal agreement line ($TSV_{men} = TSV_{women}$) intersect at a point of -0.30. The equation of the fitting line in Figure 6 is:

$$TPV_{men} = 0.4758TPV_{women} - 0.1509 \quad (3)$$

While the coefficient of determination R^2 is 0.31. In fact, the values of R^2 of equations 2 and 3 seem to be not particularly high; however, since many factors impact thermal comfort and human sensations are generally subjective, these values of the coefficient of determination should be regarded as enough to develop proper discussion and form proper conclusions about the character of thermal sensations of the respondents.

Indeed, the spread of the experimental data in Figure 6 can be explained by the fact that thermal preferences are highly subjective. Some people prefer warmer environments, while some prefer colder ones. It might come from childhood behavioral patterns or even financial situations (reduced temperature at homes during the winter to reduce heating costs). However, the general trend could be seen clearly in the figure due to the large collected dataset.

The analysis of Figures 4 and 6 reveals that TSV and TPV need to be correlated. Namely, if a person feels hot (and indicates a high TSV value in the questionnaire), that person will want to reduce the air temperature (TPV will be below zero). This theoretical concept agrees very well with the experimental result in Figure 7. If people are highly satisfied with the indoor environment and experience thermal comfort ($TSV = 0$), they don't want any change in their surroundings (TPV also equals 0). The linear fitting lines in the figure confirm it perfectly.

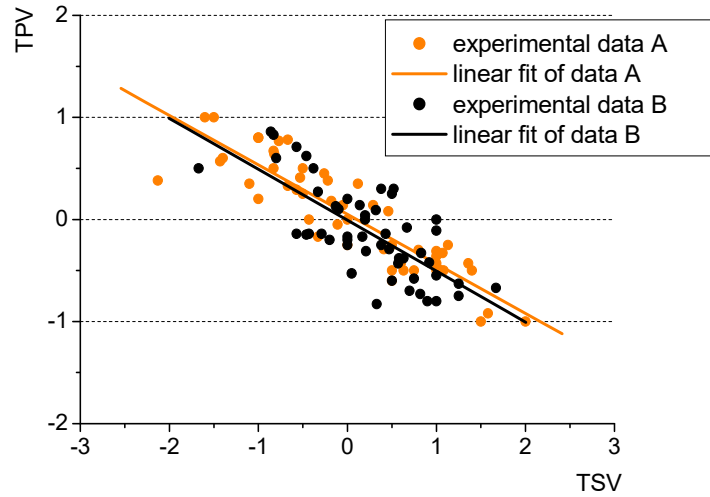


Fig. 7. Dependence of thermal preference vote vs. thermal sensation vote in 52 rooms: A – data for women, B – data for men

Thermal sensations in the cold region ($TSV < 0$) relate to higher TPV values because people want to increase the prevailing temperature. For high TSV values, the opposite is true. Moreover, both fitting lines (for men and women) are almost identical. It proves that internal sensations and the forces behind them are the same for both genders. The equations of the fitting lines in Figure 7 are as follows:

$$TPV_{men} = -0.498TSV_{men} - 0.0069 \quad (4)$$

$$TPV_{women} = -0.4846TSV_{women} + 0.0503 \quad (5)$$

The values of the coefficient of determination of the equations presented above are quite high and amount to 0.53 regarding equation 4 and 0.79 regarding equation 5.

It seems that there might be no clear differences since the heat transfer mechanisms are the same. The surroundings typically have lower temperatures than human beings, so we are talking about the release of thermal energy from the bodies so that the cooling process can occur effectively. It occurs due to conduction, convection, and radiation (especially in low-temperature environments) and through evaporation – in high-temperature environments. It results from phase change being a highly efficient heat exchange mode (Chatys & Orman 2017, Dąbek et al. 2018, Pavlenko & Basok 2005).

Another problem worth considering is the relationship between thermal sensations experienced by the volunteers and their acceptance of the indoor conditions in the investigated rooms. It seems logical that when the students were satisfied with the thermal conditions and marked "0" in the questionnaire as the answer to the question regarding thermal sensations (which means that they felt comfortable), they would also indicate that they highly accept the conditions (and the answers to the question regarding acceptability would be highest – namely +2 or slightly below). Figure 8, which presents a dependence of thermal acceptability vote vs. sensation vote for both genders, confirms this way of thinking. There are, however, some differences between men and women in the shapes of the polynomial fitting curves. Still, they can be attributed to lower values of TAV indicated by the females.

The analysis of the figure above reveals that the highest thermal acceptability rating was recorded for the same range of thermal sensation vote from 0 to 0.25 for both women and men – determined based on the polynomial fitting curves, however, the area marked with the green box in the figure, which groups the highest results occurs for TSV in the range of about -0.25 to +0.25. It confirms the theoretical analysis of this phenomenon that people are most satisfied with the thermal conditions close to neutral. Both cold and hot environments lead to lowering the acceptability rating. It is clearly visible in the experimental data of women due to the fact that they only considered acceptability to be below zero (in the case of men, mean TAV responses were always positive). It seems that no other differences could be observed between both genders in Figure 8. The equations obtained due to the polynomial fitting procedure of the data shown in Figure 7 are given below for men and women, respectively:

$$TAV_{men} = -0.19TSV^2 + 0.14TSV + 1.09 \quad (6)$$

$$TAV_{women} = -0.43TSV^2 + 0.08TSV + 1.24 \quad (7)$$

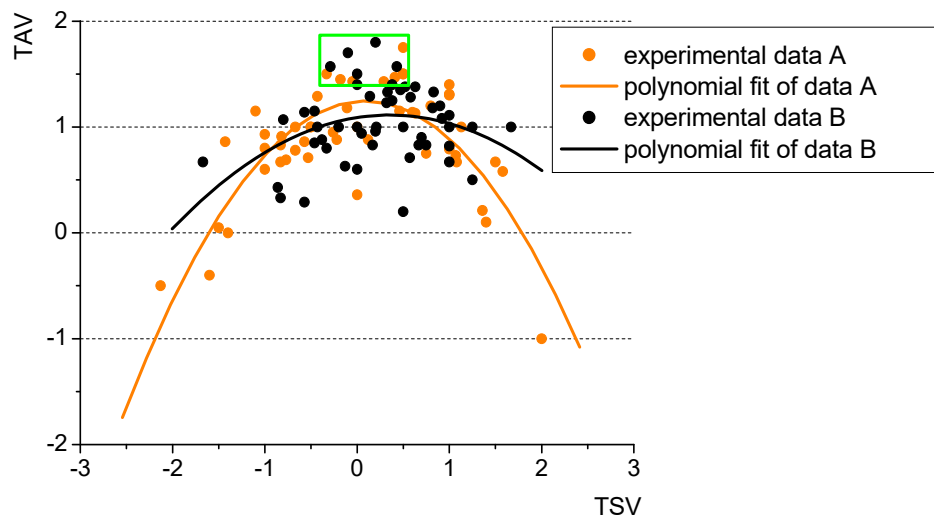


Fig. 8. Dependence of thermal acceptability vote vs. sensation vote in 52 rooms: A – data for women, B – data for men

The coefficients of determination of the above equations equal 0.13 for equation 6 and 0.65 for equation 7.

Naturally, the acceptability of the surroundings could be influenced by other factors in the rooms, such as smell, noise, air movement, and solar radiation through the windows, however, the large dataset seems to overcome a potential influence of these unfavorable factors. Of course, in the same room, they act for each person situated there (both men and women), however, some might be more sensitive to the above-mentioned environmental factors.

A limitation of the study is that it covered experimental data obtained from the age group of the students. Thus, the results might apply to people about 22 years old. Moreover, the measurements were limited to one building, which was an intelligent building. The results in traditional buildings would probably show similar (if not the same) results, however, this has not been validated in the present study.

Another issue of considerable importance is the problem of proper determination of thermal sensations. Various thermal comfort models are available, and the calculations can be performed according to the standards (ASHRAE Standard 55 2017, ISO Standard 7730 2005), however, any modeling is a complex issue (Koshlak & Pavlenko 2020). The Fanger model of thermal comfort is the most widely used, however, its accuracy is often disputed – as discussed in the paper by the authors (Krawczyk et al. 2023), though based on a smaller group of the respondents in only one large lecture theatre. Nevertheless, it would be vital to verify the influence of gender on the calculation results according to the model. The authors can consider this issue in future papers.

4. Summary and Conclusions

Thermal comfort is an important element of the indoor environment. The study took place in the intelligent building "Energis" and covered the analysis of a large dataset of 1143 anonymous questionnaire forms (with an almost equal share of females: 593 and males: 550). In total, 52 rooms were investigated. Based on this large dataset, the following conclusions can be drawn regarding the influence of personal identity (e.g., gender) on thermal comfort conditions:

- men rated colder environments ($TSV < 0$) as warmer, while hotter environments ($TSV > 0$) as cooler in comparison to the female sensations;
- generally speaking, men turned out to be more accepting of the environment than women (when women assessed their surroundings in a negative way ($TAV < 0$), the responses from men were positive (in the range 0-1), also a larger share of women considered the environment as very acceptable ($TAV > 1.4$), as opposed to men (about 30% fewer such answers);
- women typically opted for warmer environments ($TPV > 0$) than men, a share of women who wanted the air temperature to be higher was larger (56%) than in the case of the male voices (37%);
- dependence of thermal preference vs. thermal sensation votes was almost identical for both genders, indicating the same character of perception of both parameters when they are considered together, which might be related to the same mechanisms of thermal balance maintenance;

- the highest thermal acceptability rating was recorded for the same range of thermal sensation votes from about -0.25 to +0.25 for both women and men. At the same time, cold and hot environments have led to a lower acceptability rating. Although some differences between men and women in the shapes of the polynomial fitting curves exist, they could be attributed to lower values of TAV indicated by the female participants.

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