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Investigation of thermal comfort under face masks wearing conditions in the smart building

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The paper analyses thermal comfort of people wearing face masks. The study took place in the selected classrooms of the smart building "Energis" located in Poland. In the experiments 100 respondents participated. They filled in the questionnaire forms, in which they expressed their subjective assessment of the indoor thermal environment. Simultaneously, measurements of the physical parameters within the rooms were performed with a microclimate meter. The results clearly show that the use of face masks influenced thermal sensations of the people - they felt warmer than without the face mask on (at the same air temperature). Moreover, the respondents who wore the masks indicated that the air was more humid in relation to the case when the masks are not applied. The comparison of the obtained actual thermal sensations of the respondents with the calculation results according to the thermal comfort model proved that the model was unable to properly predict thermal sensations of people wearing face masks.

KEYWORDS

heat transfer, smart building, thermal comfort, thermal environment, thermal sensations

1 Introduction

The need to provide thermal comfort to people in buildings require energy input - for example in commercial buildings air conditioning can consume even. 40%–50% (Li et al., 2022). Such high energy needs are associated mainly with the operation of heating, ventilation and air conditioning systems, whose goal is to create and maintain proper indoor air parameters (with air temperature being most important) (Lin and Yang, 2018; Ratajczak et al., 2023). Consequently, depending on the climate, buildings can consume significant amounts of energy just to keep the room users satisfied. Thus, any reduction in excess energy consumption while maintaining the satisfactory level of comfort is highly welcome. In order to achieve it, thermal comfort studies have been conducted around the world for decades, however they do not focus thoroughly on the problem which is a new phenomenon – thermal comfort on people wearing face masks. The occurrence of the COVID-19 pandemic led to a widespread use of such masks. Their influence on thermal comfort is poorly understood due to a short period of time, during which the investigations have been carried out, as well as difficulties in conducting the measurements.

In the experimental study (Rus et al., 2023) male students filled in questionnaires focused on thermal sensations in two university teaching rooms. It was reported that 70% of the respondents who did not wear face masks considered conditions as comfortable, while only 49% of those wearing masks expressed such a favourable opinion. The paper (Zhang et al., 2021) presents the test results conducted with thirty volunteers wearing masks in a climate chamber. The neutral temperature under these conditions was in the range 24–25 °C. Additionally, the authors stated that breathing discomfort increased as the ambient temperature rose. Naturally, thermal sensations experienced in various types of masks can be different, as observed by (Lin and Chen, 2019). According to (Zheng et al., 2023) people with face masks require lower air temperature to feel comfortable. Moreover, it was stated that wearing masks increased the heat sensation within the face to a higher degree and caused discomfort to the face. This study was conducted outside of the buildings, like the next one–on walking people with face masks on (Hu et al., 2024), which shows that they experience higher thermal sensations together with lower thermal comfort. It was also discovered that a person who wears a face mask is more prone to thermal stress. However, according to (Liu et al., 2022) thermal sensations of the respondents wearing and not wearing masks were comparable in the air temperature range of 22–28°C.

On the other hand the authors (Tang et al., 2022) found out that thermal sensations of people wearing masks were only slightly worse than those without masks. These tests took place in a university library and 73.9% of the volunteers indicated that face masks produced discomfort. Some sick building syndrome symptoms were also reported (including dizziness, increased heart rate and sweating) as a result of the usage of masks. In (Liu et al., 2020) different types of face masks were considered to verify their influence on the development of sick building syndrome, for example headache, concentration problems, breathing difficulties. This kinds of problems were also considered by (Krawczyk et al., 2023).

The problems related to the continuous use of masks led to the development of concepts that could provide a remedy. Ventilated masks with additional HEPA filters were proposed in (Huo and Hang, 2021).While in (Zhang et al., 2022) an additional cardboard support frame with openings was designed into the mask, which increased filtration efficiency. It is vital, because better breathing comfort and air quality are key components of indoor environment in modern buildings (Hormigos-Jimenez et al., 2019; Zender - Świercz, 2021; Telejko and Zender-Świercz, 2017).

The literature on thermal comfort with face masks is very scarce due to the fact that the problem began only 4 years ago. Moreover, there were significant difficulties in conducting experiments during the pandemic (only due to the fact that people worked and studied online). The majority of the studies deals with health related problems caused by wearing masks (such as breathing difficulties, headache), while thermal comfort investigations are not very common and quite limited in their scope. Naturally, there are some reports on this issue, however they often focus on the urban environment and are conducted outside of the buildings. The present study aims to bridge this research gap. Moreover, the experiments in the present paper have been carried out in the smart building. Such a study of thermal comfort with face masks inside a modern smart building located in the Eastern Europe has not been found in literature.

2 Material and method

The study took place in Kielce (a medium size city in central Poland), in the smart building called "Energis." It was built in 2012 as part of Kielce University of Technology. Figure 1A presents the photo taken from the North - Western side. The building is equipped with renewable energy sources such as photovoltaic panels, solar collectors and a wind turbine (all of them located on the rooftop), while in the basement four heat pumps are situated that utilise the ground and groundwater as low temperature reservoirs.

The experiments took place in 5 classrooms. Figure 1B presents one of them with the microclimate meter (marked with a red arrow) with the probes – all located on the tripod. The experimental set-up consists of the Testo 400 microclimate meter with probes that measure air temperature, globe temperature (made of a black sphere of the diameter 15 cm), air flow speed as well as relative humidity. The elevation of the probes on the tripod was set at the height of the seated respondents – at a distance, which ensured that no local disturbance from the people occurred (additional air movement due to breathing or locally elevated air humidity and temperature also due to breathing). Moreover, the meter was usually situated in the middle of the room (wherever it was possible). In total one hundred students of similar age took part in the experimental procedure. The selection of the sample groups was based on their willingness to participate in the study. The students participated in regular educational classes. There were between 10 and 17 people in each room. The respondents were 20–30 years old (mean: 22.7 y.o., standard deviation: 2.06 y.o.). Their weight varied from 45 to 100 kg (mean: 72.6 kg, standard deviation: 14.5 kg), while height from 155 to 192 cm (mean: 173.8 cm, standard deviation: 9.9 cm). The respondents wore various types of clothes. The thermal resistance value of their clothing differed from 0.38 to 0.98 clo (mean: 0.64 clo, standard deviation: 0.12 clo). The share of female and male respondents was 43% and 57%, respectively. Figure 2 presents histograms of the physical features, which characterize the volunteers.

The study was designed in such a way that in three classrooms (denoted as A, B and C) the measurements and completing the questionnaires were performed first with the students not wearing masks for the whole lecture and - after it was finished and the next class began after a break - with the students wearing masks. In two other classrooms (X and Y) the volunteers first filled in the questionnaires without the masks on their faces, while after 15 min, they put face masks on and also completed the questionnaires. The air temperature and relative humidity for each experimental pair: with the masks and without them were almost identical.

The survey consisted of four questions and its design was based on the ISO 7730 (ISO Standard 7730, 2005) and EN 15251 (CEN, EN 15251, 2007) Standards. The main criterion of selection was the need to obtain a broad and, at the same time, thorough opinion of the respondents on the subjective qualities of their environment, in which they were situated. Moreover, the view had to be true and unbiased, so the questionnaire was anonymous. The thirst three questions dealt with thermal sensations. The respondents answers the questions on their current thermal state (ranging from very cold to very hot) as well as the level of their acceptance to thermal conditions within the rooms and their possible willingness to change/adjust the air temperature there. The

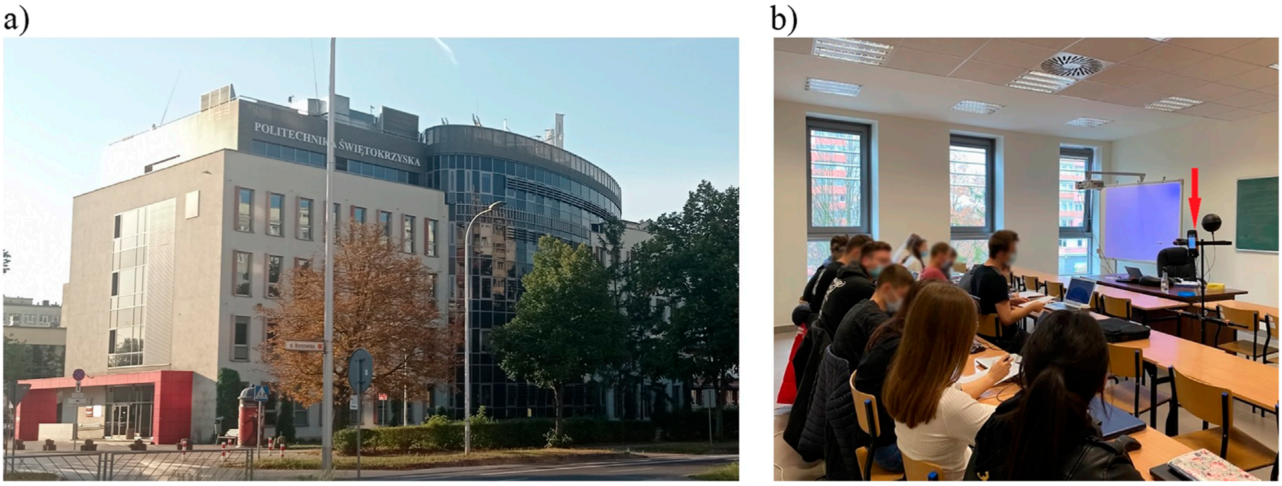

FIGURE 1
(A) Smart building "Energis, **(B)** experimental set-up in a classroom (the red arrow marks the microclimate meter).

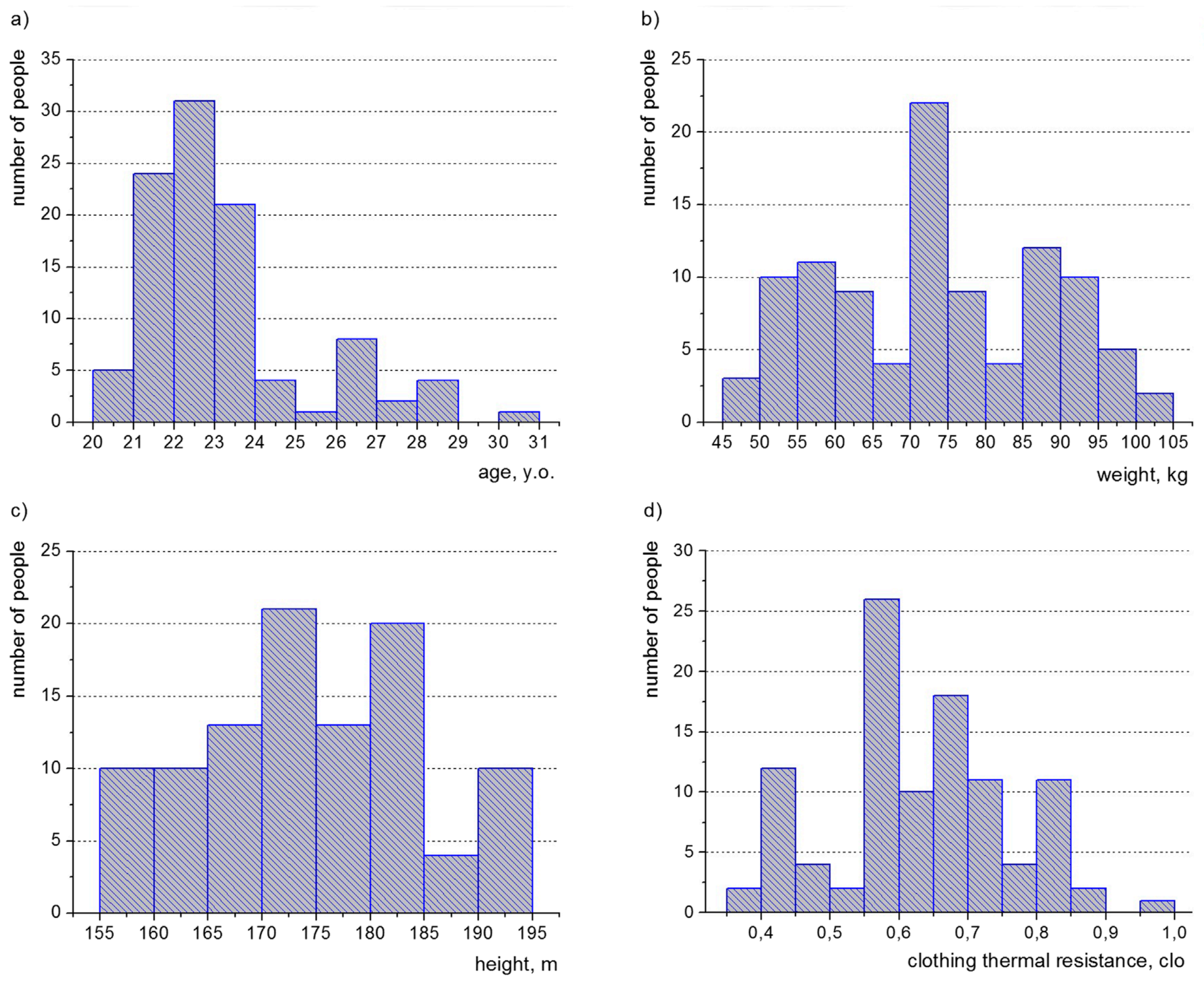

FIGURE 2
Histograms of age **(A)**, weight **(B)**, height **(C)** and clothing thermal insulation **(D)** of the respondents.

TABLE 1 Questions and answers used in the questionnaire survey.

No	Question	Possible answers
1	How would you assess your thermal sensation now?	- too hot (+3) - too warm (+2) - comfortably warm (+1) - comfortable (0) - comfortably cool (−1) - too cool (−2) - too cold (−3)
2	How do you rate the air temperature?	- comfortable (+2) - acceptable (+1) - unpleasant (−1) - highly unpleasant (−2)
3	I wish it would be	- much warmer (+2) - warmer (+1) - no change (0) - colder (−1) - much colder (−2)
4	How do you assess air humidity?	- too humid (+2) - quite humid (+1) - pleasantly (0) - quite dry (−1) - too dry (−2)

last question was focused on the assessment of humidity. Table 1 presents the questions and possible answers to them. The mean answer to question number one ("How would you assess your thermal sensation now?") will be refereed to as "Thermal sensation vote" (TSV), to question number two ("How do you rate the air temperature?") as "Thermal acceptability vote" (TAV), to question number 3 ("I wish it would be.") as "Thermal preference vote" (TPV) and to question number four ("How do you assess air humidity?") as "Humidity Assessment Vote" (HAV).

The volunteers marked the selected answer by ticking the appropriate box among the answers provided in the questionnaire. After the study, the answers provided by the respondents on paper forms were transferred to the computer for further analyses. It needs to be emphasized that the study focused on collecting data on subjective sensations experienced by people under normal operation of the building. It did not interfere with the educational activities, which took place during the measurements.

3 Results and discussion

The air temperature in the investigated rooms ranged from 23.2 to 27.2°C, relative humidity from 24% to 40%, while air flow velocity from 0.05 to 0.08 m/s. Figures 3A–D presents the mean values of the above mentioned parameters calculated based on the answers given by the respondents in the questionnaires for each room (separately for the case of either wearing or not wearing face masks).

As can be seen in Figure 3A thermal sensations of the respondents wearing the masks were higher (except for room B, where there was almost no difference between these two cases) in comparison to the case where the face masks were not applied. The students, who had the masks on their faces, indicated that the environment was warmer or even much warmer than without the masks. Rooms X and Y show the largest and most clearly visible differences. Here, the same group of the respondents did not have any masks on at first, but after a short period of time (15 min) during which they completed the questionnaires, they put the masks on their faces and after some acclimatisation time also filled in the questionnaires. This rapid change and very fresh memory of thermal sensations without the masks seems to be the reason for a sudden increase in the mean Thermal Sensation Vote. Thus, it is very likely that this immediate subjective heat experience may be the most significant contributor which produced this kind of results (naturally, the second factor would be the actual impact of the mask on breathing and thermal insulation). The results presented in Figure 3A show that there is indeed an influence of wearing masks on thermal comfort, however the extent of this effect should be studied in more detail based on a larger dataset. In all the rooms the carbon dioxide concentration was quite similar (about one thousand ppm), with the exception of room X, where almost two thousand ppm were recorded. In this room the difference between thermal sensation vote with and without the mask was largest.

Thermal acceptability (Figure 3B) of the environment when there were no masks applied was higher in three rooms. In room B, where almost no differences were observed regarding thermal sensations, the acceptability level with the masks was quite high. It might be explained by current indoor conditions within this room other then thermal ones such as unpleasant smell or stuffy air (in the case of poorer air quality related to smell, wearing masks could actually help cope with this problem). Thus, the application of the masks could help overcome those unfavourable conditions and, as a result, the respondents assessed the conditions wore positively.

Since the volunteers generally considered that it was warmer while wearing masks, they preferred the air temperature to be lower (Figure 3C), with the exception of room B. Here, almost no difference between the sensations of the people wearing and not wearing masks was observed–which is a reflection of the data in Figure 3A, where also only marginal differences were recorded. The analysis of the degree of preference in rooms X and Y (where exactly the same parameters were observed for the case of wearing and not wearing face masks) indicates that the difference between thermal preference vote with and without the masks was 0.56 in room X and 0.40 in room Y. The air temperature and relative humidity in room X was 23.6°C and 38%, while in room Y: 23.2°C and 32%. Thus, a higher enthalpy environment generated larger degree of preference (stronger willingness of people who were masks to reduce their temperature), which seems reasonable due to meeting the cooling needs. It needs to be added that in all the rooms the respondents felt quite warm due to prevailing air temperature in the range 23.2–27.2°C and, consequently, expressed willingness to reduce the temperature, however it was additionally strengthened by the application of the face masks.

The subjective assessment of humidity (Figure 3D) clearly shows that in all the rooms people with the face masks assessed the air as more humid than in the case when no masks were applied. It seems quite straightforward because the masks act as a barrier between the face and the surrounding air. Due to a high level of water vapour in the exhaled air and its accumulation in the space between the face and the mask (as well as its condensation within the mask's material), the volunteers might have indeed thought that the outside air was

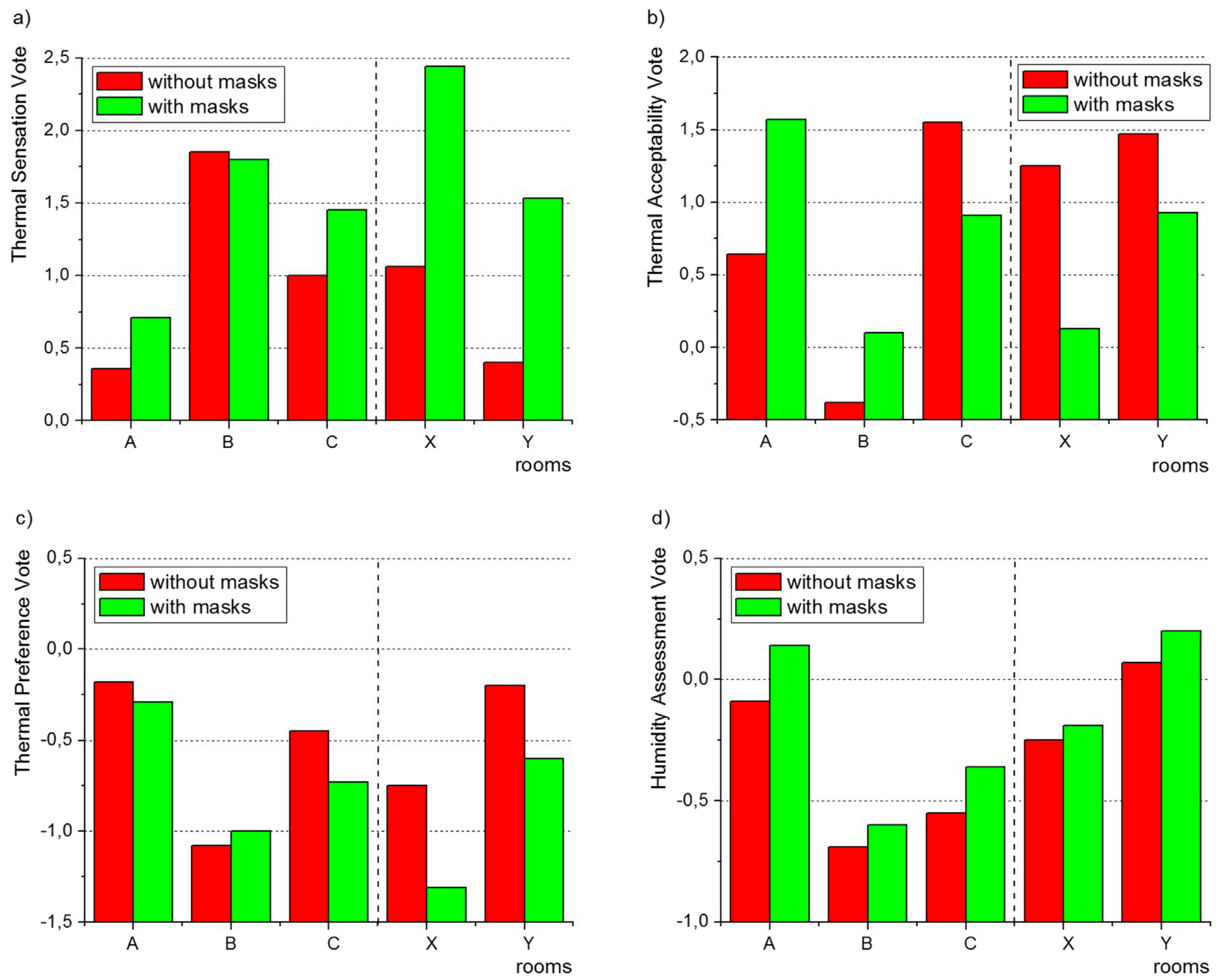

FIGURE 3
Mean values of Thermal Sensation **(A)**, Acceptability **(B)**, Preference **(C)** Votes and Humidity Assessment Vote **(D)** in the educational rooms.

more humid. However, it needs to be added that the difference in the sensations between the case of the presence and absence of the masks is not significant. This proves that despite high vapour content in the air that people wearing face masks breath, they are not able to properly assess humidity level basing only on their senses. It is in line with the findings of the authors regarding humidity sensations of people without face masks (Orman et al., 2024). It seems to be common knowledge that humans are sensitive to temperature change and can (sometimes quite precisely) determine the air temperature in their surroundings, however equally precise determination of humidity is not possible (but of course a rough estimate of a "wet" or "dry" environment can be done). The influence of the use of face masks on thermal comfort within the classrooms has been analysed in more detail in Figure 4.

The dependence of thermal sensations on air temperature (Figure 4A) clearly shows that as the temperature rises, so does subjective sensations of the respondents – into the area of warmer/hotter environment. There are, however, differences between the experimental data where the face masks are used and not used, especially for the low temperature region. As the air temperature increases these differences diminish. It means that the largest impact of the masks is recorded when people do not experience problems with heat removal. Rising temperature leads to elevated thermal sensations and it seems that the additional barrier in the form of the mask becomes more and more neglected in comparison to the thermal stimulation from the surroundings due to high air temperature. The smaller influence of the masks at high temperatures might be related to already high ratings of the thermal environment (there is no large room for maneuver when Thermal Sensation Vote without the masks is already about 2, while the maximal value is 3).

As people feel warmer (Thermal Sensation Vote rises), they would want to reduce the air temperature. Thus, their Thermal Preference Vote decreases. This phenomenon is very well reflected in Figure 4B. The dependence is very strong, however data from the experiments with the masks are higher than in the case of the absence of the masks on the faces (the fitting lines are ideally parallel). It means that for the same value of Thermal

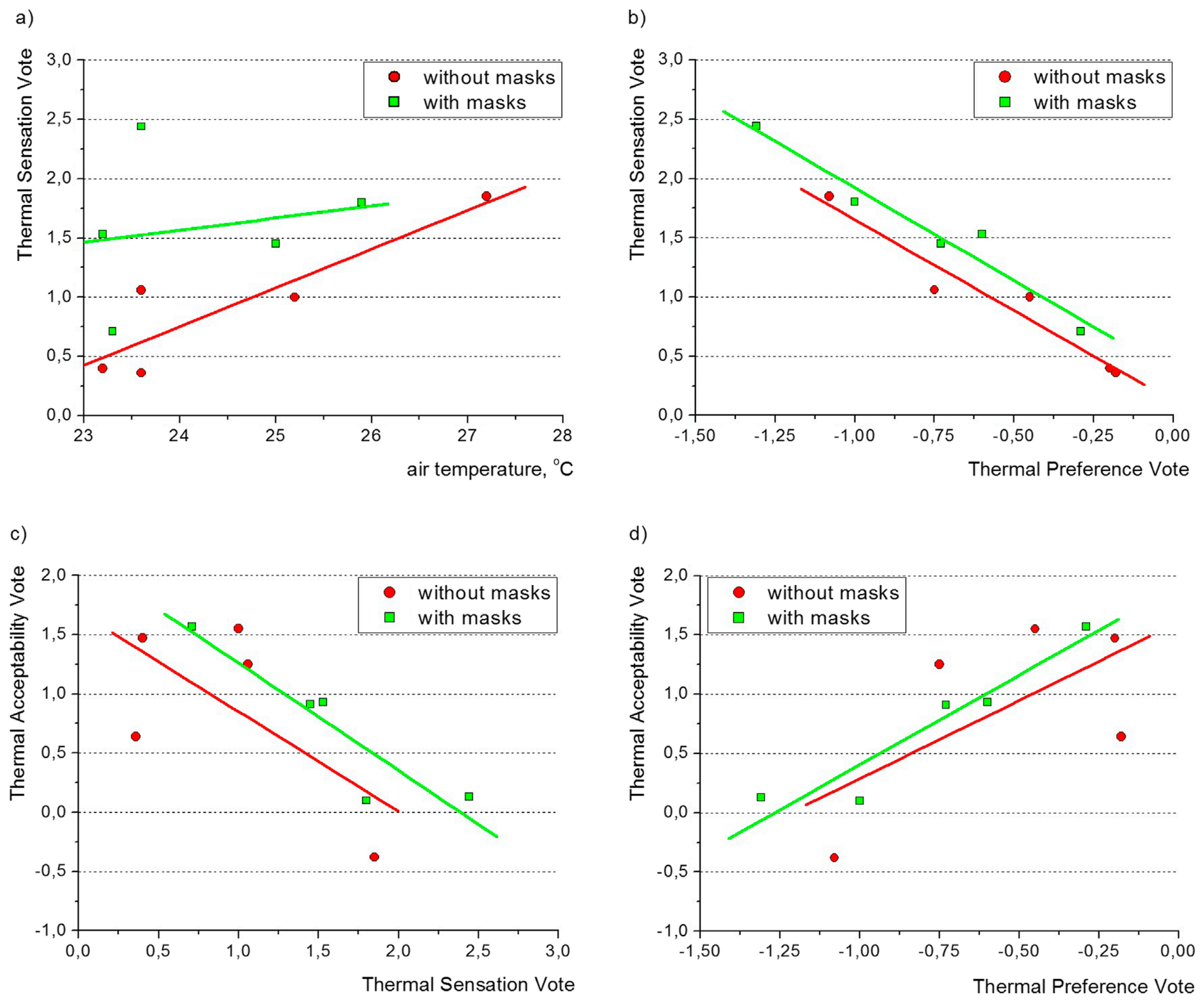

FIGURE 4
Relations between: Thermal Sensation Vote and air temperature **(A)**, Thermal Sensation Vote and Thermal Preference Vote **(B)**, Thermal Acceptability Vote and Thermal Sensation Vote **(C)**, Thermal Acceptability Vote and Thermal Preference Vote **(D)**.

Preference Vote (for example "-1," which indicates willingness to reduce the air temperature), people wearing masks experience higher thermal sensations ("+2" - in the example) than those not wearing them (+1.7). The fitting equations in Figure 4B take the following forms:

$$TSV_{\text{with masks}} = -1.566TPV + 0.355, R2 = 0.95$$

$$TSV_{\text{without masks}} = -1.535TPV + 0.118, R2 = 0.94$$

The same parallel character of the dependence between data recorded in the presence and absence of the masks on the faces can be seen between Thermal Acceptability and Thermal Sensation Votes (Figure 4C). A different trend can be detected on Figure 4D (where the acceptability level for the data obtained with the face masks on is higher than the acceptability level without them), but it can be easily explained. It people are not satisfied with their thermal environment and want to change it (e.g. reduce the temperature significantly–Thermal Preference Vote falls to highly negative values), the acceptability (comfort) level also goes down regardless of the fact whether the masks are present on the faces or not. The fitting equations in Figures 4C, D take the following forms:

$$TAV_{\text{with masks}} = -0.907TSV + 2.167, R^2 = 0.83$$

$$TAV_{\text{without masks}} = -0.842TSV + 1.692, R^2 = 0.41$$

$$TAV_{\text{with masks}} = 1.512TPV + 1.916, R^2 = 0.90$$

$$TAV_{\text{without masks}} = 1.319TPV + 1.607, R^2 = 0.40$$

The discrepancies between the results obtained in the case of wearing and not wearing masks reported in the study can be attributed to both physiological nature of the use of masks due to breathing resistance but also to psychological effects. The separation of these effects is difficult mostly due to the individual nature of their interaction in each person.

Naturally, the role of the face masks under pandemic conditions is to prevent the spread of the airborne contaminants between people. However, knowledge of the peculiarities of thermal comfort sensations experienced by the respondents who had the face masks on provides valuable experimental data that could be used to more accurately set indoor air parameters in the heating, ventilation and air conditioning units for people wearing face masks. However, another problem is an accurate prediction of thermal sensations of people in buildings based on the physical parameters of the indoor environment. The calculation methodology according to the most common model of thermal comfort is available in the ISO 7730 Standard (ISO Standard 7730, 2005). It has been used here to determine the Predicted Mean Vote (PMV) for each room, where the respondents wore the face masks. Ideally, the calculated value of PMV should equal the Thermal Sensation Vote (Figure 3A) obtained as the mean of the answers from the questionnaires. If that was true, the model would be considered successful in predicting thermal sensations of people wearing face masks, however this does not seem to be true. The following results were obtained for the rooms in the study:

A:PMV = −0.83 (while Thermal Sensation Vote from the questionnaires: + 0.71)

B:PMV = +0.12 (while Thermal Sensation Vote from the questionnaires: + 1.80)

C:PMV = −0.20 (while Thermal Sensation Vote from the questionnaires: + 1.45)

X:PMV = −0.59 (while Thermal Sensation Vote from the questionnaires: + 2.44)

Y:PMV = −0.80 (while Thermal Sensation Vote from the questionnaires: + 1.53)

As can be seen the discrepancies between thermal sensations calculated according to the standard (PMV) are significant comparing to the actual sensations experienced by the respondents and expressed by them in the questionnaires. The differences range from 1.54 to 3.03, which is very large considering the fact that the scale range is 6 (from −3 to +3). Consequently, it can be stated that the thermal comfort model is unable to precisely determine thermal sensations of people wearing face masks. It might not be related to the additional thermal insulation offered by the mask, but rather more difficult breathing and local discomfort caused by the presence of the mask on the face.

The model (ISO Standard 7730, 2005) considers many parameters (including physical parameters of the environment and the respondents), however the differences observed in the values of actual and calculated (predicted) thermal sensations are so large that they can be attributed mainly to the use of the face masks. It is difficult to precisely determine if the impact of the physiological effect (related mostly to breathing difficulties) or psychological one is more dominant, but it seems that it might be different for each individual.

In the present study, in which 20–30 y.o. people participated, the impact of the use of face masks on thermal sensations has proved to be quite clearly visible. In four out of five cases subjective thermal sensations of the respondents wearing the masks were higher (they felt warmer) than in the case of not wearing them. On average $TSV_{with\ masks} = 2.1 TSV_{without\ masks}$. The largest and most clearly visible differences were observed in rooms, where the same group of the respondents did not have any masks on at first, but after 15 min they put the masks on their faces. This immediate subjective heat experience and additional physical barrier (influencing breathing and thermal resistance) is responsible for elevated thermal sensation votes and adequate thermal preferences (the respondents opted for a reduction in the air temperature value). It needs to be noted that according to data in Figure 4A, a rise in air temperature leads to elevated thermal sensation votes, however the rate of this increase is not the same for both the cases (with and without the masks). At high temperatures people tend to assess the environment as hot regardless of whether they wear face masks or not (that is why both linear fitting curves in Figure 4A tend to converge at high air temperature values). Moreover, the respondents assessed air as more humid when they had their face masks on, which should be attributed to a high level of water vapour in the exhaled air and its accumulation in the space between the face and the mask.

The research results on the effect of face masks on thermal comfort can be used to more precisely set the HVAC systems operating parameters under pandemic conditions in order to maximize thermal comfort sensation of the people. Moreover, the issue might be important nowadays in healthcare buildings, where face masks are used on a regular basis. The scientific aspect of providing a successful and reliable thermal comfort model for such conditions is a vital subject of future work in this area. The model can be improved by modifying the algorithm in such a way that it would consider the fact that a mask (of certain parameters: thermal resistance, permeability) has been applied onto a selected body area.

4 Conclusion

The experimental analysis of thermal comfort in the smart building has shown that the use of face masks influences thermal comfort of the people situated there. They experience warmer sensations than in the case of not wearing the masks - at the same air temperature in the room. The use of the masks also results in the respondents assessing air as being more humid than in the case when no masks are applied on the faces. The fact that the differences in humidity assessment are not significant leads to a conclusion that humans cannot precisely assess humidity in the air (at least not as precise as the air temperature).

The relative dependences of Thermal Sensation, Acceptability and Preference Votes indicate differences (manifested in the form of vertical shirts on the presented graphs) between the experimental data obtained when the face masks were applied and not applied. It means that, although the character of changes is the same, the presence of the masks on the faces affects human thermal sensations at the level that can be clearly noticed.

The thermal comfort model failed to properly determine thermal sensation of the respondents, who wore the face masks. This model was developed several decades ago and does not take into account the fact of wearing masks, which resulted in significant discrepancies between the actual and calculated thermal sensations.

The results of the research on thermal comfort of people wearing masks have a large practical application potential. Proper setting of indoor air parameters is essential for providing room users with high quality indoor conditions that can maximize their working/learning performance, while – at the same time – optimising energy costs.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the [patients/ participants OR patients/participants legal guardian/next of kin] was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

ŁO: Conceptualization, Methodology, Resources, Software, Supervision, Validation, Writing–original draft, Writing–review and editing. LD: Investigation, Writing–original draft, Writing–review and editing. SH: Data curation, Funding acquisition, Software, Writing–original draft, Writing–review and editing. NR: Formal Analysis, Software, Writing–original draft, Writing–review and editing. SA: Writing–original draft, Writing–review and editing. NS: Investigation, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher’s note

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