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Analysis of Thermal Comfort in Intelligent and Traditional Buildings

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Abstract: The paper analyses thermal comfort in intelligent and traditional buildings in Poland. It provides a comprehensive study on the subjective assessment of indoor environment conditions as well as on parameters that influence human thermal sensations and preferences. Direct measurements of physical parameters (e.g., air and globe temperature, relative humidity) as well as simultaneously conducted anonymous questionnaire studies were used to provide the necessary data. The study covered all seasons and a large number of participants representing various age groups and body build types, who completed a total of 1778 questionnaires. The results indicate that typically smart buildings offer higher levels of thermal comfort than the traditional ones and that people tend to prefer warmer environments. Moreover, it has been observed that the BMI index, air movement and the number of people per surface area can have an impact on the perceived thermal sensations.

Keywords: indoor environment; thermal comfort; thermal sensations

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1. Introduction

Nowadays, people tend to spend large amounts of time indoors—either working, studying, shopping, or living. Thus, the issue of providing users with proper indoor environment conditions has become absolutely crucial not only for their satisfaction and well-being, but also due to health-related issues. Consequently, thermal comfort within buildings has attracted a lot of attention. Moreover, the building sector itself is the focus of attention in terms of its energy needs. It is estimated that it accounts for 30% of the final energy consumption in the world, including about 55% of the global electricity consumption [1]. This has a direct result in the ever-growing costs of buildings' daily operation, but it has also a detrimental effect on the environment e.g., due to CO_2 emissions. One of the features of very modern (often intelligent) buildings is the presence of sophisticated installations and services, especially heating, ventilation, and air conditioning (HVAC) systems. Their energy consumption can be considerable—for example in commercial buildings the largest electrical loads are those linked with HVAC systems and lighting [2], while in office facilities HVAC installations are reported to consume over 60% of energy [3]. Moreover, findings from a three-year study on the final energy consumption of a modern French school building show that about 80% of the energy is consumed to cover heating and ventilation needs [4]. Considering the large share of energy consumption of HVAC systems in modern buildings and the necessity to provide room users with thermal comfort conditions, research to determine if the additional costs related to the development and operation of intelligent buildings (in comparison to traditional ones) is justified. The rising amount of time that people spent indoors and the necessity to provide the best possible indoor conditions for high quality living, working as well as studying, are the reasons behind using thermal comfort as the main assessment tool for the comparison of intelligent and traditional buildings.

Thermal comfort is a subjective feeling of experiencing neither cold nor warmth. A number of factors effect this sensation e.g., air temperature, radiant temperature, humidity, air flow and human related factors (metabolism rate and the level of clothing thermal resistance). These parameters are considered by the most commonly used thermal comfort model (developed by O.Fanger in the 1960s) and applied to predict the collective occupants' satisfaction rating [5]. Two indices were proposed in the model: the Predicted Mean Vote (PMV) and Percentage of People Dissatisfied (PPD). These are now incorporated with the most common building standards: EN-ISO 7730 [6] and ASHRAE-55 [7]. PMV is a thermal sensation rating of people located in a considered room on a seven-point scale: from cold (−3) to hot (+3). The most favourable value is 0 (neutral state) with limited deviations into positive and negative values, whose levels are dependent on the building category and given in the standard [8].

Indoor thermal comfort has been the focus of scientific interest worldwide as confirmed by growing numbers of original papers as well as reviews. The tests have been conducted in all types of closed spaces such as residential buildings, public utility buildings or vehicles. Considering public utility buildings (mainly educational and office facilities), which are the focus of the present paper, people staying there are typically less able to control their indoor environment conditions then at homes. Public utility buildings, apart from significant amount of time spent there, are also interesting from the energy consumption point of view due to the necessity to meet the energy needs of HVAC systems and combining the proper level of thermal comfort with the requirements related to the energy performance of buildings. It is important both for newly constructed buildings and also for the renovated ones [9]

University buildings are usually most advanced among various educational buildings throughout the world. Aghniaey et al. [10] conduced a study on thermal comfort evaluation at the campus of the University of Georgia (USA). The tests were performed in eleven classrooms. The operative temperature range was between 21 and 27 °C, while the CO_2 level 700–1300 ppm. The indoor thermal conditions proved to be highly acceptable and the value of the operative temperature of about 23.5 °C was regarded as optimal for this geographical location. Fang et al. [11] tested thermal comfort in air-conditioned classrooms at the City University of Hong Kong. The neutral temperature proved to be quite close to the preferred temperature and amounted to ca. 24 °C, while the comfort range was given as 21.56–26.75 °C. Moreover, a strong linear relation of the mean thermal sensation vote vs. operative temperature was recorded. Zhang et al. [12] analysed thermal environment at Chinese university classrooms during winter and found that population density is important regarding temperature and humidity variations in rooms. The authors observed that an increase in relative humidity improved overall thermal comfort. A work by Buratti and Ricciardi [13] was conduced at the University of Pavia. The study showed that thermal comfort conditions were very fine in three classrooms, where the values of thermal sensation vote were within 0.08–0.36, but for the other two rooms they were not satisfactory (beyond ±1.1). Shi et al. [14] analysed classrooms and dormitory rooms. Thermal acceptability proved to be almost 100%, while clothing insulation was negatively correlated to the operative temperature. The study [15] on thermal comfort of 900 students carried out in summer at three Indian universities in thirty classrooms showed that the average comfort temperature determined with the Griffiths method amounted to 29.8 °C. The average value of indoor air temperature was 30.4 °C, while relative humidity was 39.4%. It was recorded that for such environmental conditions almost 60% of votes expressed neutral thermal sensation and almost 70% opted for the "no change" answer regarding their thermal preference vote. What is more, over 80% of student responses fell within the comfort band, which proves their satisfaction of the indoor environment. Thus, the optimal indoor thermal conditions can be considered to be dependent on the climatic factors and highly subjective. This finding is supported by a very recent work of Budiawan and Tsuzuki [16], who analysed thermal comfort of Indonesian students living in Japan. Despite the fact that the comfort temperature of Indonesian students in Japan is well within the comfort temperature range in Indonesia, their comfort temperature proved to be higher than those of Japanese and foreigner students.

At school buildings and other educational facilities children and their teachers spend substantial amounts of time. Almeida et al. [17] conducted a field study in three kindergarten and three primary school classrooms as well as four higher education spaces in Portugal. Generally, indoor environment was assessed as acceptable with half of the volunteers opting for maintaining their current thermal conditions. Moreover, the respondents showed a preference for slightly warmer indoor conditions, however the relationship between the mean thermal preference vote and the operative temperature proved to be quite weak. Vilcekova et al. [18] analysed indoor air quality as well as thermal comfort in a school building in Slovakia. Thirty-three pupils up to 15 years of age and five teachers filled in the questionnaires. The obtained thermal sensation votes showed very high acceptability; however, the CO_2 concentration was relatively high (reaching almost 1800 ppm).

Thermal comfort analyses in intelligent educational buildings are quite rare. One of such papers—by Merabtine et al. [4]—has been focused on the tests of indoor air quality and thermal sensations at the modern building of the ex-Ecole Polytechnique Féminine (EPF) School of Engineering (France) equipped with the Building Management System. The study covered 41 students and was performed at the foyer. A dissatisfaction of thermal environment was recorded with the PPD value falling beyond 10%. Similarly, the thermal sensation vote below -1 indicated the presence of unsatisfactory conditions. Moreover, carbon dioxide concentration exceeded the permissible value at times. Measurements at three teacher rooms also revealed high CO_2 levels of up to ca. 1300 ppm. Thus, the obtained results might mean that even modern and smart buildings can provide uncomfortable indoor environment conditions.

Apart from university campuses and schools, also at office buildings people tend to spend significant amounts of time—as employees, clients, visitors. Consequently, satisfaction regarding thermal comfort conditions is also vital at such locations. Moujalled et al. [3] analysed thermal comfort in five French office buildings. The air temperature values were up to 32.9 °C. It was reported that ca. 35% of people were not satisfied with the indoor environment at the warm season, while at the cold one—below 10%. Hens [19] performed an experimental study at two air-conditioned Belgian office buildings. The dissatisfaction with the thermal indoor environment was greater than the permissible level. Moreover, health complains at work were quite common such as burning eyes, coughing. This phenomenon can also have an impact of thermal sensations reported by the volunteers. Kuchen and Fisch [20] analysed thermal comfort in twenty-five modern German office buildings and obtained 345 measurements. The authors claimed that people in very similar spaces, in the same climate and from the common culture might experience different thermal sensations despite the fact that sensors render the same results. Maykot et al. [21] performed a study in four office buildings in Brazil. The majority of people were in thermal neutrality or felt slightly cool/warm and preferred no changes to the environment. Moreover, women tended to feel colder compared to men. Indraganti et al. [22] studied thermal responses of 435 volunteers in four Japanese office buildings under summer conditions. The average air temperature amounted to 28.2 °C. Equally elevated was the carbon dioxide level of 1055 ppm. Despite such conditions thermal acceptability turned out to be significant (almost 90%). It was also concluded that the average sensation votes in natural ventilation buildings are higher in comparison to buildings equipped with air conditioning systems. This phenomenon has been partly confirmed by the same authors in [23], where twenty-five Indian office facilities were considered. Fedorczak-Cisak et al. [24] focused their test on a 'nearly zero energy consumption' building in Poland, where the indoor air temperatures did not exceed 24 °C. The authors found out that the use of Venetian blinds reduced the values of ambient air temperatures as well as the number of discomfort hours by 92%. Jazizadeh et al. [25], based on the test results in office buildings, stated that ambient temperature is the most effective parameter of the largest impact on thermal sensation votes. Thus, the temperature set points of HVAC systems can be applied as a control factor. The impact of the type of a HVAC system was analysed in [26] during the summer season in three office buildings. Despite the use of mechanical ventilation, the air quality proved to be weak as evidenced by a high level of carbon dioxide in all considered buildings. Lodi et al. [27] considered the impact of electric radiant panels in offices located in historical buildings on indoor environment. The findings indicate a high thermal comfort improvement accompanied by annual heating energy savings reaching 70%. A very recent study [28] performed in British office spaces proved that thermal sensation is linked to both air quality and noise perception. Moreover, the authors observed a considerable correlation between operative temperature and thermal sensation votes as well as a relation of operative temperature with noise perception and acoustic satisfaction.

Providing room users with thermal comfort is a crucial issue due to meeting their well-being needs. However, the indoor conditions can also influence work productivity [29] as well as learning performance [30]. Consequently, ensuring thermal comfort conditions in buildings should be a crucial factor of broader importance.

A common definition of an "intelligent building" proposed by Leifer [31] states that its fundamental constituents are mainly: automation, building management systems and information communication networks. According to Kubba [32] such buildings should keep people comfortable and environmentally satisfied. Moreover, an intelligent building ought to maximise the performance of its users/residents and effectively manage the available resources while keeping the operational costs to the minimum [33]. In practical applications, buildings are considered "intelligent" if they are equipped with a Building Management System (BMS). In such building all the building services such as heating, ventilation, air conditioning (HVAC) systems as well as networks of electric lighting, audiovisual, room access and anti-theft control, fire safety as well as internal transport systems are interconnected with one another [34]. High level of technical sophistication of intelligent buildings (in relation to the traditional buildings) and proper air treatment/filtration might influence not only indoor air parameters or air quality (which might influence thermal sensations as considered in [28]) but also human subjective sensations regarding safety, proper lighting conditions, outdoor traffic noise reduction (due to closed windows). Besides, the very possibility of people being able to change and adjust indoor environment to suit individual needs, being more in control of the indoor conditions can, in turn, indirectly affect thermal sensations of room users.

Despite a number of studies on thermal comfort over decades, only a fraction of those have been done in intelligent buildings, which might result from the fact that such buildings are typically a rarity (especially in Central and Eastern Europe) and only recently have become more prevalent throughout the world. Thus, there is a research gap regarding the performance of intelligent buildings in comparison to the traditional buildings in the above-mentioned climatic conditions. The current study provides a comprehensive and thorough comparative analysis of thermal comfort in traditional and intelligent buildings (during their normal operation) conducted with a large number of participants and in many rooms—within a long time span that covers all seasons and various indoor and outdoor environmental conditions. Such a thorough experimental analysis focused on a comparative study of traditional and intelligent buildings located in Central/Eastern European climate has not been found in literature. Moreover, the paper also discusses a possible influence of body mass index (BMI) and occupational density (number of people per unit area) on their thermal sensations—based on a large data set. Such analyses—for the above-mentioned experimental and climatic conditions—have not been found in the literature. The present paper aims to bridge this research gap.

Moreover, the study was conducted in normal, real-life operation of the buildings (as opposed to thermal comfort studies in climatic chambers). Consequently, it provides valuable practical information regarding, among others, user sensations and preferences, which are of significant value to engineers, building managers and designers of HVAC systems. The normal operating conditions throughout a large time span (as in the present study) might be different than those under controlled climatic chamber conditions. Thus, the results given in the paper can be used to prepare guidelines for building operators.

The objective of the paper is a detailed study of thermal sensations, preferences, and acceptability of room users in traditional and intelligent buildings and their comparative analysis as well as the examination of the influence of relative humidity, air movement, BMI, and occupational density on thermal sensations throughout all seasons.

2. Materials and Methods

2.1. Focus of Study

The analyses were performed at two intelligent, and one traditional building in two Polish cities: Kielce and Radom, located 70 km away from each other. Figure 1a presents the first smart building called "Energis", while Figure 1b the traditional building "A"—both located next to each other and part of the Kielce University of Technology campus. The other intelligent building considered in the study is the Courthouse in Radom (Figure 1c).

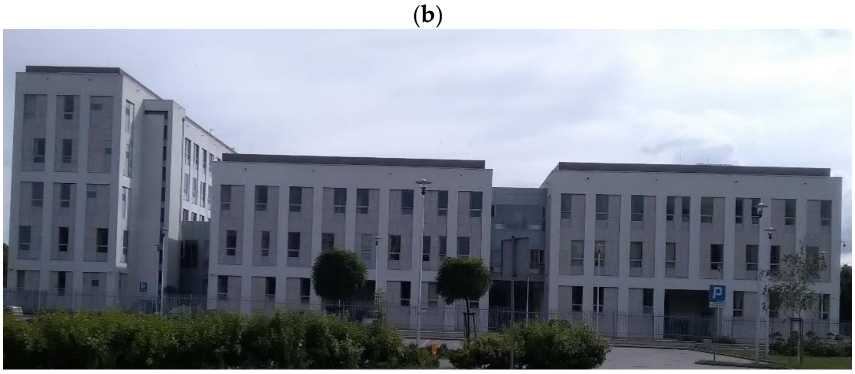
The "Energis" building was completed in 2012, the Courthouse in 2017, while building "A" in 1976 (although renovated in 2012). They occupy the following surface areas: 925 m^2, 3239.3 m^2 and 1356 m^2, respectively, while their cubature is: 21,211 m^3, 61,661 m^3 and 38,485 m^3. An assessment of their physical state, conducted before the actual tests of thermal comfort, revealed that all of them, even the oldest one, are in proper condition. Figure 2 presents examples of thermographs of all the buildings taken within the example rooms.

The ventilation ducts (both for air supply and removal) in the intelligent buildings are located in the suspended ceilings. Cooling is provided with the cassette indoor units (in "Energis") and with fan coils (in the Courthouse) connected with the outdoor chillers (located on the rooftops). Heating in all the considered buildings has been achieved with hot water radiators ("A" building and Courthouse) as well as floor heating (only in the case of "Energis"). In "Energis" air heating with the cassette indoor units is also available. The temperature in intelligent buildings can be changed by room users with the control panels situated in each room. The range of allowable changes is fixed and determined in the BMS system.

In both intelligent buildings the mechanical ventilation system is equipped with heat recovery units (rotary heat exchangers). Air treatment in central air handling units (located on the rooftops and in the basement) involves filtering, heating, and heat recovery. Partial air recirculation is also used to reduce operational costs (however a minimal fresh air flowrate must be maintained for breathing). In the two buildings steam vaporisers are installed on selected systems. The cooling system in both buildings consists of rooftop chillers, which operates at the parameters 7 °C (supply)/12 °C (return) at the Courthouse and 6 °C/12 °C for "Energis" circulating between the indoor units and the chillers (multi-split systems). Air from the toilets is removed outside using exhaust fans; however, in the case of "Energis" it undergoes a heat recovery process in air heat pumps. The Courthouse has 18 separate systems for air supply and removal with the designed air flowrate ranging from 150 m^3/h to 8340 m^3/h, while "Energis" only five with the air flowrate from 2450 m^3/h to 21,650 m^3/h. Naturally, the traditional "A" building, equipped with natural ventilation, can rely on gravitational force to enable the flow of fresh air via window intakes and their removal by the exhaust ducts in the upper parts of the rooms.

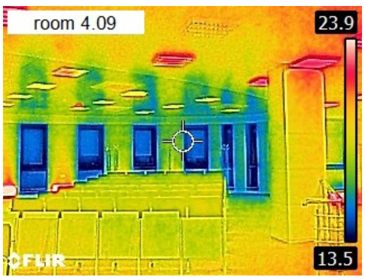
(**a**)

(**b**)

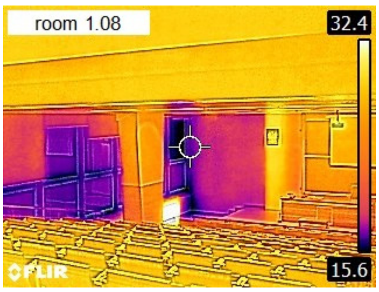


(**c**)

Figure 1. Photographs of "Energis" (**a**), building "A" (**b**) and Courthouse (**c**).



(**a**)



(**b**)

(**c**)

Figure 2. Thermal images from "Energies" (**a**), building "A" (**b**) and Courthouse (**c**).

2.2. Testing Method and Equipment

The experimental procedure was based on conducting direct measurements of physical parameters (indoor air and globe temperature, air velocity and relative humidity as well as CO_2 level) in rooms in each building and the use of questionnaires completed by their occupants. Table 1 lists the basic technical features of the testing system.

Table 1. Details of the parameters measured in the study.

Parameter	Range	Accuracy Level
Air temperature	Up to 45 °C	0.5 °C
Relative humidity	Up to 100%	3%
Globe temperature	Up to 70 °C	1 °C
CO_2 level	Up to 5000 ppm	20 ppm + 3% of the value
Air velocity	Up to 30 m/s	3% (at 25 °C)

Figure 3 presents the measuring unit consisting of the microclimate meter and the probes on the tripod in example rooms in the teaching facility "Energis" (a) and the Courthouse (b). The measuring station was located as close as possible to the area where the respondents were located, so that most accurate indoor parameters (of the air surrounding the volunteers) could have been collected. Usually, it was in the center of the rooms, however, this might have been different in large lecture rooms where the occupancy (number of students attending lectures) was relatively low.

(**a**) (**b**)

Figure 3. The measuring station in the lecture room of "Energis" (**a**); and the office room in the Courthouse (**b**).

The testing procedure was based on simultaneous measurements of the physical parameters and anonymous questionnaire surveys in each room. A total of 1778 questionnaires were collected (1257 at "Energies", 339 at "A" building and 182 at the Courthouse), while the number of data sets (a set is considered as data collected in an individual room comprising indoor environmental parameters and questionnaire survey's results) collected at individual rooms in the study was 134, of which 64 were in "Energies", 57 were in the Courthouse, and 13 were in "A" building, but they were limited to 109 due to the assumption of a minimal number of people in a room (this criterion actually only concerned the offices of the Courthouse, where the number of people is typically low). Thus, the number of points to analyse was 109. Those were the rooms occupied by at least three persons. However, in the analysis of thermal sensations, acceptability, and preferences all the individual votes (namely, 1778) were considered. In the survey conducted at the university buildings full time and part time students participated, while in the Courthouse-office workers. The volunteers were asked to provide answers on their subjective sensations regarding thermal environment, their preferences and acceptability level. Besides votes on humidity and air movement were also obtained together with data on the respondents' age and body built (weight and height). The questionnaire was designed based mostly on the standards [6–8,35] as well as journal papers [15,36–38]. The room users filled the questionnaires twice in a given room—as they entered it and after ca. 1.2 h. The data analyses presented in the paper were conducted on the questionnaires obtained after this additional time of 1.2 h in order to allow for accommodation to the environment.

The results presented in the next section will form the basis for discussion on the comparison of the traditional and smart buildings selected for study.

2.3. Statistical Methods and Exploration of Data

The study utilises the concept of a questionnaire survey combined with the physical measurements of indoor air parameters. The raw data were qualitative and quantitative in line with the Stevens measurement scales classification. Qualitative observations were located on the seven-point Likert scale, which implements the qualitative ordinal scale. Quantitative measurements were related to a quotient scale, i.e., the values were non-negative. Based on the experimental data an assessment of possible cause-effect relationships between the objective properties of the environment and subjective evaluations of comfort was carried out. In the case of significant correlation values, linear regressions were performed to illustrate the trend. In some cases where the correlation index was low and linear regression failed, the parabolic regression model (2nd-degree polynomial) turned out to be prognostically effective. However, it should be noted that concluding the marginal ranges is still subject to high uncertainty due to the small number of extreme observations. Probability distributions of changes in subjective assessments follow the "bell curve"; however, these distributions are much more slender than the normal distribution.

3. Results and Discussion

3.1. Analysis of Thermal Comfort Conditions for a Large Number of Occupants

The study covers 1778 questionnaires filled in by room users of various age (18–63 y.o.), gender (51.2% women and 48.8% men: 911 women and 867 men) and body build (considered as Body Mass Index BMI: 15.06–39.25). Such a broad range of data can provide a valuable insight into the nature of current human thermal comfort needs and preferences, as will be discussed later.

Before the experiment in each room the volunteers were duly informed how to complete the questionnaire. They wore their normal clothing as chosen for the day and season. Despite the fact that some people were dressed in thick/thin garment, overall-taking all the data into account—no major differences were recorded in the mean values of clothing thermal resistance, and it typically varied from 0.45 to 0.72 clo.

During the measurements the indoor air temperature for the Courthouse ranged from 22.4 to 28.8 °C, relative humidity from 20.7 to 64.6% and carbon dioxide level from 585 to 1287 ppm. The same parameters recorded in "Energis" were as follows: 21.1–29.8 °C, 34–60.4% and 550–2288 ppm, while for "A" building: 23.8–31.9 °C, 23.6–49.4% and 549–1600 ppm. As expected, the highest levels of carbon dioxide were recorded in the educational buildings—due to a large number of people occupying lecture rooms and classrooms, with the largest value measured in "Energis". Probably at that time mechanical ventilation was off in the analysed room. The air temperature was typically highest in the traditional building "A", which can be linked with no proper control strategy regarding the operation of the heating system there. The air parameters for the spring and summer conditions were characterized by higher indoor air temperatures (in the range of 23.6–31.9 °C) and relative humidity (21.8–64.6%), while the carbon dioxide concentration varied from 549 to 2288 ppm. The whole study took part before the COVID-19 pandemic

(2017–2019), which enabled to perform the experiments without the sanitary restrictions (Energis: February 2017–October 2018, Building "A": March 2017–October 2018, Courthouse: January 2018–January 2019; within the following hours: 8 a.m.–6.40 p.m.).

The largest number of tests (sixteen) took place in lecture room 4.09 in Energis (shown in Figure 3a), followed by two other lecture rooms: 1.09 and 1.14 also in Energis (10 tests in each of them). In six classrooms/lecture rooms and the majority of the office rooms in the Courthouse the experiments were carried out only once. In the case of the Courthouse the tests took place once or maximally twice in a given room, so that the experimental work would not obstruct the normal working and professional duties of the employees there. The classrooms and lecture rooms in the educational buildings (as well as in the Courthouse) were selected based on the willingness of the room users to participate in the study as well as the provision of a broad spectrum of experimental parameters (both related to indoor air conditions and geometry of rooms, their orientation and occupational density). Despite a different character of educational and office buildings considered in this study, they share a general common function: they are public utility buildings, where people spend up to only a few hours a day during daytime.

Naturally, the values of the recorded parameters in each room showed changes during the course of the experiment (to a smaller or larger extent). Figure 4 presents example changes of air temperature, relative humidity and carbon dioxide concentration in a room located in the traditional building "A" (data recorded for the summer conditions).

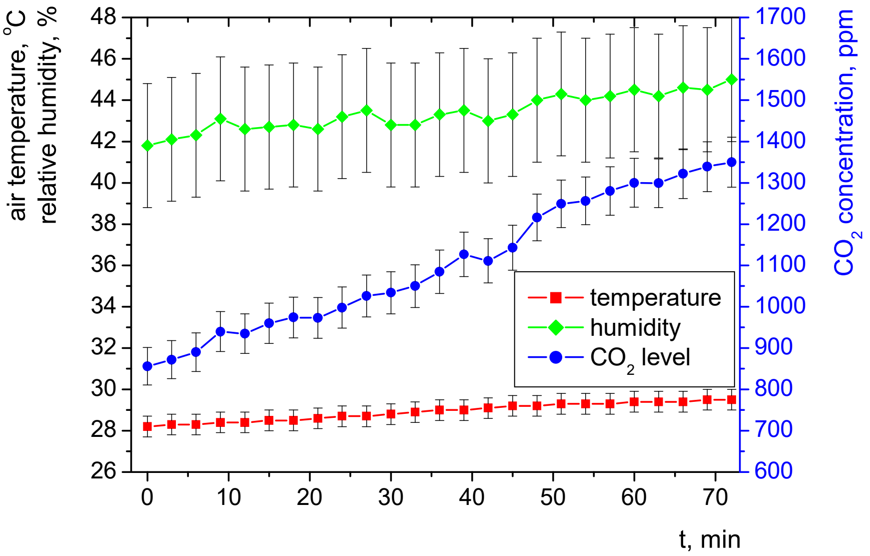


Figure 4. Example chances of air temperature, relative humidity and carbon dioxide concentration in a room of "A" building—together with measurement error bands.

A subjective assessment of indoor environment was done using anonymous questionnaires on a large number of volunteers. Thus, it is possible to conclude the nature of human sensations in the analysed smart and traditional buildings. The first question in the questionnaire stated: "How do you assess your current thermal sensation". The following responses were possible: "too hot" (+3), "too warm" (+2), "pleasantly warm" (+1), "neutral" (0), "pleasantly cool" (−1), "too cool" (−2), "too cold" (−3). Figure 5 presents the results of this thermal sensation vote (TSV) for each building based on data from collected from 1778 questionnaires.

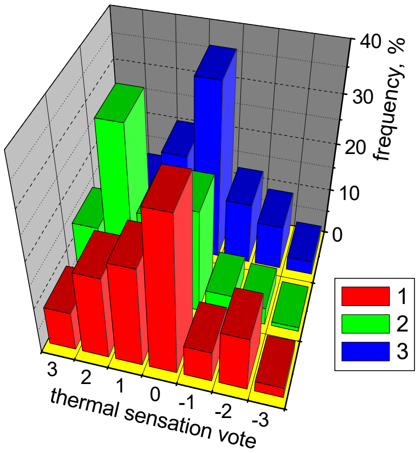


Figure 5. Distribution of thermal sensation votes in the Courthouse (1), "A" building (2) and "Energies" (3).

As is clearly visible, people in the intelligent buildings were—in the majority– satisfied with the thermal environment (as evidenced by the largest number of "neutral" votes), while in the traditional building the answer "too warm" was the most common (35.7%). The votes in the range −1 to +1 represent the positive assessment of the microclimate and can be considered quite similar for the smart buildings (70.5% in "Energies" and 60.5% in the Courthouse). While for the traditional building it amounts to 45.5%, proving the lowest level of comfort. On the other hand, in all the buildings people were not complaining about the fact that it might be too cold. The study confirms the finding by Merabtine et al. [4], who also observed a large number of the dissatisfied in the French smart educational building. It is quite also in line with the claims by Indraganti et al. [22] that the average sensation votes in natural ventilation buildings are higher in comparison to buildings equipped with air conditioning systems. A relatively large number of "too warm" and "too hot" votes in the traditional building indicate that the heating system is not properly regulated and leads to rooms overheating during the heating season, while in the summer, the lack of air conditioning systems contributes to the negative opinions of the thermal environment expressed by the respondents. The traditional building seems to perform well only in periods of the year characterized by moderate temperatures.

The next question dealt with thermal preference of the respondents. The volunteers chose the following: "much warmer" (+2), "warmer" (+1), "no change" (0), "cooler" (−1), "much cooler" (−2) as they answered the question: "I would like in this room to be . . . ". Again, the smart buildings had the largest numbers of "no change" option (ca. 50% in "Energies" and 45% in the Courthouse). In building "A" only 29.1% selected this option. It indicates quite a positive assessment of thermal environment in the smart buildings, as opposed to the sensations in the traditional building, where also the number of votes calling for drastic change in temperature was highest. Studies of other authors (e.g., [17,35]) hardly ever report a significant number of room users calling for considerable changes in temperature, as observed in building "A". However, it might be quite understandable in the present study due to the elevated temperatures in the traditional building "A" both in the summer period (due to the lack of air conditioning) and during winter, when the heating system provides more heat than the thermal comfort conditions require. The details of user preferences have been shown in Figure 6 as thermal preference vote (TPV). It needs to be noted that the results for both intelligent buildings are quite similar, which might be related to similar HVAC systems' concepts and their operation throughout the year.

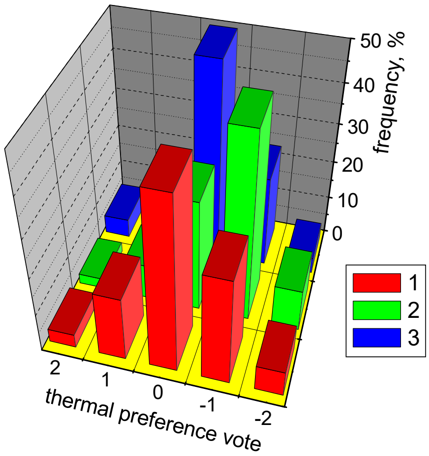


Figure 6. Distribution of thermal preference votes in the Courthouse (1), "A" building (2) and "Energies" (3).

However, when room users were asked about the acceptability of their current environment in the form: "How do you rate your thermal environment?", in all the buildings the same answer was chosen in the majority of the questionnaires, namely "still acceptable" (+1), followed by "absolutely acceptable" (+2). The other answers were "already unacceptable" (−1) and "absolutely unacceptable" (−2) and they were selected by comparable percentage of the volunteers for all the buildings (15.3–20.2%). General high acceptability might result from the fact that people who spend significant amounts of time in a certain building have learned to accept environmental conditions there. The intelligent buildings provided the highest number of "absolutely acceptable" votes, further confirming very positive sensations of people there in comparison to the feelings expressed in the traditional building. However, it needs to be noted that the acceptability level in the considered buildings was relatively high as compared to other studies (such as [23,39]). Figure 7 shows the details of thermal acceptability vote (TAV).

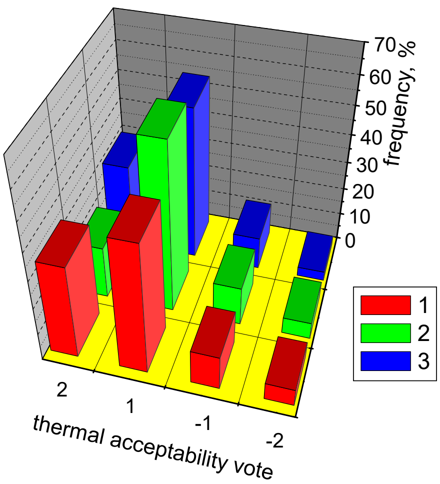


Figure 7. Distribution of thermal acceptability votes in the Courthouse (1), "A" building (2) and "Energies" (3).

The room users also answered a question about air humidity. The problem with this parameter can be significant during winter, when moisture content in the outside air is typically low. Thus, the relative humidity of the air flowing into the building and undergoing heating is low. The distribution of the answers obtained from 1778 questionnaires has been presented in Figure 8 as humidity preference vote (HPV). The precise question took the following form: "I would like the air in this room to be . . . ". The possible answers were: "more humid" (+1), "no change" (0) and "drier" (−1). Over 70% of the respondents in "Energies" proved to be satisfied with humidity level and wanted no change, while data for the other two buildings indicate a much lower frequency (about 50%). It is also worth noting that only some respondents in all the considered facilities wanted the air to be drier—probably due to the fact that the humidity levels recorded during the measurements were not too high and did not reach values of over 70%. But even with this in mind, a few percent (up to 5% in building "A") considered air as too humid. The results by Yao et al. [40] of tests conducted in China have shown that the majority of people were also satisfied with the humidity level, but much fewer seemed to complain about the dryness of air (with the exception of the summer months).

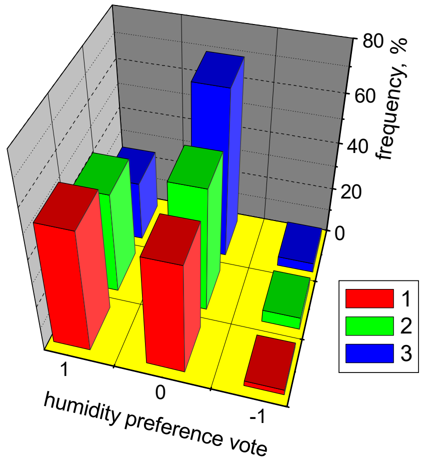


Figure 8. Distribution of humidity preference votes in the Courthouse (1), "A" building (2) and "Energies" (3).

A high percentage of the dissatisfied with humidity in the traditional "A" building can be explained by the lack of humidifiers and room overheating, which reduces relative humidity values. While in the case of the Courthouse, only courtrooms are supplied with vapour generated by steam humidifiers and the office rooms (where the tests took place) are not. Thus, a high level of dissatisfaction with humidity by the Courthouse office workers (similar to the value recorded in the traditional building) is understandable.

Thermal sensations depend on air temperature (as indicated by e.g., Jazizadeh et al. [25] who claimed that ambient temperature is of the largest impact on thermal sensation votes). However, the character of this dependency might be different. Figure 9 presents the average values of thermal sensation votes for each room (calculated from the questionnaires). The minimal number of people in the group was three (although it was overwhelmingly larger in the majority of the tested rooms). At the educational facilities the maximal number of respondents was 86.

As can be seen a rise in air temperature results in higher thermal sensation votes. The type of changes is typically the same for the educational buildings—there is only a vertical shift that can be explained by human accommodation to the indoor conditions of a building, where they are situated. Air temperatures in "Energies" were generally lower than those at building "A", thus, the blue line of TSV-T relationship for "Energies" is located lower than the green one. However, the data for the Courthouse indicate a different character of changes. The angle is steeper, and variability is larger. It might result from the fact that the office workers represent various age groups and BMI. Consequently, individual preferences might play a significant role. Moreover, they spend eight hours in the building each day and might be more tired more than the students (who might even have only one lecture in a day).

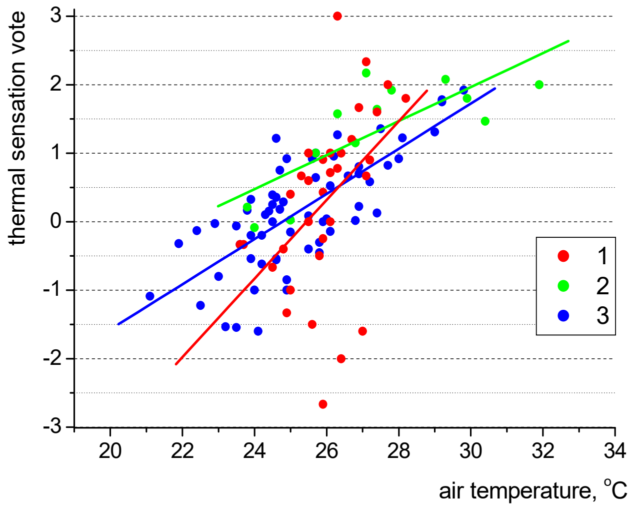


Figure 9. Thermal sensation vote vs. indoor air temperature in the Courthouse (1), "A" building (2) and "Energies" (3) with the best fit linear approximations (the red line is for the Courthouse, the green line for "A" building and the blue line for "Energis"),.

A regression analysis performed for the three buildings separately, with a linear prediction model assumed, and generated the following equations:

$$\begin{gathered} TSV(1) = 0.57T_a - 14.60 \\ TSV(2) = 0.25T_a - 5.48, \\ TSV(3) = 0.33T_a - 8.17 \end{gathered} \quad (1)$$

The respective regions of confidence for the mean (CI) and the prediction (PI) have been presented in the Supplementary Material (Figure S1a–c). The R^2 values for the linear fitting curves (1), (2) and (3) are 0.22, 0.60 and 0.53, respectively. Such values of the coefficient of determination might be considered relatively low, however thermal comfort depends on a number of factors and thermal sensations are highly subjective (as indicated e.g., in [15,16,20]). Even in very similar spaces, people in the same climate and from the common culture might experience different thermal sensations [20]. Thus, even not significantly high coefficients of determination ($R^2 > 0.5$) might be considered satisfactory and of interest in thermal comfort studies (as in other applications [41–43]. Thus, in the case of equation (1) models (b: TSV(2)) and (c: TSV(3)) may be treated as practically applicable, but model (a: TSV(3)) is dominated by noise from uncontrolled factors and cannot be the base for prediction.

A similar trend of TSV change with air temperature can be observed in [15] as well as in [44,45] (though for a much smaller number of data points). The linear regression presented in [15] took the form of:

$$TSV = 0.19T_a - 5.04, \quad (2)$$

Moreover, the papers [11,28] report a considerable correlation between thermal sensation votes and operative temperature.

As mentioned earlier, the volunteers indicated their thermal preferences regarding either increasing the current temperature (by choosing "warmer" (+1) or "much warmer (+2)) or decreasing it (by choosing "cooler" (−1) or "much cooler (−2). The ideal situation involved maintaining the temperature value ("no change" (0)). The average values of TPV vs. indoor air temperature have been presented in Figure 10. Naturally, as the temperature rises people would like the air to be cooler (average answers are below 0 for the air temperature above ca 26 °C). Here, room users in all the buildings generally follow the same trend, especially for the educational buildings; however, the dissimilarity in the

Courthouse data is again visible with a steeper angle of inclination. It might be explained by large individual differences between people working there.

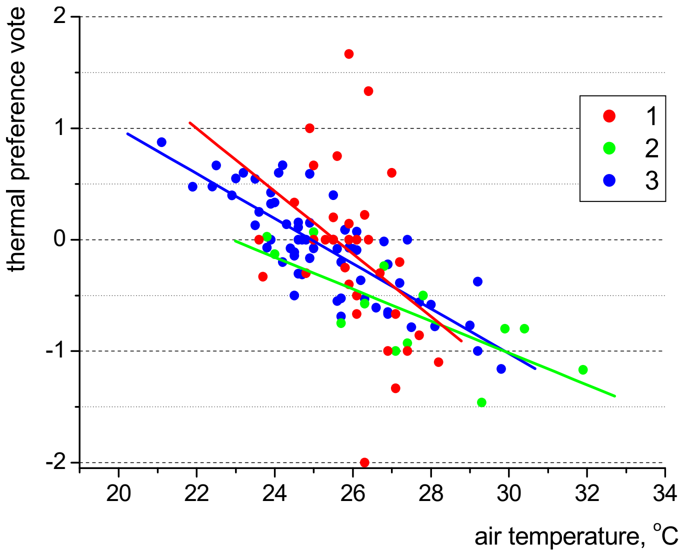


Figure 10. Thermal preference votes vs. indoor air temperature in the Courthouse (1), "A" building (2) and "Energies" (3) with the best fit linear approximations. (the red line is for the Courthouse, the green line for "A" building and the blue line for "Energis"),.

The formulae of each linear regression in the above figure are as follows:

$$\begin{array}{c} \mathrm{TPV}(1) = -0.28\mathrm{T_a} + 7.18 \\ \mathrm{TPV}(2) = -0.14\mathrm{T_a} + 3.28, \\ \mathrm{TPV}(3) = -0.20\mathrm{T_a} + 5.03 \end{array} \quad (3)$$

The regression proposed in [10] indicates a second-degree polynomial, however data presented there refer to a different range of temperature variations and only nineteen measurement points.

Although the R^2 values for the linear fitting curves (1), (2) and (3) are typically low (as commented earlier regarding data in Figure 9), namely: 0.16, 0.58 and 0.65, the character of changes can easily be noticed.

Despite above observed differences related to human preferences regarding indoor environmental parameters, it should be anticipated that the inborn perceptions are the same for all the respondents despite the type of building they are located or individuality. Namely, if a person feels very warm (TSV = 2), he or she would like the temperature to be reduced (TPV = −1). If, on the other hand, a person feels cold (TSV = −2), they would opt for a warmer environment (TPV = 1). This should be a universal concept, and it is—as presented in Figure 11, where a dependence of thermal preference vote and thermal sensation vote has been shown. As expected, all the data points for 109 rooms and linear fit approximations (which are almost identical) for each building follow the same line. It needs to be noted that when room users are pleased with their thermal condition (TSV = 0), they would want "no change" (TPV = 0), as clearly seen on the graph where all the lines cross the point (0,0). A linear relationship between thermal preference vote and thermal sensation vote has also been presented in [3], although that observation was based on a much smaller data set.

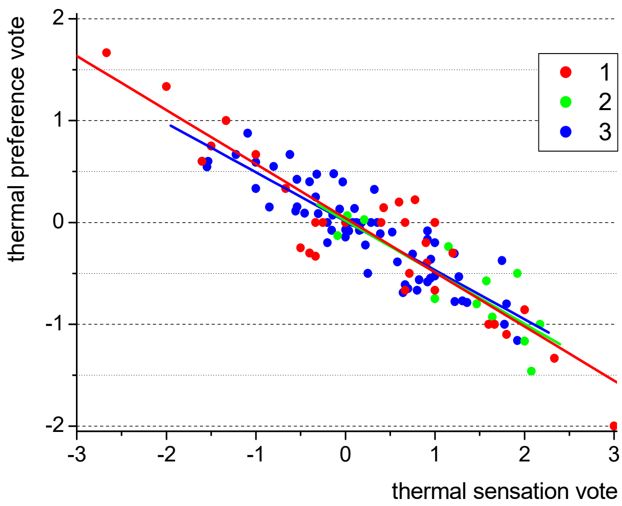


Figure 11. Thermal preference vote vs. thermal sensation vote: in the Courthouse (1), "A" building (2) and "Energies" (3) with the best fit linear approximations. (the red line is for the Courthouse, the green line for "A" building and the blue line for "Energis").

The formulae of each linear regression for the considered buildings are similar to each other and take the following form:

$$\begin{array}{c} \text{TPV}(1) = -\,0.53\text{TSV} + 0.04 \\ \text{TPV}(2) = -\,0.51\text{TSV} + 0.02, \\ \text{TPV}(3) = -\,0.48\text{TSV} + 0.01 \end{array} \quad (4)$$

The strength of the TPV–TSV relation is greater than in the previously analysed data sets. The R^2 values for the linear fitting curves (1), (2) and (3) are 0.82, 0.72 and 0.78, respectively, which indicates proper determination.

Apart from temperature (indoor air or operative), two other factors are considered to have an impact on human sensations, although a lot smaller. The first one is humidity. Its relative value in the current long-term study has been within the normal limits (20–65%) and should not cause any problems related to either dry or humid air. However, as indicated by the questionnaire results (Figure 8) many respondents were not satisfied with the current humidity lever and wanted a change in the form of "more humid" (+1) air, and a few "drier" (−1). The value for "no change" was (0). Based on the obtained results, an average value of HPV (humidity preference vote) for each room was determined and presented below in Figure 12.

Positive values indicate a more humid preference, while negative values indicate a a preference for drier.air The data show that generally, as humidity rises, people tend to opt for "drier air" (HPV linear approximation decreases). Although it might have been anticipated, the values of relative humidity were not large enough to justify such responses. It indicates that people can be sensitive to humidity values in the current experimental range and this factor should be considered as an important element of thermal comfort conditions. However, it needs to be noted that Kong et al. [46] found almost no or very marginal influence of mean humid sensation vote and air humidity in the range of 20–70% in tests conducted in China. The current study was limited to ca. 65% of relative humidity, while above 70% strong thermal responses were reported by other researchers ([46,47]), especially at high indoor air temperatures.

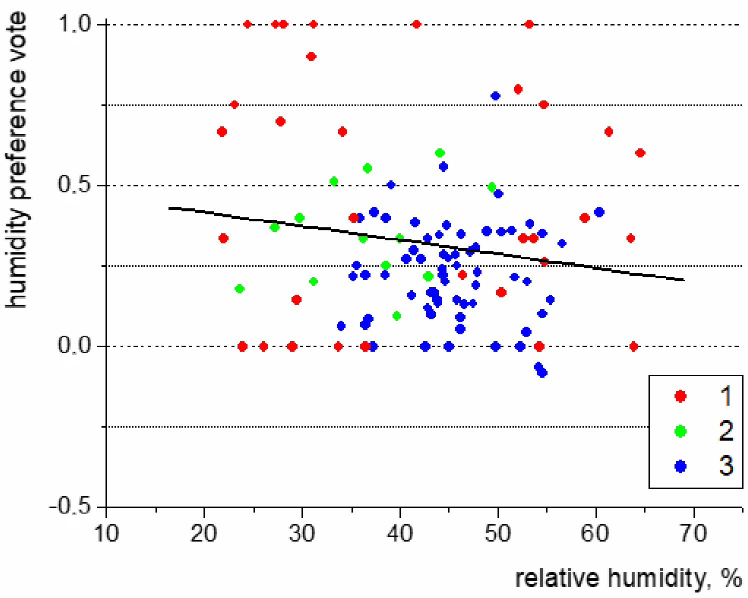


Figure 12. Humidity preference vote vs. relative humidity: in the Courthouse (1), "A" building (2) and "Energies" (3) with the best fit linear approximation of all the data represented by the black line.

Air movement is one of the factors influencing thermal perception. However, it is more of the subjective sensation of air movement than the actual value of its velocity that seem to be of most attention. Having made such an assumption, a question in the questionnaire was proposed: "Do you feel air movement?", while the possible answers consisted of: "yes, of significant speed" (+2), "yes, of low speed" (+1) and "no" (0). Here, despite obvious differences in the function and operation of the considered buildings, the answers were quite similar for each of them. In total 53.1–62.8% of the respondents indicated no air movement in the analysed buildings, 32.3–39.8% considered the movement as "low speed", while 4.9–7.1% as "high speed". The fact that there are only small differences (maximally of a few percent) between the responses recorded in buildings equipped with mechanical ventilation (the Courthouse and "Energies") and building "A", where natural ventilation and window opening ensure air exchange might be surprising, but it might prove that the presence of highly sophisticated mechanical systems and their operation might not be noticed by room users, possibly due to their accommodation over time. On the other hand, the impact of air movement on thermal sensation has been clearly demonstrated with the field data of 1778 questionnaires. Figure 13 presents the relationship between mean thermal sensation votes experienced in 109 rooms (mean TSV) and the average rating of air movement for each room (as a mean value out of 0, 1, 2 indicated by each respondent regarding air movement assessment).

The data for all the buildings follow the same trend. As the air movement intensifies (or that's how people subjectively perceive it), the respondents feel colder and thermal sensation vote decreases. A similar trend, but of non-linear nature, has been presented in the computational study by [48]. The phenomenon can be explained by enhanced heat transfer via convection. This relationship is turned out to be quite strong and, thus, air movement should be considered as an important parameter in thermal comfort analyses even in low air velocity environments. It needs to be noted, however, that the impact of the air flow is more complex and involves the influence of other factors such as metabolic rate and air flow pattern, as indicated in [49]. Besides, the current study shows that perceived high air flow velocities lead to low thermal sensation votes. It might not be true for hot thermal environments, as indicated by Yao et al. [40], where people tend to prefer high air velocities, because they assist skin evaporation. Similar findings were reported in [50] for the hot and dry climate, where most preferable thermal sensations were reported for high air movement, as well as in [47] for the hot and humid climate, where the increase in air speed resulted in improved thermal sensation as it reduced warm sensations without resorting to air-conditioning systems.

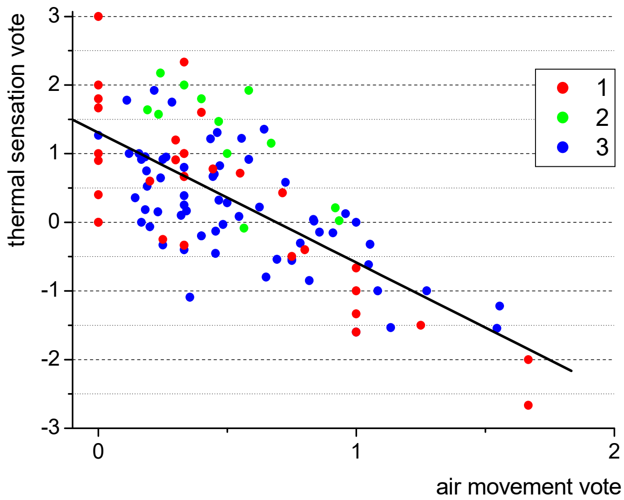


Figure 13. Thermal sensation vote vs. air movement: in the Courthouse (1), "A" building (2) and "Energies" (3) with the best fit linear approximation of all the data represented by the black line.

Since thermal sensation, preference and acceptability votes are just subjective assessments of certain human states, the question arises how acceptability of the respondents to environmental conditions they are in, interconnect with TSV and TPV. Figure 14 presents the relationship between thermal sensation vote and thermal acceptability for 109 rooms regardless of the type of building. The data points represent the average values as taken from 1778 questionnaires. The confidence bands for the mean (CI) and the prediction (PI) that correspond to the regression presented in Figure 14 have been given in Figure S2 in the Supplementary Material.

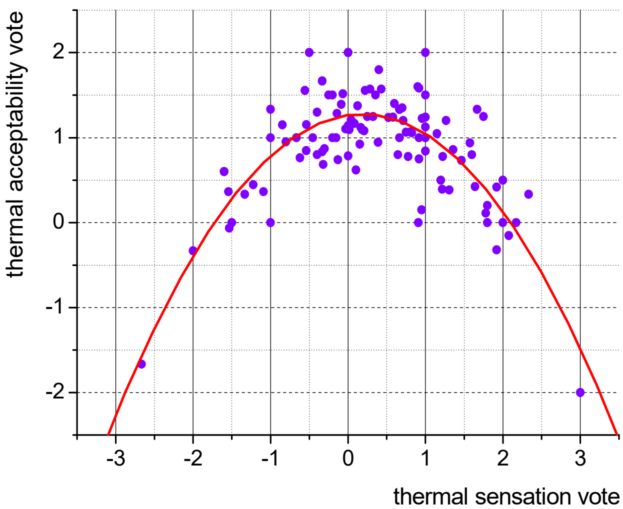


Figure 14. Thermal acceptability vote vs. thermal sensation vote—data for all the buildings, the red line represents the approximation curve, while the purple dots the average values of TAV.

High levels of thermal acceptability (above 1.5) typically occur when thermal sensation vote is within the range of −0.5 to +1. It indicates that the values given in the standard [6] for buildings category II (from −0.5 to + 0.5) can be extended into the area of higher temperatures, since it seems that people tend to like them. The approximation curve has its maximum for TSV = +0.25, which further proves that the room users would more like warmer environments (as also confirmed by [17]), at least in the moderate Central European climate. In hot climates a greater preference for cooler environments has been observed (at least during the summer season), as shown in [22].

The equation of the regression curve in Figure 14 takes the following form:

$$TAV = -0.349TSV^2 + 0.13TSV + 1.27\,, \tag{5}$$

with the R^2 value of 0.65. The dependence proposed by Zhang and Zhao [51] is a linear function:

$$TAV = -0.41TSV + 0.58\,, \tag{6}$$

However, the paper [51] only considers a limited TSV range from 0 to about 1.5; while the present paper analyses the whole range of possible TSV values (from −3 do +3), as given in Figure 14.

The relationship between average thermal acceptability and average thermal preference vote (Figure 15) indicates that highest acceptability occurs when people have no intension to change the current state of their environment (TPV = 0). However, high values of TAV (above 1.5) have also been observed if TPV is within the range of −0.25 to +0.25 (when room users might want very small changes to their thermal environment). The above finding is in line with the conclusion from the study by Aghniaey et al. [10] that when occupants' mean thermal preference vote equaled zero, the acceptability was highest and thermal sensation vote was almost neutral (namely "0").

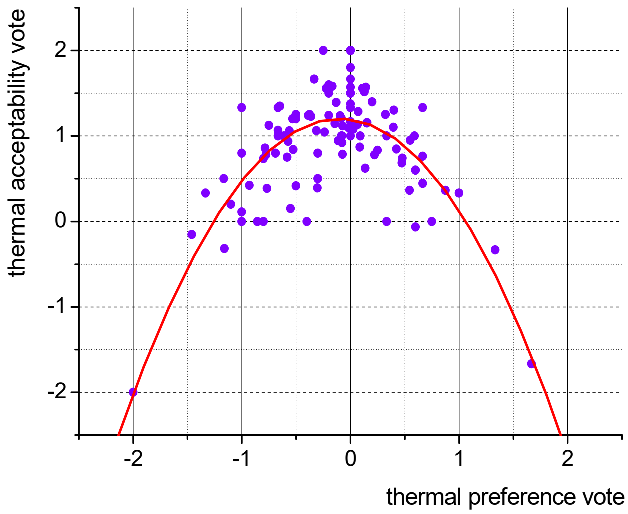


Figure 15. Thermal acceptability vote vs. thermal preference vote—data for all the buildings, the red line represents the approximation curve, while the purple dots the average values of TAV.

Figure S3 in the Supplementary Material presents the confidence bands for the mean (CI) and the prediction (PI) that correspond to the regression presented in Figure 15. The identified quadratic predicting model for TAV is as follows:

$$TAV = -0.893TPV^2 + 0.18TPV + 1.20\,, \tag{7}$$

while the R^2 value is 0.62.

All the above analyses have been performed on the questionnaires filled in after ca. 1.2 h after the respondents entered the rooms in order to allow for thermal accommodation. However, the questionnaires were also filled in at the beginning (as they entered the rooms). A large set of data as collected in the present study enables to quantify and qualify the changes occurring in the rooms during their normal usage. Figure 16 presents how TSV changed after 1.2 h (TSV_1) over its initial values at the beginning of the tests (TSV_0), for three buildings.

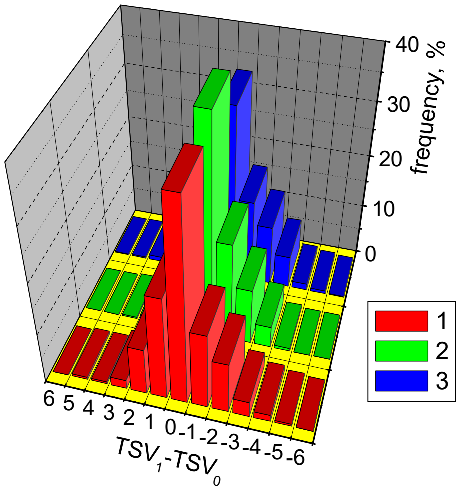


Figure 16. Changes of thermal sensation vote during the measurements in the Courthouse (1), "A" building (2) and "Energies" (3).

Despite differences between the buildings similar trends can be detected. The largest number of people (between 33–41%) did not change their thermal perceptions or changed them slightly by ±1 (33–36%). Actually, a comparable number of people experienced increased thermal sensation votes as the decreased ones. A large datasheet generated in the study enables us to conclude that there will always be changes in environmental states and some people are more sensitive to them. Marginally, changes of ±5 have also be reported, which makes maintaining proper indoor conditions challenging for these small groups of occupants. However, it needs to be noted that indoor conditions and their perceptions are never a steady-state phenomenon.

3.2. Thermal Comfort Assessment in the Selected Traditional and 'Smart' Rooms

The analyses of large databases are highly useful and provide a broad picture of thermal comfort and its factors, however, a more detailed study should be focused on certain rooms, where indoor conditions are the same for all the room users. The comparative analysis has been focused on four rooms with a significant number of people (228 in total)—two in building "A" and the other two in "Energis" conducted under the same outside air conditions in two seasons: spring (March) and summer (June)—Figure 17.

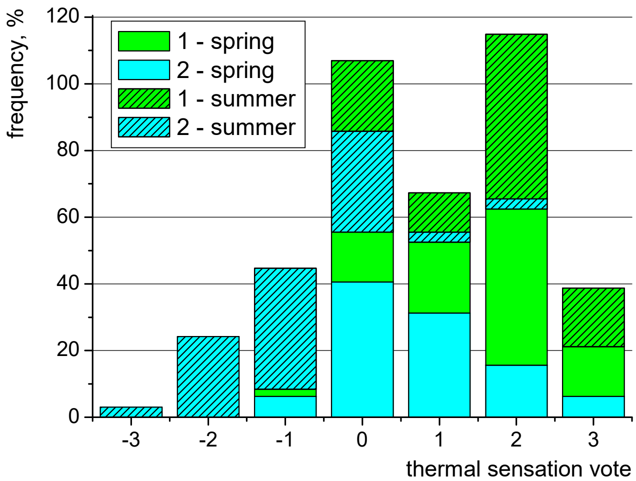


Figure 17. Thermal sensation votes in room 1.03/1.08 of the traditional "A" building (1) and in room 3.20/4.09 of the intelligent "Energis" (2).

During the spring season the respondents were quite satisfied with the conditions in the smart "Energies" building. About 40% opted for the "neutral" (0) answer in the questionnaire, over 30% indicated "pleasantly warm" and ca. 6% "pleasantly cool". Thus, the share of the satisfied exceeded 76%. On the contrary, in the traditional "A" building ca. 15% felt "neutral" and ca. 21% considered the conditions as "pleasantly warm" and ca. 2% as "pleasantly cool". Thus, the number of the satisfied reached 38%, with the rest being dissatisfied with the indoor air parameters. It might result from the fact that the indoor conditions can be more easily modified in the smart building. In building "A" overheating is a problem during winter and cold days occurring in spring. Thus, the occupants complain about high air temperatures. Undoubtedly, the level of thermal comfort in the intelligent building proved to be much higher for the same weather conditions.

In the summer conditions the traditional "A" building provides comfort to only 33% of the room users (who indicated answers "0" and "1"). The rest feel too warm and even hot, thus, are largely dissatisfied (67%). The lack of air conditioning is the reason behind such sensations. A similar observation regarding thermal sensations in a traditional building has been reported in [52], where a shift towards "warmer" sensations during the spring and summer was recorded (although not so pronounced as in the current study). On the contrary, the intelligent building provides cooling and the share of the satisfied reaches almost 70% (the combined number of (−1), (0) and (+1)), which is over twice as many as in the traditional building. Undoubtedly, the smart building provides higher levels of thermal comfort for the same weather conditions.

3.3. Other Factors in Thermal Comfort Assessment

Classic analysis of thermal comfort is based on the measurements of certain physical parameters (including air temperature, humidity and etc.) and the consideration of thermal resistance of clothing and the kind of activity a person performs. There might, however, be other factors of larger or smaller impact on thermal sensations.

Body Mass Index (BMI) can have a possible influence on the perceived thermal sensation of people. In order to clarify this impact data collected in one lecture room (of the same indoor air parameters for all the occupants) and a large dataset collected in all three buildings (of various conditions of indoor environment, based on 1778 questionnaires) will be used. A single lecture room selected for this analysis was room 1.08 in "A" building where as many as 85 students filled in the questionnaires. They were 21–25 years old, their BMI varied significantly—from 16.9 to 35 kg/m^2. The air temperature in the room was measured to be 27.4 °C, relative humidity 49.4% and carbon dioxide concentration 1006 ppm. Figure 18 presents the relation between the BMI value of each person and the declared actual thermal sensation vote (in grey). The same figure contains data for 109 rooms. In this case the relation between the average value of thermal sensation vote for each room and the corresponding average value of BMI index of people in those rooms has been presented (in red).

The linear fit of the data—both for the single room and 109 rooms—indicate a linear correlation between the analysed parameters (the vertical shift between the two fitting lines is only related to the values of indoor parameters). As the person's BMI rises, their subjective thermal sensation also increases. Among quite limited studies on this subject, Maykot et al. [53] indicated only a weak correlation between TSV and BMI, while Indraganti et al. [54] found no differences among people with low and high BMI with regard to their thermal acceptability (the authors did not focus on thermal sensation, thus, a direct relation of their paper to the current study is difficult).

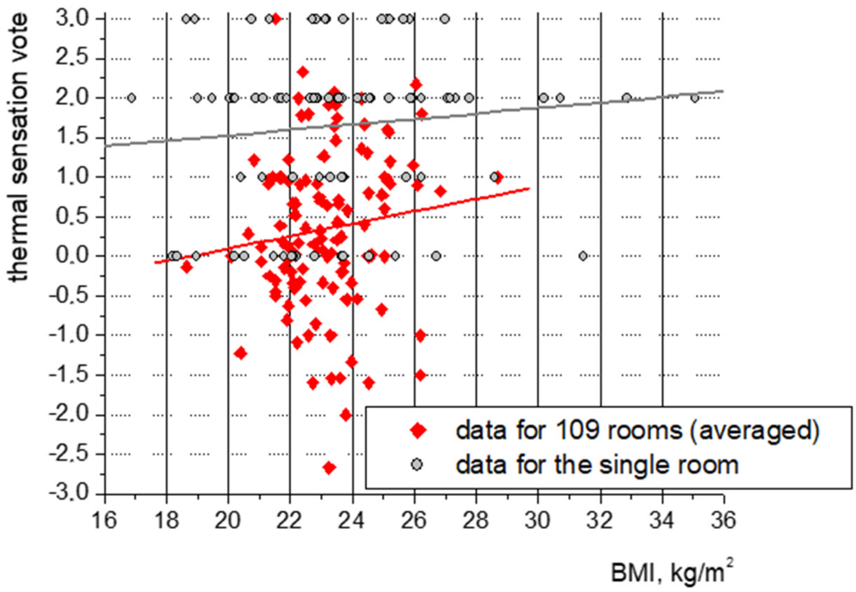


Figure 18. Relation between thermal sensation vote and BMI index for the single room and for 109 rooms, the red line represents linear fitting for the single room data, while the grey line for 109 rooms.

Another element to consider is the occupational density of people—namely, their number occupying 1 m^2 of floorspace or 1 m^3 of volume in a given room. This parameter influences the ability of a person to exchange heat between the skin and the surroundings. Since most of the time humans dissipate heat—in the form of conductivity, convection, and radiation as well as evaporation—any disruption in this process can adversely affect thermal sensations. Cooling by radiation from the body to colder surfaces (e.g., walls) can only be effective if there is nothing between the body and the surface. The presence of other persons, who also need to cool themselves and dissipate heat via radiation, hampers the heat exchange and can lead to elevated TSV values. Figure 19 presents the relation between the average thermal sensation vote and the number of people per surface area. A very similar dependence has been obtained if the mean TSV values are related to the unit volume.

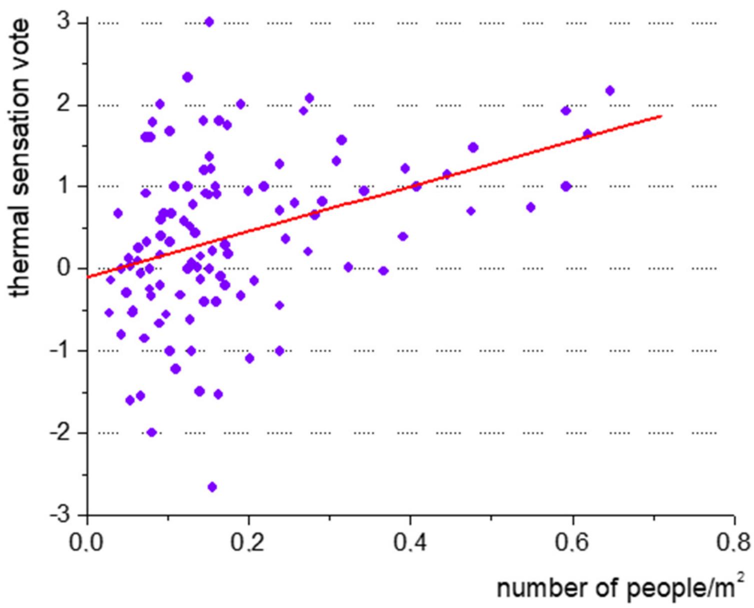


Figure 19. Thermal sensation vote vs. number of people per unit area, the red line represents the linear fitting, while the purple dots the average values of TSV.

The identified linear predicting model for TSV is as follows (where NOP is the number of people per unit area of a square meter):

$$\mathrm{TSV} = 2.79\mathrm{NOP} - 0.11\,, \tag{8}$$

Although the R^2 value is very low (0.14), the analysis of the above figure indicates that the occupational density might be responsible for elevated values of TSV in crowded rooms, where heat transfer to the surroundings is hampered. Similarly to the impact of BMI, this phenomenon has not been considered in the international standards of thermal comfort [6,7], while a combined effect of both of them can explain discrepancies between the calculated and measured values of thermal sensations, which are often reported in literature (e.g., [3,19,22]).

It needs to be noted that although all three considered buildings are subject to very similar climatic conditions and the tests were conducted in relatively close time span with the same experimental method and equipment, the differences or discrepancies of data presented in this section could be attributed to individual and subjective perceptions of the respondents as well as the factors that have not been considered in the study such as sunlight intensity through windows, location of individual persons relative to the air supply units and etc. Nevertheless, the data presented in the graphs indicate that the influence of those factors might not have been significant if a large number of people is considered (as evidenced e.g., by the fact that the data points in Figures 11, 14 and 15 follow the same trend). However, care should be exercised when a broader application of the presented results is done, especially in the case of regions of considerably different climates (for example, Africa or South America), where people are used to different thermal conditions. Another weak point to consider is the fact that although the study covered a large range of age (up to 63 y.o.), the majority of the respondents were full time students (19–24 y.o.), namely: 78.4% of the participants. Thus, the thermal responses obtained in the present study might not fully represent the whole population.

4. Conclusions

The analysis of thermal comfort conducted on a large group of people (1778 questionnaires), in three buildings and at various indoor environment conditions enable us to draw important and general conclusions, namely:

1. Intelligent buildings provided higher levels of thermal comfort than the traditional building. The positive assessment of the thermal environment for the intelligent buildings was recorded for over 60% of the votes, while for the traditional building only ca. 45%. Consequently, on average about half of the room users in the smart buildings did not want any change to their thermal surroundings, as opposed to only 29% in the traditional building. However, the acceptability in all the buildings was comparable, which might result from the fact that people who spend significant amounts of time in a certain building have learned to accept and adopt to its indoor environment conditions;

2. Human preferences regarding indoor thermal environment in relation to thermal sensations did not depend on the type of building. The dependence of thermal preference vote on thermal sensation vote shows the same trend for all the buildings, which can be linked to human inborn thermal assessment mechanisms rather then the surrounding environment. Mean thermal preference votes proved to be well correlated with indoor air temperature, but only for the educational buildings. This might be influenced by individual features of office workers in the Courthouse, which have an impact on the mean value of TPV generated for a smaller number of people in comparison to typically large student groups in “Energis” and “A” building;

3. Individual subjective assessment of air movement was significantly correlated with thermal sensations experienced by the room users. As air movement was perceived to intensify, people tended to feel colder and their thermal sensation vote moved towards lower values. The difference of the mean TSV between “no air movement” and “movement

of significant speed” was about −3.5 points. It seems to be clearly related to the heat loss intensification by convection;

4. People participating in the study proved to find their environment most acceptable when TSV was within the range of −0.5 to +1 (with the maximum at TSV = +0.25). It indicates that the respondents were more satisfied with warmer environments. Moreover, when high acceptability was observed for a group of people, they were typically either unwilling to make any changes to their thermal environment or the proposed changes were marginal (TPV within the range of −0.25 to +0.25);

5. Other parameters that affected thermal responses in the analysed groups of volonteers were identified, namely BMI and the number of people per surface area. As the BMI of a person increases, so does their thermal sensation vote in a given room. This relation was observed both in the case of individual responses of 85 students situated in one lecture room as well as for the mean values obtained in 109 rooms. The same kind of relation was observed for the occupational density, which typically led to elevated TSV values as it increased. These phenomena need to be studied more closely since they—in certain cases—can have a considerable influence on thermal comfort assessment.

6. The applicability of the results should consider the fact that the data have been obtained for the Central European moderate climate and the respondents were mostly young adults (19–24 y.o.). This fact should be thought of when a broader application of the test results is taken into account.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en15186522/s1, Figure S1: Regressions for individual buildings with regions of confidence for mean and prediction for: the Courthouse (a), “A” building (b) and “Energies” (c); Figure S2: Thermal acceptability vote vs. thermal sensation vote-data for all the buildings; Figure S3: Thermal acceptability vote vs. thermal preference vote-data for all the buildings; Figure S4: Thermal sensation vote vs. the number of people per unit area; Table S1: Details of the rooms. Table S2. Data of the participants.

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Abbreviations

BMI	body mass index
HPV	humidity preference vote
HVAC	heating, ventilation and air conditioning
NOP	occupational density
PMV	Predicted Mean Vote
PPD	Percentage of People Dissatisfied
ppm	parts per million
T	temperature
TAV	thermal acceptability vote
TPV	thermal preference vote
TSV	thermal sensation vote

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