

Article

How Can We Adapt Thermal Comfort for Disabled Patients? A Case Study of French Healthcare Buildings in Summer

Youcef Bouzidi ^{1,*} , Zoubayre El Akili ^{1,*}, Antoine Gademer ², Nacef Tazi ³ and Adil Chahboun ⁴ 

¹ Interdisciplinary Research on Society-Technology-Environment Interactions (InSyTE), CREIDD, University of Technology of Troyes, 12 Rue Marie Curie, CS 42060, CEDEX, 10004 Troyes, France

² Institute of Electronics and Systems UMR 5214, EPF Graduate School of Engineering, 21 Bd Berthelot, 34000 Montpellier, France; antoine.gademer@epf.fr

³ Cerema, 112 Rue de Paris, 77171 Sourdun, France; nacef.tazi@cerema.fr

⁴ Thin Films and Nanomaterials Laboratory, Faculty of Science and Technology, Abdelmalek Essaadi University, Ancienne Route de l'Aéroport, Km 10, Ziaten, Tanger BP: 416, Morocco; adil.chahboun@gmail.com

* Correspondence: youcef.bouzidi@utt.fr (Y.B.); zoubayre.el_akili@utt.fr (Z.E.A.)

Abstract: This paper investigates adaptive thermal comfort during summer in medical residences that are located in the French city of Troyes and managed by the Association of Parents of Disabled Children (APEI). Thermal comfort in these buildings is evaluated using subjective measurements and objective physical parameters. The thermal sensations of respondents were determined by questionnaires, while thermal comfort was estimated using the predicted mean vote (PMV) model. Indoor environmental parameters (relative humidity, mean radiant temperature, air temperature, and air velocity) were measured using a thermal environment sensor during the summer period in July and August 2018. A good correlation was found between operative temperature, mean radiant temperature, and PMV. The neutral temperature was determined by linear regression analysis of the operative temperature and Fanger's PMV model. The obtained neutral temperature is 23.7 °C. Based on the datasets and questionnaires, the adaptive coefficient α representing patients' capacity to adapt to heat was found to be 1.261. A strong correlation was also observed between the sequential thermal index $n(t)$ and the adaptive temperature. Finally, a new empirical model of adaptive temperature was developed using the data collected from a longitudinal survey in four residential buildings of APEI in summer, and the obtained adaptive temperature is 25.0 °C with upper and lower limits of 24.7 °C and 25.4 °C.

Keywords: thermal comfort; healthcare facility; disabled people; adaptive thermal comfort; indoor environment; air-conditioned building



Citation: Bouzidi, Y.; El Akili, Z.; Gademer, A.; Tazi, N.; Chahboun, A. How Can We Adapt Thermal Comfort for Disabled Patients? A Case Study of French Healthcare Buildings in Summer. *Energies* **2021**, *14*, 4530. <https://doi.org/10.3390/en14154530>

Academic Editor: Boris Igor Palella

Received: 24 June 2021

Accepted: 22 July 2021

Published: 27 July 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Indoor thermal comfort has become an important topic in the context of sustainable living. Providing an adequate indoor climate, especially in healthcare facilities, is important because these residential buildings accommodate people with medical conditions who are significantly affected by lower or higher temperatures [1]. In the case of the healthcare facilities studied in the French city of Troyes, the challenge of managers is to ensure adaptive thermal comfort for patients inside the buildings in summer. Thermal comfort is defined as a state of mind that expresses satisfaction with the thermal environment [2]. The majority of thermal comfort studies are related to healthy groups of occupants, with few studies exploring the thermal comfort of disabled people due to a lack of knowledge in this area [3]. Similarly, the ASHRAE Standard 55-2020 [4], as well as ISO/TS 14415 [5], have limited information on this issue. To establish guidelines for the design and control of building systems, it is therefore necessary to determine all the environmental parameters of the healthcare facility and the thermal comfort requirements of its residents. In this paper, both objective and subjective methods are used to achieve this aim.

Thermal comfort parameters were investigated during the summer season in residential buildings managed by the Association of Parents of Disabled Children (APEI) in the French city of Troyes. These medico-social buildings accommodate people with physical (motor disabilities, multiple disabilities, etc.) and mental disabilities. Constructed in 1992, they are managed by the “APEI of Aube” located in eastern France (latitude 48.32°, longitude 4.04°). The measurement of thermal comfort in a healthcare environment is a challenging and even daunting task. The challenge is therefore to meet the thermal comfort needs of all occupants, whether patients or staff, in an optimal way [6]. The physical environment has an impact on the health and wellbeing of occupants [7]. Providing a good indoor climate is important not only because it makes the occupants more comfortable, but also because it reduces the building’s energy consumption. The thermal comfort of patients with physical or mental disabilities can differ from that of healthy people [8]. It is therefore important to study the various environmental and personal parameters that affect the patient’s thermal comfort.

Adaptive thermal comfort is a topic that has interested researchers for the last 20 years [9] because people have a natural tendency to adapt to changing conditions in their environment [10]. The adaptive approach is often used in a naturally ventilated building because there are more opportunities for adaptation, however, it may still be valid if there are possibilities for adaptation in air-conditioned buildings. Indeed, Parkinson et al. [11] has recently shown that adaptive comfort processes could be relevant in buildings with air conditioning.

For this purpose, ISO 14415 [12] was designed for application along with ISO 7730 for determining the thermal comfort of people with disabilities. Adaptive thermal comfort in healthcare facilities is necessary due to the diverse comfort and health needs of patients and medical staff. People with physical disabilities may have different thermal requirements compared to healthy people. This is mainly due to thermoregulatory dysfunctions as well as technological devices such as wheelchairs [13] used by some patients in the long term. After comparing the association between actual mean vote (AMV) and predicted mean vote (PMV) values on the one hand and age and gender on the other, Del Ferraro et al. [14] highlighted that gender and age are important factors when evaluating thermal comfort in hospital settings. Thermal requirements should be considered on an individual level for people with physical disabilities [15].

Hill et al. [1] showed that the most common request among patients with physical disabilities was to be warmer, whereas staff tended to want to be cooler. The study of Hashiguchi et al. [16] compared the thermal comfort of patients and medical staff, concluding that most patients were comfortable, while medical staff were uncomfortable, although this study did not compare subjective responses and objective measurements with PMV predictions. Khodakarami et al. [17] reported that the user groups in a hospital setting had different thermal comfort requirements that were difficult to accommodate in one single space. Therefore, ensuring adaptive comfort for each group is necessary.

To accommodate the different thermal comfort requirements of healthcare occupants, Sattayakorn et al. [18] determined the acceptable temperature ranges for patients, visitors, and medical staff to be 21.8–27.9 °C, 22.0–27.1 °C, and 24.1–25.6 °C, respectively. Nuria et al. [19] investigated the thermal comfort of aging people in nursing homes in the Mediterranean summer, showing that the thermal comfort temperature for elderly residents is around 24.4 °C compared to 23.5 °C for non-elderly persons. Kim et al. [20] indicated that indoor hygrothermal conditions should be carefully managed in healthcare facilities to improve staff comfort and satisfaction with their working environment. This indirectly brings positive health outcomes for patients.

Verheyen et al. [8] investigated the thermal comfort of patients in a Belgian healthcare facility using objective and subjective methods for different patient groups. They concluded that PMV may adequately predict mean thermal sensation for patients. According to Sattayakorn et al. [17], the PMV model is unsuitable for determining the thermal comfort of healthcare occupants in tropical climates, with this result being confirmed by Yau et al. [21]

who reported that the PMV model might not be suitable for tropical hospitals. Alotaibi et al. [22] studied the thermal comfort of hospital patients in air-conditioned environments in hot climates. Their main objective was to determine to what extent the thermal environment of hospitals, often designed on standard office comfort, is suitable for hospital patients. They confirmed that the thermal sensation votes (TSV) strongly overestimated the PMV index of all patients, meaning that a warmer indoor environment was desired. Zaniboni et al. [23] investigated the thermal comfort of patients in physiotherapy centers by comparing objective parameters and subjective measurements of thermal comfort for different groups of patients and therapists. They confirmed that the PMV was unsuitable for accurately predicting the thermal sensation of therapists and patients. Thus, the application of the PMV index for this type of population is questionable, and its efficiency is limited.

Carlucci et al. [24], investigated the five regulatory documents that have incorporated an adaptive thermal comfort model (ANSI/ASHRAE 55, EN 15251, prEN 16798-1, ISO 74 and GB/T 50784), results indicated that several sources of uncertainty affecting the application of the standards in practice. Pereira et al. [25], conducted a literature review of papers published between 1968 and August 2020 on thermal comfort in hospitals, health centers, and elderly centers. The main findings of this research are as follows: (i) only 12 papers where there was a comparison TSV with PMV; (ii) an adequate thermal environment for professionals and patients is necessary; (iii) little explored study topics, such as staff productivity or consideration of patient health status in the assessment of thermal comfort.

To overcome this issue, this paper presents the adaptive thermal comfort model based on the “Black Box” theory in the residential buildings of APEI. This model is known as the adaptive predicted mean vote (PMVa) model in the adaptive comfort literature and takes into account factors such as climate, culture, as well as psychological and behavioral adaptations. It is necessary to estimate the environmental parameters of the healthcare facility and the thermal comfort requirements of its residents to establish guidelines for the design and control of building systems. This paper proposes an adaptive model of temperature to create a more sustainable environment in which disabled patients are more comfortable.

2. Materials and Methods

The purpose of this field study is to assess thermal comfort and determine the rate of change of thermal sensation (subjective and objective measurements were collected simultaneously) to better adapt the thermal approaches implemented for the disabled people living in the APEI residential buildings (Figure 1).

2.1. Survey Description

The longitudinal thermal comfort survey was conducted in the four APEI residential buildings (which are air-conditioned spaces), from 2 July to 31 August 2018 (Figures 2 and 3). During this period, the buildings were occupied permanently (10 am–6 pm). Each building group consists of 12 private rooms along with a shared living space and is managed by five caregivers. The four studied buildings are similar in terms of their architecture and medical services. Table 1 below gives the sex distribution of subjects living in the different building groups and Table 2 lists the physical parameters. The reduced number of respondents is a limitation of this survey although some studies have been conducted with small groups on hospitals: for example, Del Ferraro et al. with 58 subjects [14] and Skoog et al. with only 35 subjects [26].

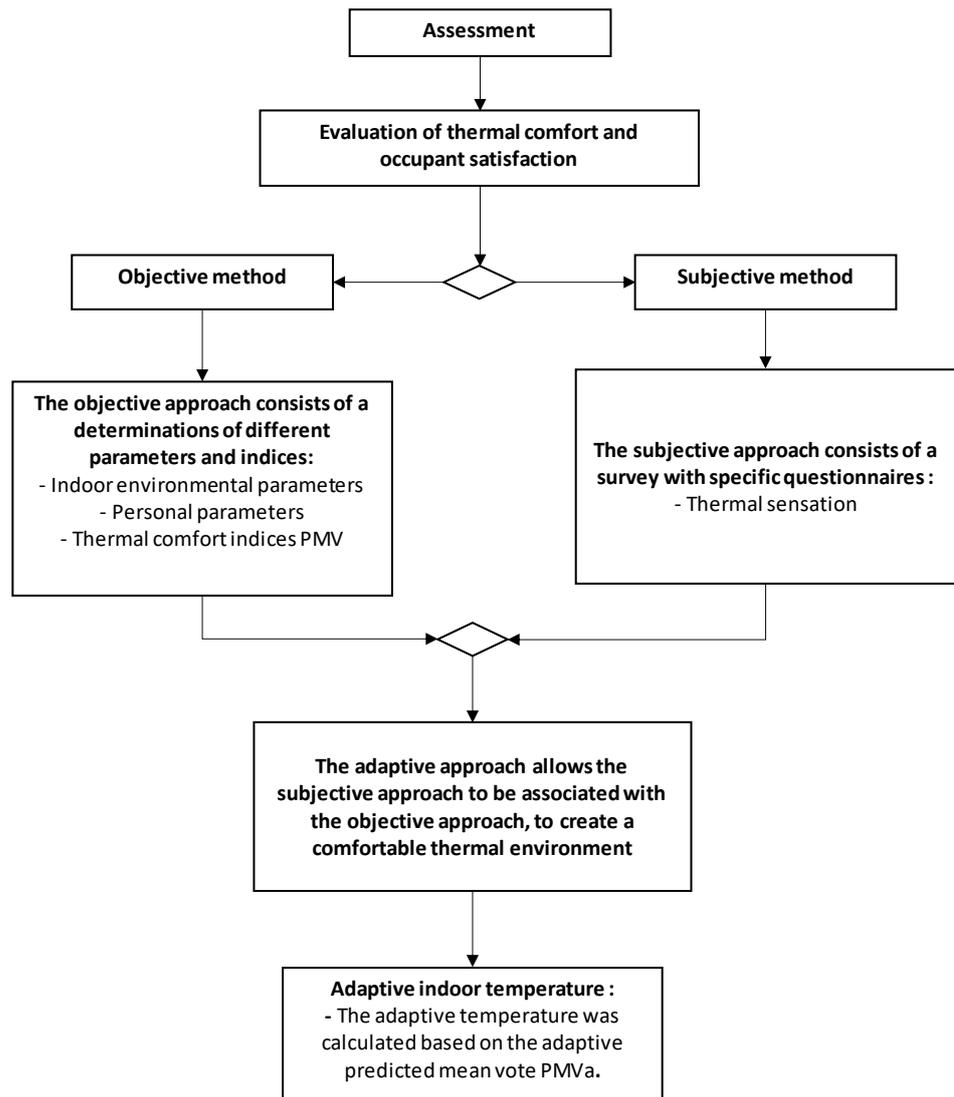


Figure 1. Flowchart of the methodology used.

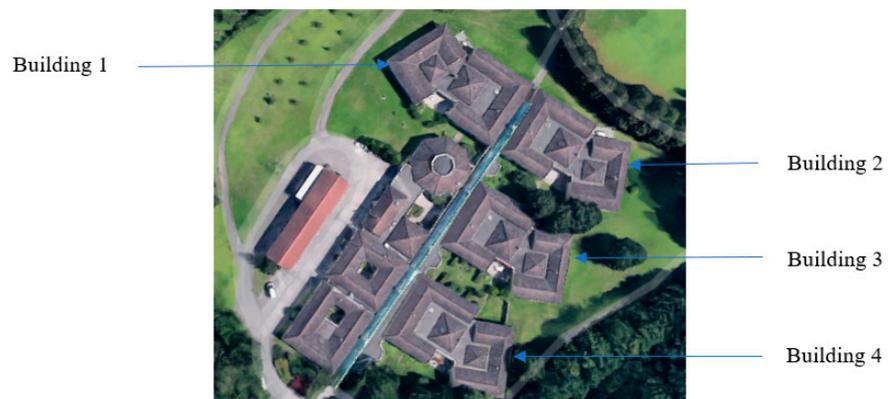


Figure 2. Locations of the survey sites.

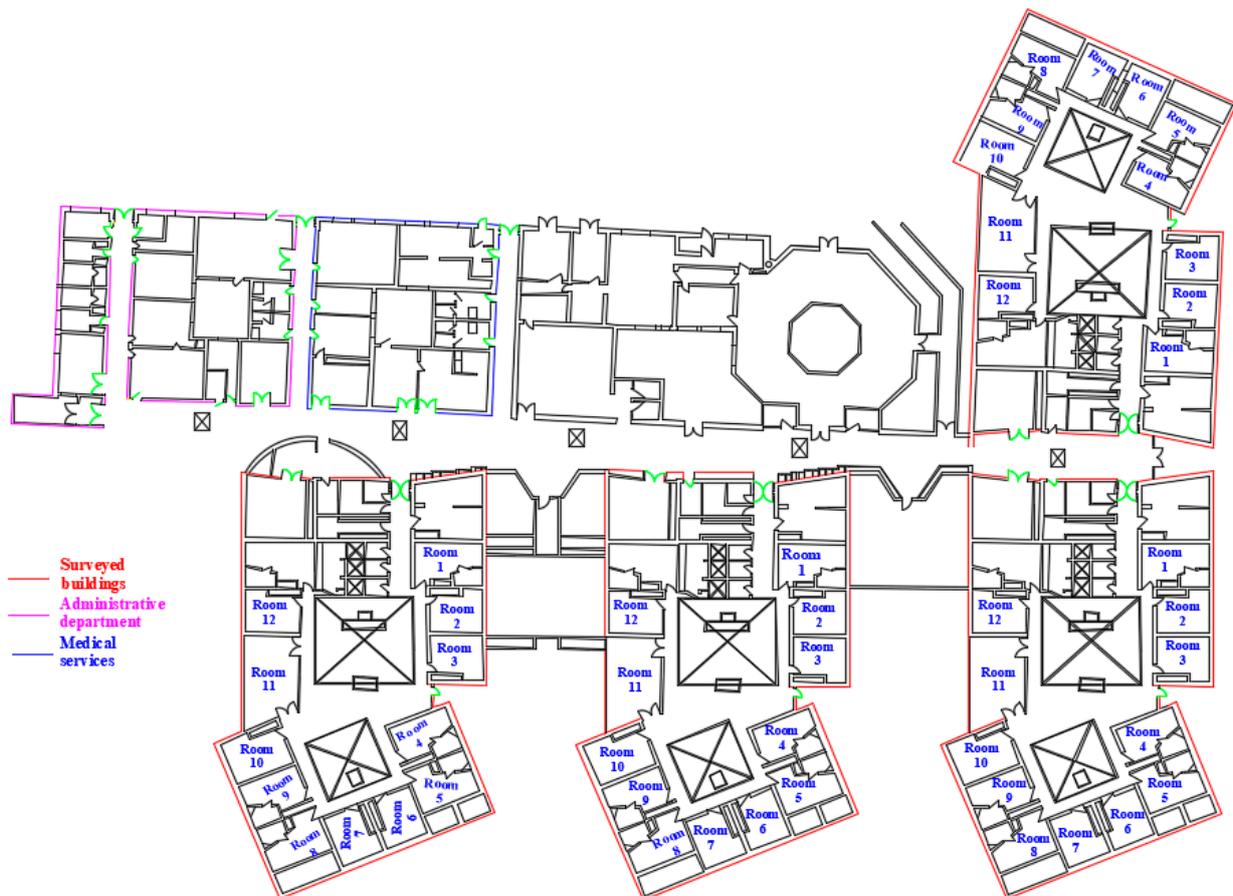


Figure 3. Surveyed building.

Table 1. Population sex distribution.

	Women	Men	Total
Building 1	5	6	11
Building 2	5	4	9
Building 3	5	3	8
Building 4	6	3	9
Total	21	16	37

Table 2. Summary of patients' physiological parameters.

	Age (Years)	Weight (kg)	Height (m)	BMR (Kcal)
Maximum	72.00	95.00	1.88	1880.49
Minimum	21.00	28.10	1.37	887.75
Average	47.95	59.69	1.57	1338.56
SD	13.59	16.78	0.12	250.72

Table 2 summarizes the physiological parameters of participants in which we find strong discrepancies in age, weight, and height. The patients engage in light physical activities around once per week. They were interviewed in their bedrooms where they spend most of their time, as they only leave their rooms for meals, showers, and activities. To improve the discipline of patients and psychologically prepare them for this investigation, we conducted a 7-day trial study to explain our methodology. In total, 320 valid questionnaires were collected during the study period. All questionnaires were conducted

in summer, corresponding to July and August in Troyes. We focused our study on the summer season to overcome the issue of a lack of data mentioned in the literature for this population. Furthermore, APEI buildings are heated permanently during winter.

2.2. Objective Parameters

Physical parameters (Table 3) were continuously measured by the station placed at a height of 1.1 m from the ground according to ASHRAE Standard 55 for seated persons [4]. Indoor environmental parameters including relative humidity, mean radiant temperature, air temperature, and air velocity were measured using a thermal microclimate station (HD32.3 instrument by Delta Ohm) (Figure 4); The station is placed at 0.8–1 m from the respondents, and the metabolic rate was estimated in accordance with ISO 7730 and set at 1.2, which corresponds to sedentary activities. Being the metabolic rate of the investigated sample close to sedentary activity conditions, the relative air velocity has been assumed equal to air velocity as proposed by researchers at DTU [27]. The mean radiant temperature T_r is calculated by the microclimate thermal station in the case of forced convection (see Appendix B). Tables 3 and 4 show respectively the indoor parameters and instrument accuracy.

Table 3. Statistical summary of environmental parameters and clothing insulation values.

Parameter	$T_{a_{out}}$ (°C)	$T_{a_{in}}$ (°C)	T_r (°C)	RH (%)	V_{air} (m/s)	I_{cl} (clo)
Min	19.10	24.15	24.00	25.10	00.00	00.41
Max	41.20	29.55	29.86	68.60	00.19	00.77
Average	29.30	26.35	26.29	45.09	00.01	00.53
SD	04.89	01.23	01.27	07.47	00.02	00.07



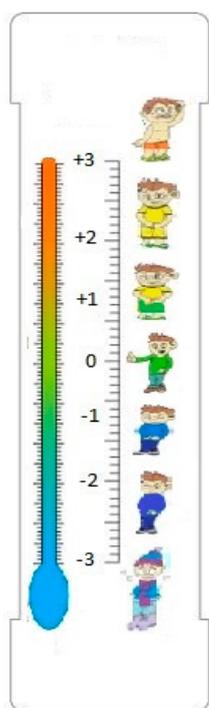
Figure 4. Thermal microclimate station.

Table 4. Physical measurements and accuracy of the thermal microclimate station.

Parameter	Accuracy	Valid Range
Air Velocity (m/s)	± 0.2	0–1
Relative Humidity (%)	± 0.3	1–5
	± 1.5	0–90
Temperature (°C)	± 2.0	90–100
	Class 1/3 DIN	–40–+100
Globe Temperature (°C)	Class 1/3 DIN	–10–+100

2.3. Subjective Measurement

Thermal sensation was evaluated using a subjective ruler with pictorial representations developed in collaboration with the medical service of APEI. As shown in Figure 5, the ruler is a subjective measuring tool based on the standard seven-point thermal sensation scale. This vertical ruler has the shape of a large thermometer with the pictorial representation of a man. Each man corresponds to a value to describe the thermal sensations of occupants using different types of clothing and colors.

**Figure 5.** Subjective ruler for measuring thermal sensations.

3. Results and Discussion

3.1. Thermal Comfort Survey

During the field study period (July–August), the outdoor temperature oscillated between 19.1 °C and 41.2 °C, with mean temperatures around 29.3 °C. The corresponding indoor temperature during the surveys varied from 24.15 °C to 29.55 °C.

Figure 6 shows the results obtained for the thermal sensations of occupants. In general, the positive values (slightly warm, warm, hot) obtained during the measurement campaign indicate a warm thermal sensation from the patient's point of view in the APEI residential buildings. The initial conclusions from this survey show that most of the respondents were thermally uncomfortable in all the investigated locations: 26.9% of respondents rated their thermal sensations within an acceptable range (–1;+1), whereas 73.1% considered their thermal environment to be “unacceptable.” This difference is essentially due to the possibility of adapting to the conditions of the thermal environment, which differs from one patient to another, and indeed, some patients simultaneously suffer from multiple

illnesses (Table 5). This could also be explained by the drugs taken by patients, which may increase the risk of dehydration and heat-related diseases by the following mechanisms: thermoregulation, diuresis, and electrolyte imbalance, sedation and cognitive impairment, hypotension, and reduced cardiac output [28]. Age-related diseases are the most critical issues affecting the thermal comfort requirements of patients. The literature indicates that certain thermophysiological parameters significantly change with aging such as basal metabolic rate (metabolic disorders), cardiac output, blood flow, fat distribution, and body weight [29,30]. Neurological disorders can also play an important role in thermal discomfort. Indeed, heat is produced by the brain when it consumes oxygen that is removed by the blood flow [31].

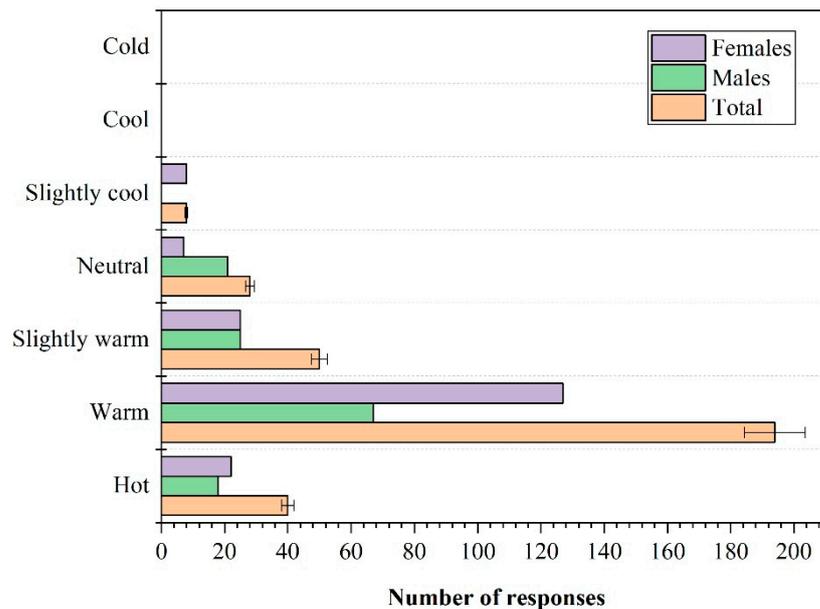


Figure 6. Distribution of thermal sensation responses according to the sex of respondents.

Table 5. List of diseases among the APEI patients.

Type of Disease	Number of Patients
Multiple disabilities	27
Intellectual disability	16
Autism	11
Physical disorders	10
Age-related diseases	9
Motor disabilities	5
Visual impairment	5
Metabolic disorders	4
Hearing impairment	3
Progressive neurological disorders	2

In order to ensure that patients are not in a febrile state [32], which could skew the results of the survey, body temperature measurements were taken beforehand. Figure 7 shows forehead temperature variations measured by a noncontact infrared thermometer (Accuracy: ± 0.2 °C) along with the corresponding indoor temperature during the surveys. In our study, the overall temperature measurements do not indicate a febrile state with a mean forehead temperature of 36.6 °C.

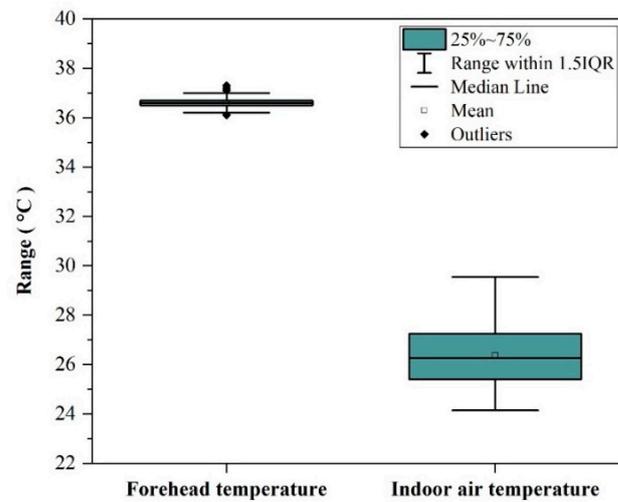


Figure 7. Forehead temperature and indoor air temperature measurements.

3.2. Predicted Mean Vote and Actual Mean Vote

Subjective and objective measurements were conducted simultaneously. Fanger's equation was used to calculate the PMV index (see Appendix A). Figure 8 shows the regression relationship between PMV and AMV. The p -value was 0.00, indicating that the result was significant (analysis of variance in combination with Fisher's statistical test was used to test the significance of the model [33]). The comparison of AMV and PMV values revealed that Fanger's PMV model generally underpredicts the thermal sensation reported by occupants; PMV can thus only partially predict thermal sensation in the studied healthcare buildings. Figure 9 compares PMV and AMV values in relation to indoor air temperatures ranging from 24.15 °C to 29.55 °C, revealing that the fitted regression line for subjects PMV is below the AMV linear curve, with the regression coefficients showing that the fitted model was statistically significant: PMV ($p < 0.05$, $R^2 = 0.68$). Therefore, patients experienced the indoor environment as warmer than the measurement results according to Fanger's model. This discrepancy can be explained by the limited ability of patients to adapt to warming temperatures, which is not considered in Fanger's PMV model.

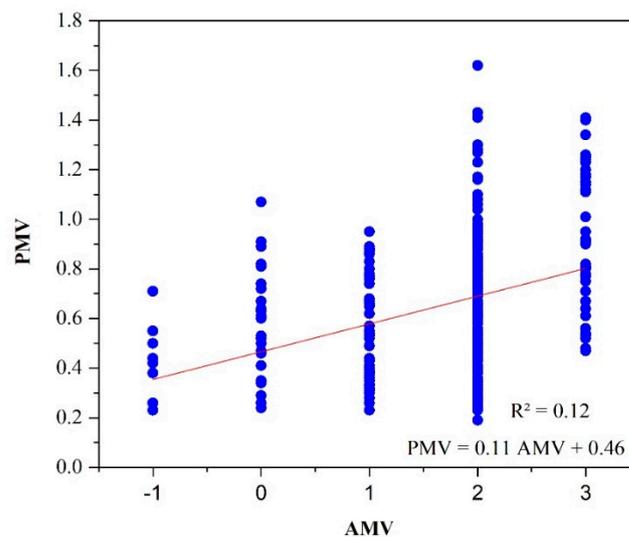


Figure 8. Relationship between predicted mean vote (PMV) and actual mean vote (AMV).

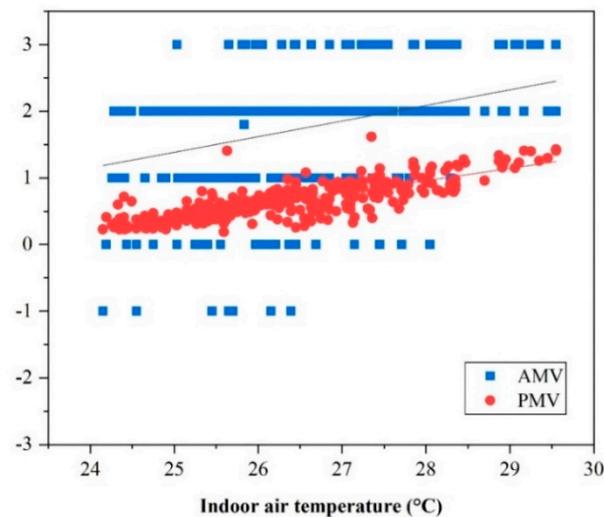


Figure 9. Comparison between PMV and AMV in relation to indoor air temperature.

3.3. Predicted Mean Vote and Indoor Operative and Neutral Temperatures

As a significant factor influencing thermal comfort, operative temperature combines the impact of both air and radiant temperatures without air movement in addition to relative humidity [34]. For most indoor comfort studies, the relationship between PMV and operative temperature is considered [35,36]. This relationship was successfully established with the determination coefficient $R^2 = 0.70$ ($p < 0.05$) in Equation (1), which indicates the significant influence of operative temperature on PMV (Figure 10).

$$PMV = 0.18 T_o - 4.26 \quad (1)$$

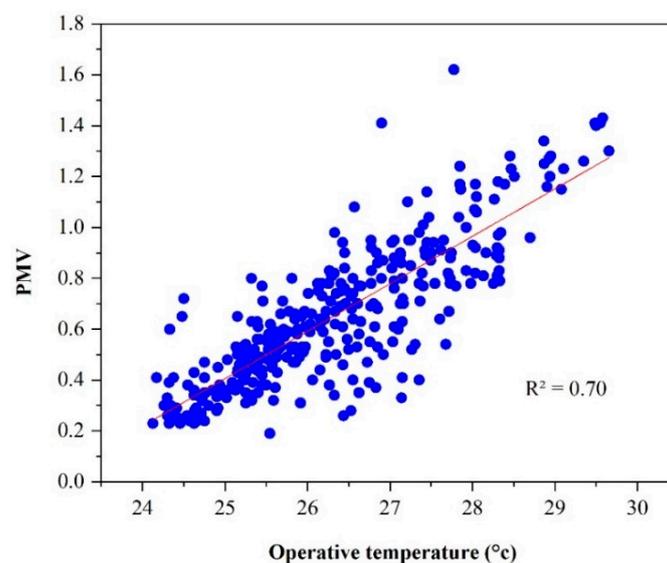


Figure 10. Relationship between PMV and operative temperature.

Based on Equation (1), at indoor operative temperatures exceeding $24.8\text{ }^{\circ}\text{C}$, the PMV is outside the neutral thermal comfort zone ($-0.2, +0.2$) recommended for spaces occupied by vulnerable people with special requirements such as the patients included in our study [37]. Therefore, the neutral temperature needs to be calculated.

The thermal neutrality temperature, T_n , is defined as the optimal temperature to guarantee comfortable conditions [38]. The neutral temperature corresponding to the thermal comfort in APEI residential buildings was calculated using Equation (1) (when

$PMV = 0$, $T_o = T_n$, the neutral temperature is $23.65\text{ }^\circ\text{C}$). Table 6 shows the thermal comfort ranges according to the ASHRAE Standards. However, the obtained neutral temperature is acceptable.

Table 6. Thermal comfort ranges according to the ASHRAE Standards.

Standard	Design Temperature ($^\circ\text{C}$)	Location
ASHRAE 2008 [39]	21–24	Inpatient nursing: patient room
ASHRAE 2007 [40]	21–24	Hospital and outpatient facilities: patient room

3.4. Predicted Mean Vote and Mean Radiant Temperature

The mean radiant temperature (T_r) is defined as “The uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space” [41]. T_r has the strongest influence on significant thermo-physiological indices such as PMV [42]. The correlation between PMV and T_r can be seen in Figure 11 and is represented in Equation (2):

$$PMV = 0.18 T_r - 4.21 \quad (2)$$

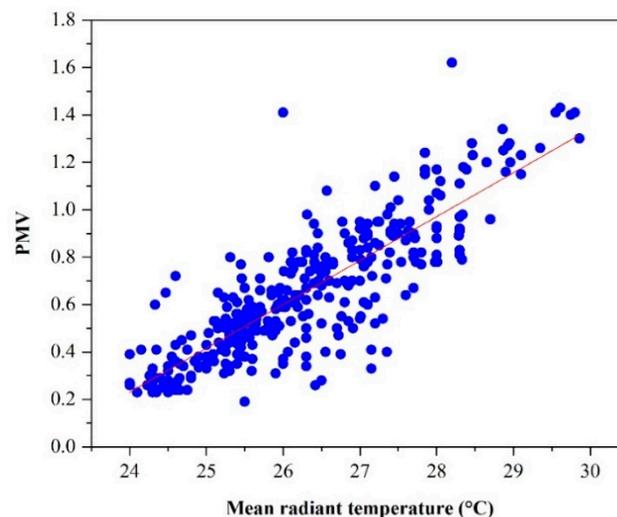


Figure 11. Relationship between predicted mean vote (PMV) and mean radiant temperature (T_r).

The determination coefficient ($R^2 = 0.71$) indicates the influence of T_r on PMV. Therefore, high intensity of solar radiation leads to an increase in PMV, ultimately increasing occupants’ thermal discomfort on sunny days (since solar radiation increases the interior surface temperature, leading to an increase in the mean radiant temperature).

T_r was correlated with the measured indoor temperature by means of linear regression (Figure 12). We observed a strong relationship between these parameters ($R^2 = 0.97$), which is in agreement with previous studies [43,44]. This indicates that the radiant heat gain was not significant in the surveyed building spaces. Therefore, we considered the indoor air temperature as the operative temperature when calculating the thermal comfort.

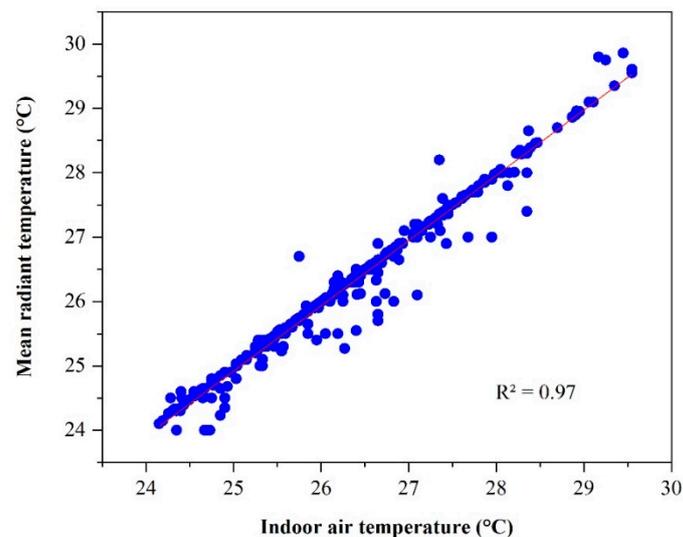


Figure 12. Relationship between mean radiant temperature (T_r) and indoor air temperature.

3.5. Effect of Thermal Insulation of Clothing on Patients' Thermal Comfort

The amount of thermal insulation worn by people has a substantial impact on their thermal comfort [45]. The estimation of clothing insulation took into account all the garments worn by people such as underwear, t-shirts, socks, shorts, shoes, summer dresses, light skirts, and leggings. The estimation of clothing insulation took into account all the garments worn by people such as underwear, t-shirts, socks, shorts, shoes, summer dresses, light skirts, and leggings. Each garment indicated in the responses was converted into thermal insulation values using the ASHRAE Standard 55 [41]. Finally, the thermal insulation of the patients' clothing ensemble was estimated by summing the thermal insulation of each garment [41,46]. As patients sit for long periods of time, 0.15 clo was added to the overall thermal insulation estimate to account for the insulating value of the chair [47].

Clothing insulation in summer slightly changes (Figure 13), with the results indicating that the overall insulation of clothing worn by patients varies from 0.41 to 0.77 clo. The average thermal insulation of clothing in summer was 0.53 clo, which, according to ASHRAE Standard 55 [41], corresponds to typical clothing insulation when the environment is warm. The thermal insulation of clothing shows low sensitivity to indoor air temperature ($R^2 = 0.0008$, $p = 0.6080$), which can be attributed to the high indoor air temperature and fewer opportunities to change clothes.

3.6. Sequential Thermal Index in Residential Buildings of APEI

To study the thermal quality of the APEI residential buildings, linear regression analysis was carried out. Equation (3) represents the relationship between the sequential thermal index (statistical function) [48], and indoor temperature in the APEI environment in summer. The correlation between the sequential thermal index and indoor temperature can be seen in Figure 14 and is represented by the following equation:

$$n(t) = -7.79 T(t) + 287.17 \quad (3)$$

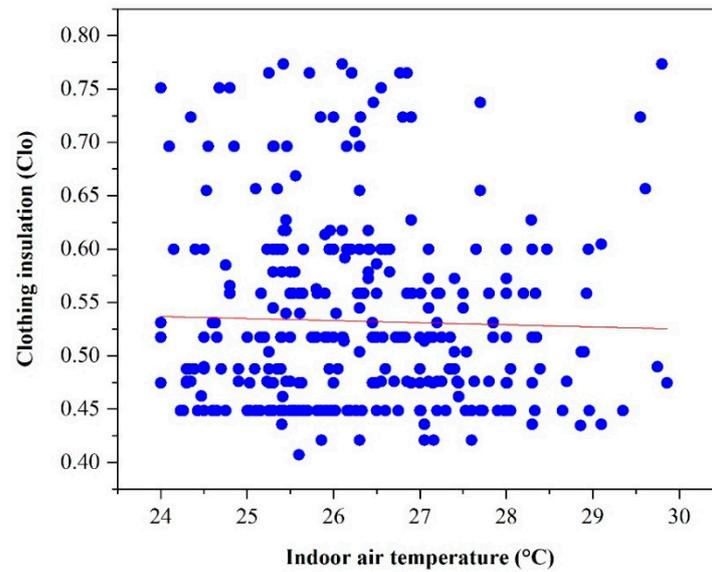


Figure 13. Indoor air temperature and overall insulation of clothing worn by patients.

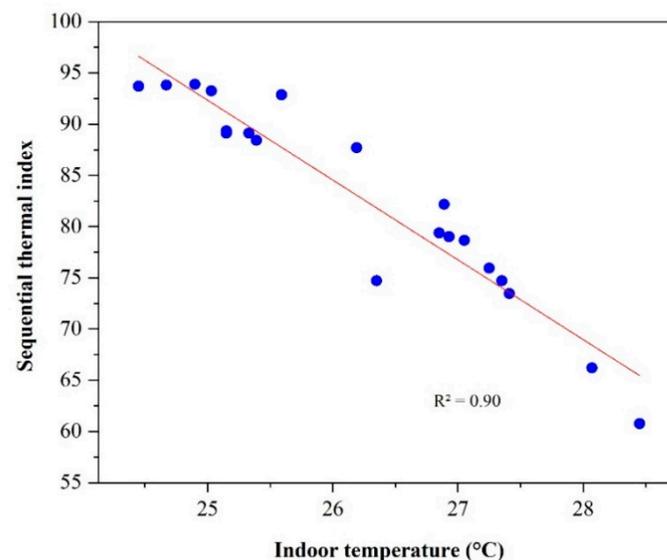


Figure 14. Relationship between indoor temperature and sequential thermal index in APEI buildings.

3.7. Comparison of Subjective Thermal Comfort Sensation in APEI Buildings

Thermal comfort requirements may differ between healthy people and people with physical disabilities. Further, people with disabilities may require drugs that can affect thermoregulatory mechanisms, while the disability may entail the use of technical devices such as wheelchairs that affect their thermal state. For people with limited adaptive opportunities (e.g., physical disabilities), an acceptable environment may be rated as unacceptable. Nevertheless, people's expectations may influence their thermal satisfaction, which may be less reliable than thermal comfort studies. For example, people may express satisfaction simply because "they don't expect any better" or dissatisfaction because "they expect much better" [49].

The present study directly compares the individual thermal comfort of patients and staff in the APEI residential buildings. Figure 15 shows the results obtained in July and August 2018 (staff: 17 subjects with 109 responses; patients: 26 subjects, with 118 responses), revealing that the thermal discomfort of patients is higher. On average, their AMV varies from 1.13 to 1.69, whereas the staff always declare a state of thermal neutrality (AMV varying from 0.26 to 0.9). The satisfaction of staff can be explained by their ability to adapt

to indoor environments by adaptive actions (i.e., opening and closing windows, changing clothing, drinking, eating, or changing their activity level). By contrast, depending on the disability and health status of patients, their adaptive opportunity may be restricted. For this reason, an adaptive indoor environment needs to be created for APEI patients.

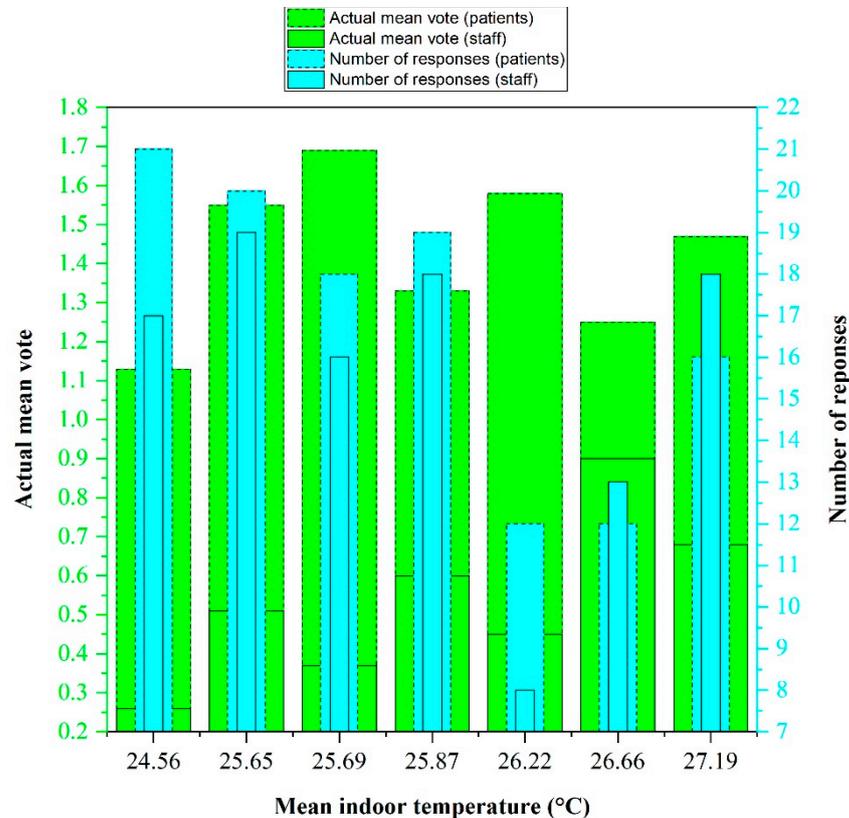


Figure 15. Difference in the subjective thermal sensations of patients and staff.

3.8. Adaptive Thermal Comfort and Patients

Overall, adaptive thermal comfort can be defined as follows: “If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort” [50]. People’s adaptive actions are generally effective in securing comfort, which happens in the case of large variations in indoor temperature [51]. Thermal adaptation can be associated with three different categories: behavioral adjustment, physiological habituation, and psychological dimensions (Figure 16) [52]. In this study, the use of an adaptive approach is necessary due to the difference between PMV and AMV; indeed, adaptive opportunities are not considered in Fanger’s PMV model.

This paper shows how the application of adaptive thermal comfort can create a comfortable thermal environment in APEI residential buildings. The theoretical adaptive model of thermal comfort based on the “Black Box” theory with the aforementioned factors is known as the adaptive predicted mean vote (PMV_a) model [11,53] and is presented in Equation (4) below:

$$PMV_a = \frac{PMV}{1 + \alpha PMV} \quad (4)$$

The adaptive coefficient α represents the patient’s capacity to adapt to warmer temperatures. It was calculated using the least square method to adjust the field data sets. α can be described by Equation (5) [54]:

$$\text{Let : } \alpha = \frac{\sum_j^j y_j - x_j}{\sum_j^j y_j} \quad \text{and } y = \frac{1}{PMV} \quad (5)$$

In our study, we have 20 data sets, so α is calculated as follows (Table 7):

$$\alpha = \frac{\sum_1^{20} y_i - x_i}{20} \quad (6)$$

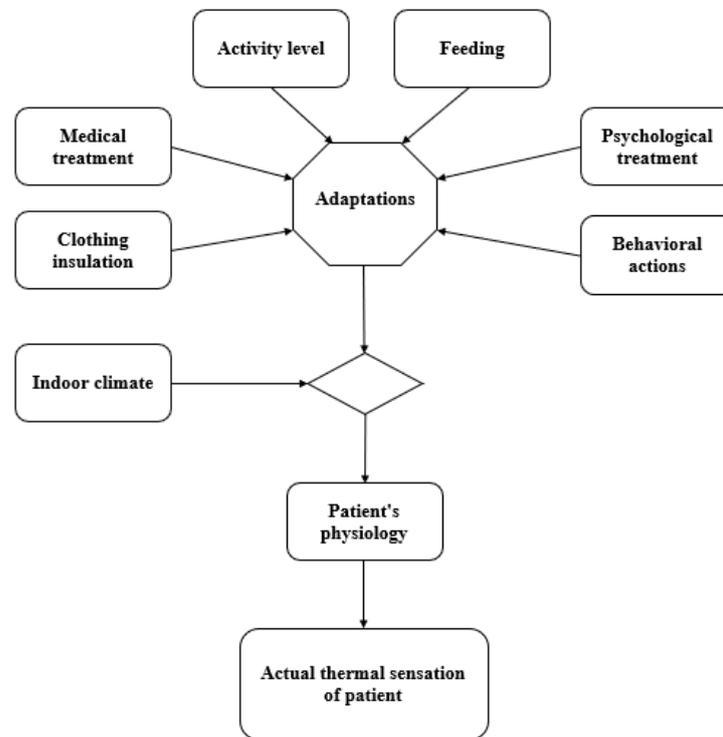


Figure 16. Flowchart of the holistic principle of the adaptive model.

Table 7. Summary of the adaptive coefficient.

Adaptive Coefficient α	
Maximum	1.875
Minimum	0.720
Average	1.261
SD	0.333

By replacing the average of this coefficient in Equation (6) [55], the following equation is obtained:

$$PMV_a = \frac{PMV}{1 + 1.261 PMV} \quad (7)$$

As seen in Equation (7), the advantage of the adaptive model is that the complex adaptation is represented as a single value. Figure 17 shows that the adaptive thermal comfort model PMV_a (varying from 0.153 to 0.532) reduces patients' sensation of discomfort by more than half when compared to the PMV model (varying from 0.19 to 1.62).

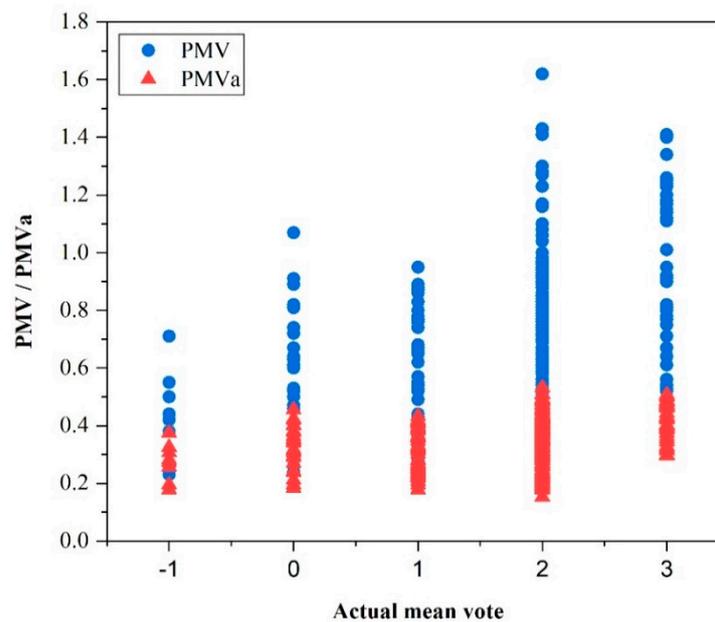


Figure 17. Comparison between adaptive predicted mean vote (PMVa) and PMV as a function of AMV.

3.9. An Adaptive Method for Indoor Temperature Control

Here, we present a new empirical equation (see Figure 18) to estimate the adaptive indoor temperature for patients in summer. It is important to estimate the adaptive temperature in order to obtain reliable results in terms of the thermal comfort of people with disabilities. The equation was based on the adaptive thermal comfort model. Figure 18 shows the different steps for determining the adaptive temperature. This study found that the patients in the APEI residential buildings can be relatively comfortable at temperatures up to 25.0 °C in summer (Table 8).

Table 8. Summary of the PMV, PMV_a, PMV', PPD', n'(t), and adaptive temperature.

	PMV	PMV _a	PMV'	PPD'	n'(t)	T _a (°C)
Maximum	1.62	0.53	0.53	10.94	89.06	25.42
Minimum	0.19	0.15	0.15	5.49	94.51	24.72
Average	0.65	0.34	0.34	7.45	92.55	24.97

The indoor temperature variation is about 5.4 °C. However, using the proposed methodology, this variation is reduced to 0.7 °C, which is substantial in terms of thermal comfort, especially in healthcare buildings that accommodate patients with specific needs that vary significantly due to the variation in hygrothermal parameters [1]. High temperatures and temperature variations harm health [56]. The advantage of adaptive temperatures is that they take into account the actual thermal feeling of patients as well as the objective measurements, whereas the calculation of the neutral temperature only considers the objective parameters. In this study, the average adaptive temperature is approximately $T_n + 1.3$ °C, while the average indoor temperature is $T_n + 2.7$ °C.

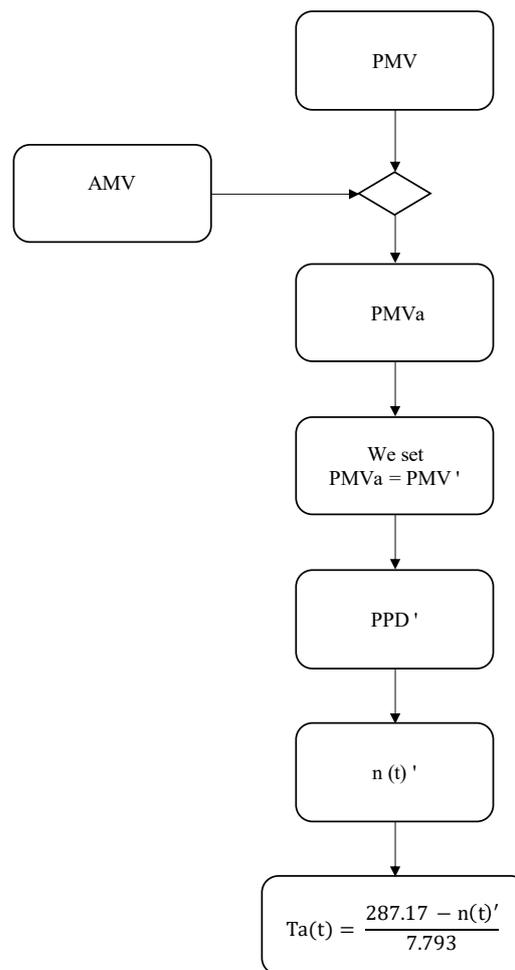


Figure 18. Steps to calculate the adaptive temperature in summer.

4. Conclusions

This study constitutes a first step toward understanding adaptive thermal comfort in French healthcare buildings for patients with disabilities. The research described in this paper was carried out in the APEI residential buildings in the summer of 2018. This research aims to broaden our understanding of thermal comfort in healthcare buildings by considering several factors relating to people with disabilities during the analysis phase. The results can improve the application of the current standards for vulnerable populations.

The most important conclusions of our study may be summarized as follows. First, simplifying the process of interviewing disabled persons by using pictures and simple language contributes greatly to obtaining reliable results. Second, the patients were generally dissatisfied with the thermal environment of their dwellings. Third, in the studied buildings, the neutral temperature is 23.65 °C, which is obtained by substituting $PMV = 0$ in Equation (1). Fourth, PMV always underestimated the thermal sensation of patients in the APEI residential buildings in summer. Fifth, the comparison between patients and staff is important to better understand the variation in comfort requirements, so that buildings can be designed to accommodate the diverse needs of all occupant groups. Sixth, this paper presents the adaptive predicted mean vote ($PMVa$) based on the relationship between measurements and field studies. Lastly, in the APEI residential buildings, the adaptive temperature is 25.0 °C with respectively upper and lower limits of 24.7 °C and 25.4 °C, respectively. This paper proposes recommendations for indoor temperatures in healthcare buildings for disabled patients based on the relationship between patients' sensations and the thermal environment.

Further studies should examine the conditions of thermal comfort in health care facilities and investigate how to personalize the comfort indices to consider the disabilities, health status, and medical treatments of this population.

Author Contributions: Conceptualization, Y.B. and Z.E.A.; methodology, Y.B. and Z.E.A.; software and materials, Z.E.A. and A.G.; Investigation, Y.B. and Z.E.A.; Writing original draft, preparation, Z.E.A.; Writing—review & editing, Y.B., N.T. and A.C.; Supervision and Funding acquisition, Y.B. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported through the research fund of Grand Est administrative region (France) for the research programme ‘Innovation’, agreement number: D 201602605 and through the European Regional Development Fund (ERDF) for the Doctoral research programme “Retcli” agreement number: CA0023755.

Informed Consent Statement: This study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Ethics committee of APEI Troyes (January 2017). Informed consent was obtained from all subjects involved in the study and in their absence by the authorised legal representative.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: This research project was conducted in collaboration with the University of Reims Champagne-Ardennes for the design of the subjective ruler, the Association of Parents of Disabled Children for allowing this study in their institution, and GH Consulting company for assistance in using the thermal microclimate station.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Abbreviations

AMV	Actual Mean Vote	[-]
I_{cl}	Clothing thermal insulation	$[KW^{-1} m^{-2}]$
M	Metabolism	$[W m^{-2}]$
T_r	Mean radiant temperature	$[^{\circ}C]$
n(t)	Sequential thermal index	[-]
PMV	Predicted Mean Vote	[-]
PMVa	Adaptive Predicted Mean Vote	[-]
PPD	Percentage People Dissatisfied	[-]
RH	Relative humidity	[%]
$T_{adaptive}$	Adaptive temperature	$[^{\circ}C]$
T_n	Neutral Temperature	$[^{\circ}C]$
T_{a-out}	Outdoor temperature	$[^{\circ}C]$
T_o	Operative Temperature	$[^{\circ}C]$
T_{a-in}	Indoor temperature	$[^{\circ}C]$
V_{air}	Air Velocity	$[m s^{-1}]$

Appendix A

Comfort Indices: PMV and PPD

$$PMV = \left(0.303 e^{(-0.036M)} + 0.028\right) \left\{ (M - W) - 3.05 \cdot 10^{-3} [5733 - 6.99(M - W) - P_a] - 0.42[(M - W) - 58.15] - 1.710^{-5} M(5867 - P_a) - 0.0014M(34 - T_a) - 3.9610^{-8} f_d \left[(T_{cl} + 273)^4 - (T_r + 273)^4 \right] - f_{cl} h_c (T_{cl} - T_a) \right\} \quad (A1)$$

$$PPD = 1 - 0.95 e^{(-0.03353 PMV^4 - 0.2179 PMV^2)} \quad (A2)$$

$$T_{cl} = 35.7 - 0.028(M - W) - 0.155 I_{cl} \left[3.96 \cdot 10^{-8} f_{cl} (T_{cl}^4 - T_{cl}^4) + f_{cl} h_c (T_{cl} - T_a) \right] \quad (A3)$$

$$h_c = \max \left[2.38 (T_{cl} - T_a)^{0.25}, 12.1 V_{ar}^{0.5} \right] \quad (A4)$$

$$f_{cl} = 1 + 0.2 I_{cl} \text{ if } I_{cl} \leq 0.5 \quad (\text{A5})$$

$$f_{cl} = 1 + 0.1 I_{cl} \text{ if } I_{cl} > 0.5 \quad (\text{A6})$$

where: M , W and P_a are the metabolic rate [W/m^2], the external work [W/m^2], and the partial vapor pressure (Pa) respectively. f_{cl} is the ratio of surface area of the body with clothes to the surface area of the naked body. h_c is the convective heat transfer coefficient $W/(m^2.K)$. T_a represents the air temperature [$^{\circ}C$], T_{cl} the surface temperature of clothing [$^{\circ}C$], T_r the mean radiant temperature [$^{\circ}C$], and V_{ar} represents the relative air velocity [m/s]. In this, study, the relative air velocity has been assumed equal to air velocity [27].

Appendix B

Mean radiant temperature

In the case of forced convection and according to ISO 7726,

$$Tr = \left[(T_g + 273)^4 + \frac{1.1 \times 10^8 \times V_a^{0.6}}{\epsilon_g \times D^{0.4}} \times (T_g - T_a) \right]^{1/4} - 273$$

where: T_r , T_g and T_a represents the mean radiant temperature [$^{\circ}C$], the globe thermometer temperature [$^{\circ}C$] and the air temperature [$^{\circ}C$] respectively, D the globe thermometer diameter, ϵ_g the globe thermometer predicted emissivity, V_a the air velocity [m/s].

References

- Hill, L.D.; Webb, L.H.; Parsons, K.C. Carers' Views of the Thermal Comfort Requirements of People with Physical Disabilities. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* **2000**, *44*, 716–719. [\[CrossRef\]](#)
- Hoof, J.; Mazej, M.; Hensen, J. Thermal comfort: Research and practice. *Front. Biosci.* **2010**, *15*, 765–788. [\[CrossRef\]](#) [\[PubMed\]](#)
- Khodakarami, J.; Nasrollahi, N. Thermal comfort in hospitals—A literature review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 4071–4077. [\[CrossRef\]](#)
- ANSI/ASHRAE. *Standard 55, 2020: Thermal Environmental Conditions for Human Occupancy*; ASHRAE: Peachtree Corners, GA, USA, 2021.
- ISO/TS 14415. *Ergonomics of the Thermal Environment—Application of International Standards to People with Physical Disabilities*; International Organization for Standardization: Geneva, Switzerland, 2005.
- Mora, R.; Meteyer, M. *Using Thermal Comfort Models in Health Care Settings: A Review*; ASHRAE Transactions: Atlanta, GA, USA, 2018; Volume 124, pp. 1–12.
- Van den Berg, A.E. *Health Impacts of Healing Environments A Review of Evidence for Benefits of Nature, Daylight, Fresh Air, and Quiet in Healthcare Setting*; University Hospital Groningen: Groningen, The Netherlands, 2005; ISBN 9032703447.
- Verheyen, J.; Theys, N.; Allonsius, L.; Descamps, F. Thermal comfort of patients: Objective and subjective measurements in patient rooms of a Belgian healthcare facility. *Build. Environ.* **2011**, *46*, 1195–1204. [\[CrossRef\]](#)
- de Dear, R.; Akimoto, T.; Arens, E.; Brager, G.; Candido, C.; Cheong, K.W.D.; Li, B.; Nishihara, N.; Sekhar, C.; Tanabe, S.-I.; et al. Progress in Thermal Comfort Research Over the Last Twenty Years. *Indoor Air* **2013**, *23*, 442–461. [\[CrossRef\]](#) [\[PubMed\]](#)
- Nicol, J.F.; Humphreys, M.A. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy Build.* **2002**, *34*, 563–572. [\[CrossRef\]](#)
- Parkinson, T.; de Dear, R.; Brager, G. Nudging the adaptive thermal comfort model. *Energy Build.* **2020**, *206*. [\[CrossRef\]](#)
- Yao, R.; Li, B.; Liu, J. A theoretical adaptive model of thermal comfort—Adaptive Predicted Mean Vote (aPMV). *Build. Environ.* **2009**, *44*, 2089–2096. [\[CrossRef\]](#)
- Parsons, K.C. The effects of gender, acclimation state, the opportunity to adjust clothing and physical disability on requirements for thermal comfort. *Energy Build.* **2002**, *34*, 593–599. [\[CrossRef\]](#)
- Del Ferraro, S.; Iavicoli, S.; Russo, S.; Molinaro, V. A field study on thermal comfort in an Italian hospital considering differences in gender and age. *Appl. Ergon.* **2015**, *50*. [\[CrossRef\]](#)
- Parsons, K.C. *Human Thermal Environments: The Effects of Hot, Moderate Andcold Environments on Human Health, Comfort and Performance*, 2nd ed.; Taylor and Francis: London, UK, 2003.
- Hashiguchi, N.; Hirakawa, M.; Tochiyama, Y.; Kaji, Y.; Karaki, C. Thermal Environment and Subjective Responses of Patients and Staff in a Hospital during Winter. *J. Physiol. Anthropol. Appl. Hum. Sci.* **2005**, *24*, 111–115. [\[CrossRef\]](#) [\[PubMed\]](#)
- Khodakarami, J.; Knight, I. Measured Thermal Comfort Conditions in Iranian Hospitals for Patients and Staff. In Proceedings of the CLIMA 2007 Wellbeing Indoors, Helsinki, Finland, 10–14 June 2007.
- Sattayakorn, S.; Ichinose, M.; Sasaki, R. Clarifying thermal comfort of healthcare occupants in tropical region: A case of indoor environment in Thai hospitals. *Energy Build.* **2017**, *149*. [\[CrossRef\]](#)

19. Forcada, N.; Gangoellis, M.; Casals, M.; Tejedor, B.; Macarulla, M.; Gaspar, K. Summer thermal comfort in nursing homes in the Mediterranean climate. *Energy Build.* **2020**, *229*, 110442. [[CrossRef](#)]
20. Kim, S.-K.; Hwang, Y.; Lee, Y.; Corser, W. Occupant Comfort and Satisfaction in Green Healthcare Environments: A Survey Study Focusing on Healthcare Staff. *J. Sustain. Dev.* **2015**, *8*. [[CrossRef](#)]
21. Yau, Y.; Chew, B.T. Thermal comfort study of hospital workers in Malaysia. *Indoor Air* **2009**, *19*, 500–510. [[CrossRef](#)] [[PubMed](#)]
22. Alotaibi, B.S.; Lo, S.; Southwood, E.; Coley, D. Evaluating the suitability of standard thermal comfort approaches for hospital patients in air-conditioned environments in hot climates. *Build. Environ.* **2020**, *169*, 106561. [[CrossRef](#)]
23. Zaniboni, L.; Pernigotto, G.; Toftum, J.; Gasparella, A.; Olesen, B.W. Subjective and objective assessment of thermal comfort in physiotherapy centers. *Build. Environ.* **2020**, *176*, 106808. [[CrossRef](#)]
24. Carlucci, S.; Lujian, B.; de Dear, R.; Yang, L. Review of adaptive thermal comfort models in built environmental regulatory documents. *Build. Environ.* **2018**, *137*. [[CrossRef](#)]
25. Pereira, P.; Broday, E.; Xavier, A.P. Thermal Comfort Applied in Hospital Environments: A Literature Review. *Appl. Sci.* **2020**, *10*, 7030. [[CrossRef](#)]
26. Skoog, J.; Fransson, N.; Jagemar, L. Thermal Environment in Swedish Hospitals: Summer and Winter Measurements. *Energy Build.* **2005**, *37*, 872–877. [[CrossRef](#)]
27. d'Ambrosio Alfano, F.R.; Olesen, B.W.; Pepe, D.; Palella, B.I.; Riccio, G. Fifty Years of PMV Model: Reliability, Implementation and Design of Software for Its Calculation. *Atmosphere* **2020**, *11*, 49. [[CrossRef](#)]
28. Westaway, K.; Frank, O.; Husband, A.; McClure, A.; Shute, R.; Edwards, S.; Curtis, J.; Rowett, D. Medicines can affect thermoregulation and accentuate the risk of dehydration and heat-related illness during hot weather. *J. Clin. Pharm. Ther.* **2015**, *40*, 363–367. [[CrossRef](#)]
29. Novieto, D.; Zhang, Y. Thermal Comfort Implications of the Aging Effect on Metabolism, Cardiac Output and Body Weight. In Proceedings of the Conference: Adapting to Change: New Thinking on Comfort, Cumberland Lodge, Windsor, UK, 9–11 April 2010.
30. Novieto, D. Adapting a Human Thermoregulation Model for Predicting the Thermal Response of Older Persons. Ph.D. Thesis, Institute of Energy and Sustainable Development, De Montfort University, Leicester, UK, June 2013.
31. Yablonskiy, D.A.; Ackerman, J.J.; Raichle, M.E. Coupling between changes in human brain temperature and oxidative metabolism during prolonged visual stimulation. *Proc. Natl. Acad. Sci. USA* **2000**, *97*, 7603–7608. [[CrossRef](#)] [[PubMed](#)]
32. Oka, T. Psychogenic fever: How psychological stress affects body temperature in the clinical population. *Temperature* **2015**, *2*. [[CrossRef](#)]
33. Montgomery Douglas, C. *Introduction to Statistical Quality Control*, 6th ed.; John Wiley & Sons, Inc.: New York, NY, USA, 2009.
34. Kaja, N.; SriKonda, R. Influence of Air Movement Preference on Thermal Comfort in Naturally Ventilated Classrooms of India. *Indian J. Sci. Technol.* **2019**, *12*, 1–8. [[CrossRef](#)]
35. Cao, B.; Zhu, Y.; Ouyang, Q.; Zhou, X.; Huang, L. Field study of human thermal comfort and thermal adaptability during summer and winter in Beijing. *Lancet* **2011**, *43*, 1051–1056. [[CrossRef](#)]
36. Fanger, P.; Toftum, J. Extension of the PMV model to non-air-conditioned buildings in warm climates. *Energy Build.* **2002**, *34*, 533–536. [[CrossRef](#)]
37. EN, CEN Standard. 16798-1. Energy performance of buildings—Ventilation for buildings—Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality. In *Thermal Environment, Lighting and Acoustics-Module M1-6. (16798-1)*; European Committee for Standardization: Brussels, Belgium, 2019.
38. ASHRAE. *ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy*; American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, GA, USA, 2010.
39. ASHRAE/ASHE STD 170-2008. *Ventilation of Health Care Facilities*; American Society of Heating, Refrigerating, and Air-conditioning Engineers: Atlanta, GA, USA, 2008.
40. ASHRAE. *Handbook HVAC Applications: Chapter 7; Healthcare Facilities*; American Society of Heating, Refrigerating, and Air-conditioning Engineers: Atlanta, GA, USA, 2007.
41. ASHRAE. *ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy*; American Society of Heating, Refrigerating and Air-conditioning Engineers: Atlanta, GA, USA, 2004.
42. Matzarakis, A.; Rutz, F.; Mayer, H. Modelling radiation fluxes in simple and complex environments: Basics of the RayMan model. *Int. J. Biometeorol.* **2009**, *54*, 131–139. [[CrossRef](#)] [[PubMed](#)]
43. Dhaka, S.; Mathur, J.; Wagner, A.; Agarwal, G.D.; Garg, V. Evaluation of thermal environmental conditions and thermal perception at naturally ventilated hostels of undergraduate students in composite climate. *Build. Environ.* **2013**, *66*, 42–53. [[CrossRef](#)]
44. Shao, T.; Jin, H. A field investigation on the winter thermal comfort of residents in rural houses at different latitudes of northeast severe cold regions, China. *J. Build. Eng.* **2020**, *32*, 101476. [[CrossRef](#)]
45. Alam, S. Impact of Clothing and Activity Level on Energy Consumption and Thermal Comfort on the Occupants in the Residential Building in Cold Climate Region. In Proceedings of the ASIM 2014 International Building Simulation Association Asia Conference (IBPSA), Nagoya, Japan, 28–29 November 2014.
46. Zhang, Y.; Wang, J.; Chen, H.; Zhang, J.; Meng, Q. Thermal comfort in naturally ventilated buildings in hot-humid area of China. *Build. Environ.* **2010**, *45*, 2562–2570. [[CrossRef](#)]

47. de Dear, R.; Brager, G.S.; Cooper, D. *Developing an Adaptive Model of Thermal Comfort and Preference*; Final Report on RP-884; ASHRAE Transactions: Atlanta, GA, USA, 1997; Volume 104.
48. Depecker, P.; Roux, J.J.; Pallier, J.M. *LE Concept De Performance Thermique des Batiments la Dualite Energie-Confort*; Bilgen, E., Hollands, K.G.T., Eds.; Intersol Eighty Five: Pergamon, Turkey, 1986; pp. 315–319. ISBN 9780080331775. [[CrossRef](#)]
49. Parsons, K. *Human Thermal Environments the Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort and Performance, 2nd ed*; CRC: Boca Raton, FL, USA, 2001.
50. Nicol, F. Adaptive comfort. *Build. Res. Inf. Build. Res. Inform.* **2011**, *39*, 105–107. [[CrossRef](#)]
51. Humphreys, M.; Nicol, F. Understanding the adaptive approach to thermal comfort. *ASHRAE Trans.* **1998**, *104*, 991–1004.
52. Brager, G.S.; de Dear, R.J. Thermal adaptation in the built environment: A literature review. *Energy Build.* **1998**, *27*, 83–96. [[CrossRef](#)]
53. Li, B.; Yao, R.; Wang, Q. The Chinese evaluation standard for the indoor thermal environment in free-running buildings. In Proceedings of the 7th Windsor Conference: The Changing Context of Comfort in an Unpredictable World Cumberland Lodge, Windsor, UK, 12–15 April 2012.
54. Kim, J.; Lim, J.; Cho, S.; Yun, G. Development of the adaptive PMV model for improving prediction performances. *Energy Build.* **2015**, *98*, 100–105. [[CrossRef](#)]
55. Wang, Z.; Xia, L.; Lu, J. Development of Adaptive Prediction Mean Vote (APMV) Model for the Elderly in Guiyang, China. *Energy Procedia* **2017**, *142*, 1848–1853. [[CrossRef](#)]
56. World Health Organization. *WHO Housing and Health Guidelines*; WHO: Geneva, Switzerland, 2018.