Hindawi
Indoor Air
Volume 2023, Article ID 9185216, 14 pages
https://doi.org/10.1155/2023/9185216

Research Article

A Field Investigation of the Thermal Comfort of Older Adults in Cold Winter Climates

María Teresa Baquero, Roger Vergés, Katia Gaspar, and Nuria Forcada

Group of Construction Research and Innovation (GRIC), Universitat Politècnica de Catalunya (UPC), Colom, 11, Ed. TR5, Barcelona, Terrassa 08222, Spain

Correspondence should be addressed to Roger Vergés; roger.verges.eiras@estudiantat.upc.edu
and Nuria Forcada; nuria.forcada@upc.edu

Received 17 May 2023; Revised 17 July 2023; Accepted 7 October 2023; Published 28 October 2023

Academic Editor: Faming Wang

Population ageing, extreme weather, and high energy costs are the current and future global scenarios. The present study analyses the factors affecting the thermal comfort of older adults and evaluates their thermal perceptions and preferences in nursing homes in a Continental Mediterranean climate during winter, through environmental measurements and surveys on site. The sample consists of 1065 occupants. Results of this study revealed that the neutral temperature of older adults in nursing homes in cold winter climates is 24.9°C, 2.3°C higher than what PMV predicts. Results also highlight that older adults feel more comfortable in those spaces with higher CO_2 concentrations than recommended by regulation. The analysis of factors affecting thermal comfort revealed that the most relevant factors affecting the thermal comfort of older adults in cold winter climates are (i) the type of room, which indirectly implies the metabolic rate of the occupants, the type of ventilation, and the CO_2 level; (ii) the occupancy density; and (iii) the relative humidity of the room. These results will help to develop more accurate thermal comfort and indoor environmental quality regulations for older people that improve their health and quality of life. The modification of temperature setpoints in nursing homes based on the results of this study could influence energy use and should be carefully considered by policy makers and facility managers.

1. Introduction

The European Union faces the challenge of being climate-neutral by 2050 [1]. In this transition, two main issues must be considered, the energy inefficiency of buildings and the need to guarantee the optimal level of comfort for users despite the increase in extreme weather conditions due to climate change. According to the Building Performance Institute Europe [2], 97% of European buildings are energy inefficient as they were mostly constructed in the period 1960-1970 and not designed under thermal efficient standards. In fact, the building stock accounts for 40% of European energy consumption, generating 36% of GHG emissions [3]. Furthermore, the growing demand for better thermal comfort and indoor air quality is increasing energy consumption due to climate change effects and the spread of heating, ventilation, and air conditioning (HVAC) systems. In general, in developed countries, HVAC is the largest energy end-use [4, 5]. In the European Mediterranean countries, the main use of energy by the residential sector is for heating (59.6% of the final energy consumption), followed by water heating. A total of 27% of this final energy consumption is provided by natural gas while 20% is provided by oil and petroleum products [6].

Buildings devoted to older people are in the spotlight as people over 65 years old are expected to triple by 2050 worldwide, and in Spain, they would represent 34.6% of the population by 2066 [7]. As older people spend more time indoors than other population groups [8, 9], this trend includes a greater demand for assisted living and residential facilities considering their indoor environmental quality [10, 11]. According to the World Health Organization, climate-related diseases cause more than 150,000 deaths each year, and those most at risk are children, older people, and the socially isolated [12]. Previous studies have identified an increase in mortality associated with both hot and cold weather [13–16].

Older adults are vulnerable to extreme temperature events, both hot and cold, due to physiological changes in their body. These circumstances affect both their thermoregulatory capacity and their ability to detect changes in body temperature [17–19]. Besides, their susceptibility is higher when suffering from preexisting medical conditions [20].

Older people are very sensitive to buildings' indoor environmental conditions. Air pollutants have major effects on their health, due to their reduced defence and multiple chronic diseases [21–29]. Low ventilation rates and congested conditions raise the quantities of CO_2 and bioeffluent, which may include bacteria, gases, odours, particulate matter, and viruses [27, 30]. Several studies have identified effects on health related to indoor low relative humidity [31–33] and high relative humidity [34–37].

Some studies have found an association between thermal comfort and cardiac mortality [38–40] and other morbidities such as arthritis, influenza, pneumonia, and asthma [34], which are exacerbated by living in cold conditions [9, 10]. Therefore, improving buildings' indoor environment could decrease the worsening of their chronic pathologies and improve their health and well-being [11, 41].

Recently, few studies have focused on thermal comfort in older people [42] due to differences with other age groups' thermal perceptions and needs [43, 44]. Many of them concluded that older adults were more tolerant to thermal environment changes than younger adults [42, 45], that their thermal comfort zones were wider than estimated by international standards [46, 47], and that they were more vulnerable to cold environments [45]. The few existing studies that assessed the factors affecting thermal comfort in older adults found that apart from the indoor thermal conditions, the climatic region is the most relevant factor affecting thermal comfort [48–50]. Therefore, the investigations focused on thermal comfort field studies of older people in diverse climatic zones [49, 51–53]. Mendes et al. [27] and Serrano-Jim et al. [37] were the only researchers that assessed the incidence of the concentration of CO_2 and other pollutants on thermal comfort in buildings for older adults in a Mediterranean climate.

During the heating season, the required indoor temperature and the longer heating periods in nursing homes suggest that the energy consumption is higher than in other buildings [54]. However, limited studies and insufficient evidence to support this assumption suggest a need to analyse the factors affecting thermal comfort for this population group, considering that the modification of setpoint temperatures and forced ventilation requirements will bring important changes in energy consumption.

The literature review revealed that there is a lack of studies on the thermal comfort of older adults for the Continental Mediterranean climate, as well as on the relationship between thermal comfort and indoor air quality in this climate. Considering the influence of the climate and the inexistence of studies on thermal comfort in older adults in the Continental Mediterranean climate, the novelties of the present study are as follows: (a) determine the thermal comfort conditions for older people under the Continental Mediterranean climate, (b) evaluate the applicability of the PMV model for older people under the Continental Mediterranean climate, and (c) identify the main variables of indoor air quality that influence thermal comfort in nursing homes during the heating season for the cold winter in the Continental Mediterranean climate. The findings of this study may help regulatory bodies develop standards for operating buildings occupied by older people, such as nursing homes, as well as establish good practices in the development of the daily activities of older people in nursing homes.

The methodology used in this study is explained in Section 2. The results and their discussion are detailed in Section 3. In Section 4, the limitations of the study along with suggestions for future research are described. Finally, the conclusions are presented in Section 5.

2. Methodology

The methodology devised to analyse the factors affecting the thermal comfort of older adults and evaluate their thermal perceptions and preferences in heated environments in the Continental Mediterranean climate consists of four steps, as indicated in Figure 1.

2.1. Case Study Location and Climatic Conditions. The selected case studies are five nursing homes located in the Madrid region in Spain: Las Rozas (LR), El Viso (EV), La Moraleja (LM), Alameda (AL), and Colmenar Viejo (CV), and are depicted in Figure 2. People over 65 years of age in the region account for 17.5% of the total population [55]. All selected nursing homes had a traditional brick façade air chamber and sliding double glazing windows and were built after 2000 except for LR that was built in 1988. All selected nursing homes have a similar resident capacity (around 120). Except for LM which has a variable refrigerant volume (VRV) HVAC system, the rest are heated by a two-pipe air-water system with fan coils. All common rooms in the selected nursing homes are operated similarly: heating is switched on from 8 : 00 to 21 : 00 during the winter while windows are operated manually by the caregivers. For ventilation, EV, AL, and LM incorporate air recovery systems installed in the roof, while LZ and CV are only ventilated naturally by opening windows.

The Community of Madrid is in the central part of Spain (40°26′N 3°41′W), at 667 m above sea level. Its climate corresponds to Continental Mediterranean (Csa) (cold winters and hot, dry summers) according to the Köppen-Geiger climate classification [56]. The Continental Mediterranean climate is characterised by very hot and cold situations. The summer is characterised by a low average relative humidity of 37%, an average temperature of 32.8°C, and maximums exceeding 35°C. In contrast, the winter presents moderately high humidity that reaches maximums of 71%, average minimum temperature of 2.7°C, and minimums below -2°C. The daily thermal oscillation presents amplitudes of up to 16°C in the summer and around 6.9°C during winter. The experimental campaign was carried out under

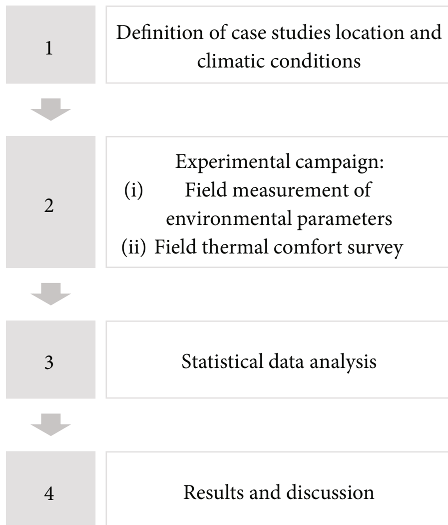

Figure 1: Research methodology.

the cold winter characteristic of the Continental Mediterranean climate.

2.2. Experimental Campaign. The experimental campaign was carried out from October 2021 to February 2022 in the common areas (living room, therapy room, dining room, gym, and physiotherapy room) of the five selected nursing homes. Each room was monitored between three and five times considering different indoor/outdoor conditions and occupancy characteristics. Considering that each nursing home has different common areas, 52 measuring points were obtained and analysed. The in situ measurements consist of field measurement of environmental parameters and field thermal comfort survey. Both field environmental measurements and surveys were performed simultaneously in the selected rooms, between 10 : 00 and 18 : 00, considering that most occupancy and activities were conducted at such time band while heating systems were turned on.

Figure 3 illustrates the daily outdoor temperature recorded during the experimental campaign. It is important to mention that the data was obtained from meteorological stations in close proximity to the nursing homes [57]. The depicted data represents the average conditions across all the nursing homes, considering the minor variations arising from their proximity to each other.

2.2.1. Field Measurement of Environmental Parameters. The monitored indoor environmental parameters were air temperature (T_a), relative humidity (RH), mean radiant temperature (T_r), air velocity (V_a), and CO_2. These parameters were measured with a portable Delta Ohm HD32.2. The equipment was placed at a maximum height of 1.1 m from the floor level, more than one meter away from the walls, windows, and air-conditioning systems according to ASHRAE 55 (American National Standards Institute [58], ISO 7730 [59] and ISO 7726 [60]. Table 1 presents the equipment specifications. After 10 minutes of equipment stabilization, measurements were recorded every 15 seconds for periods between 15 and 60 minutes, depending on the occupancy and activity of each room.

The operative temperature (T_{op}) was calculated following Equation (1) [60]:

$$T_{op} = \frac{T_a + T_r}{2}, \quad (1)$$

where T_a is the air temperature and T_r is the mean radiant temperature measured by the equipment and calculated according to the ISO 7726 standard [60] (see Equation (2)).

$$T_r = \left(T_g + 273\right)^4 + 2.5 \cdot 10^8 \cdot V_a^{0.6} \cdot \left(T_g - T_a\right)^{1/4} - 273, \quad (2)$$

where T_g is the globe temperature, V_a is the air speed, and T_a is the air temperature measured by the equipment.

Additionally, outdoor environmental variables like the mean daily outdoor air temperature (T_{out}) and relative humidity (RH_{out}) data were collected from the weather stations closest to each nursing home during the experimental campaign.

2.2.2. Field Thermal Comfort Survey. A questionnaire survey was performed simultaneously with the environmental measurements in each room, to determine the thermal perception of occupants.

The questionnaire included three simple questions: (1) thermal sensation vote (TSV), based on the ASHRAE seven-point scale (-3: cold, -2: cool, -1: slightly cool, 0: neutral, +1: slightly warm, +2: warm, and +3: hot) [58]; (2) thermal preference (TP), based on a three-point scale (-1: cooler, 0: without change, and +1: warmer); and (3) thermal acceptability (TA) by a two-option question (1: acceptable and 0: unacceptable).

The personal variables were collected by observation, such as gender, clothing insulation (Icl), and metabolic rate (M), based on ISO 7730 [59] and ASHRAE 55 [58]. The total clothing insulation of each participant's outfit was calculated by summing the insulation ratings of all of their individual clothes, according to ISO 7730 [59]. Additionally, the impact of the wheelchair or chair on the insulation of the clothes was taken into account (Table 2). Based on the routine activities of older adults, the metabolic rate was determined according to ISO 7730 [59] (Table 3).

2.3. Statistical Data Analysis. Statistical data analysis was conducted using the software IBM SPSS 22. The factors that will be taken into account to determine their impact on the thermal comfort of older adults are the gender, clothing insulation, type of room, metabolic rate, indoor air quality, and level of occupancy. The analysis of the influence of these variables on thermal comfort was performed using Pearson and Spearman correlation tests and linear regression models, with the significance of 5% ($p < 0.05$). The Spearman correlation test was used when data was aggregated by ranks and when one of the variables had an underlying ordering, while, to identify the thermal comfort perception differences between the different occupants, a chi-square test was performed.

Figure 2: Location of the nursing homes selected as case studies.

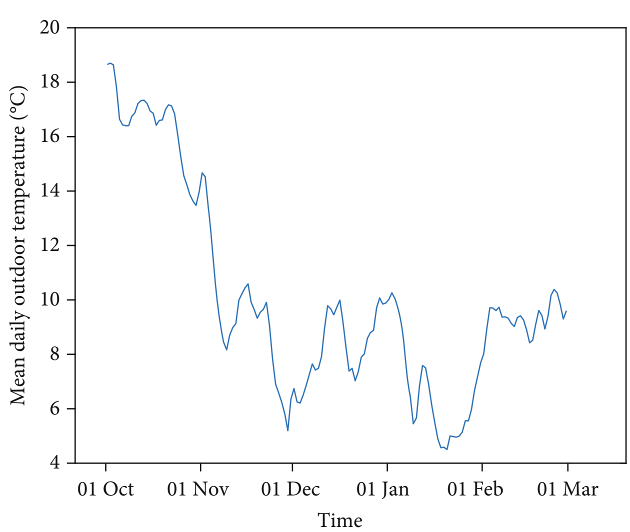

Figure 3: Daily outdoor temperature conditions during the experimental campaign.

3. Results and Discussion

3.1. Monitored Parameters during the Experimental Campaign. A summary of the mean monitored indoor environmental quality parameters during the field study in each room is presented in Tables 4 and 5.

Regarding indoor environment conditions, the CO_2 ranged between 425.66 ppm and 1388.70 ppm with an average of 672.48 ppm. In some cases, those levels exceed the recommended limits by the National Spanish regulations (900 ppm) [61] and European Standards (1000 ppm) [62, 63]. The air temperature (T_a) was 23.2°C, the operative temperature (T_{op}) was 22.9°C, the relative humidity (RH) was 30.02%, and the air velocity (V_a) was around 0.01 m/s. The indoor temperature complies with the recommendations of Spanish regulation [61] and the ASHRAE 55 standard [58] to be between 21°C-23°C and 20°C-23.5°C, respectively. The relative humidity did not meet the minimum recommended level by Spanish Regulations [61] (40%-50%) and was in the limit for the ASHRAE 55 recommendations (30%-60%) [58].

The outdoor temperature (T_{out}) ranged between 2.5°C and 14.8°C with an average of 7.81°C, and the outdoor relative humidity (RH_{out}) ranged between 41% and 71.41% with an average of 60.52%, a typical outdoor condition of a Continental Mediterranean climate in winter. Additionally, the mean TSV ranged from -1.57 to 0.43 with an average of -0.28, indicating that mostly, occupants felt colder than hotter.

Table 1: Equipment specifications for indoor environmental measurement.

Variable	Probe	Tolerance	Accuracy
T_g (°C)	TP3276.2	10°C to 100°C	±0.2°C
T_a (°C)	HP3201.2	30°C to 60°C	±0.5°C
RH (%)	HP3201.2	20% to 80%	±3%
V_a (m/s)	AP3203.2	0 m/s to 5 m/s	±0.05 m/s
CO_2 (ppm)	NDIR	0 ppm to 5000 ppm	±50 ppm

T_g: globe temperature; T_a: dry air temperature; RH: relative indoor humidity; V_a: air speed; CO_2: carbon dioxide.

Table 2: Thermal insulation for garments.

Level of clothing	Clo
Overall	
Long-sleeve shirt	0.25
Short-sleeve shirt	0.15
Long-sleeve knit sport shirt	0.2
Short-sleeve knit sport shirt	0.09
Long-sleeve (thin)	0.2
Long-sleeve (thick)	0.28
Jacket	0.35
Long trousers/thick skirt	0.25
Short trousers/thin skirt	0.06
Shoes	
Closed shoes	0.04
Sleepers	0.02
Sandals	0.01
Boot	0.1
Underwear	
With T-shirt	0.12
Without T-shirt	0.03
Socks	
With socks	0.03
Without socks	0
Accessories	
Kerchief	0.05
Scarf	0.08
Cap	0.05
Type of chair	
Normal chair	0.1
Wheelchair	0.12
Sofa	0.15

The measured environment conditions evidence that, sometimes, older people's health could be at risk due to low temperatures, low relative humidity, and high levels of CO_2 concentration. Some studies found similar results [27, 37] and recommend regulating ventilation, thermal insulation, and comfort range to improve environmental conditions, especially in winter.

Table 3: Metabolic rate of usual activities of older adults.

Activity	Met
Sport activity group	1.6
Lower activity group	1.4
Walking	1.4
Seated: bike	1.4
Individual treatment	1.2
Seated: table games/drawing	1.2
Seated: TV	1

3.2. Analysis of the Thermal Comfort of the Elderly in the Selected Nursing Homes. A total of 1065 occupants were surveyed during the experimental campaign. Of those, 78% were women, with an average age of 75 years old. During the experimental campaign, 78.3% of occupants had a neutral thermal sensation (TSV = 0).

Regarding thermal preference (TP), 81.2% of occupants stated they would "not change" the thermal environment. Even though 19% of occupants would prefer it to be warmer, 88% of them stated that the thermal environment was acceptable (TA). These results demonstrated that clothing adaptation is the most used thermal adaptive method in nursing homes, which leads to a high level of thermal acceptability. Figure 4 presents the thermal perception (TSV, TP, and TA) of the occupants.

A linear regression model was developed to obtain the neutral temperature (T_n) as a function of the mean thermal sensation vote (MTSV) and the operative temperature (T_{op}) which was 0.5°C based on the data similar to what most authors suggest [64–68] Figure 5:

$$MTSV = 0.151T_{op} - 3.76\left(R^2 = 0.75\right). \quad (3)$$

The neutral temperature is obtained when the MTSV = 0, while the thermal comfort zone is considered within the interval of TSV = −1 to 1 [45, 52, 69–73], and more than 80% of occupants were satisfied with the thermal environment in this study as per ASHRAE Standard 55 requirements (American National Standards Institute [58]. Therefore, the neutral temperature (T_n) was found to be 24.9°C, and the thermal comfort zone was found between 18.3°C and 26.3°C.

The results of this study show differences from similar studies conducted in different locations and climatic zones, which highlights the need to conduct specific studies adapted to the climatic zone and the building user typology. Generally, in warmer climates, the temperature ranges of thermal comfort zones are higher than those in cold climates [32, 49, 52, 74–76].

These variations in thermal comfort can be attributed to a combination of factors such as outdoor climate, cultural variables, activities performed in different rooms, and the adaptation and tolerance of each study case. Frontczak and Wargocki [77], Manu et al. [78], Soebarto et al. [20], Forcada et al. [49], and Baquero et al. [79] have emphasized the need to develop location-specific thermal comfort assessments

Table 4: Room characteristics, indoor thermal variables (T_a, T_{op}, V_a, RH), indoor air quality variable (CO_2), thermal comfort perception of the occupants (TSV), clothing insulation (Icl), metabolic rate (M), and outdoor conditions (T_{out}, RH_{out}) of the experimental campaign.

Case ID	Room & ventilation type	Occupancy (pers)	Area (m^2)	Occ. dens. (m^2/pers)	T_{op} (°C)	T_a (°C)	V_a (m/s)	RH (%)	CO_2 (ppm)	TSV	T_{out} (°C)	RH_{out} (%)	Icl (clo)	M (met)
Las Rozas														
LR 1	LV (N)	25	125.5	5.02	24.07	24.02	0.015	29.25	448.55	-0.077	14.8	51	1.15	1.043
LR 2	Gym (N)	17	89.2	5.25	23.47	23.48	0.002	35.53	729.39	-0.083	14.8	51	0.914	1.057
LR 3	DR (N)	48	81.5	1.70	24.93	25.15	0.007	35.72	813.35	0.065	14.8	51	1	1.059
LR 4	DR (N)	30	81.5	2.72	25.21	25.47	0.006	34.22	805.57	-0.333	14.8	51	1.044	1.054
LR 5	LV (N)	19	125.5	6.61	23.78	23.92	0.01	26.33	578.61	-0.3	9	51	0.905	1.036
LR 6	Gym (N)	12	89.2	7.43	23.03	22.78	0.001	30.02	669.00	-0.2	9	51	0.884	1.05
LR 7	DR (N)	48	81.5	1.70	24.53	24.87	0	28.52	646.31	-0.046	9	51	0.888	1.072
LR 8	DR (N)	30	81.5	2.72	24.12	24.54	0	27.76	740.26	-0.046	9	51	0.919	1.072
LR 9	LV (N)	18	125.5	6.97	23.86	24.08	0	25.1	541.51	-0.091	6.37	58.13	1.068	1.092
LR 10	Gym (N)	14	89.2	6.37	23.51	23.30	0	29.74	595.64	-0.1	6.37	58.13	1.04	1.073
LR 11	DR (N)	40	81.5	2.04	24.04	24.54	0.02	24.62	696.84	0.061	6.37	58.13	0.948	1.056
LR 12	DR (N)	29	81.5	2.81	24.35	24.90	0.01	25.6	843.84	-0.061	6.37	58.13	0.934	1.082
La Moraleja														
LM 1	Gym (F)	20	172.5	8.63	22.26	22.29	0.002	32.03	623.82	-0.333	7.13	71.41	1.277	1.1
LM 2	OT (F)	20	102	5.10	22.59	22.62	0.003	33.24	812.84	-0.923	7.13	71.41	1.277	1.08
LM 3	DR (F)	28	167.6	5.99	21.91	21.63	0.011	39.56	844.56	-0.679	7.13	71.41	1.124	1.04
LM 4	LV (N)	16	56.7	3.54	21.76	22.00	0.002	36.16	670.29	-0.571	7.13	71.41	1.11	1.075
LM 5	LV (O)	27	56.7	2.10	21.42	21.47	0	28.01	587.1	-0.333	4.97	67.43	1.27	1.14
LM 6	OT (O)	8	102	12.75	21.64	21.62	0	23.55	493.31	-1.571	4.97	67.43	1.289	1.175
LM 7	DR (F)	43	167.6	3.90	22.23	22.48	0	36.12	729.79	-0.185	4.97	67.43	1.23	1.129
LM 8	LV (O)	11	56.7	5.15	21.41	21.50	0	27.60	574.03	-0.333	4.97	67.43	1.25	1.123
LM 9	Gym (F)	25	172.5	6.90	22.79	22.88	0	31.60	565.90	-1.071	10.52	66.16	1.389	1.125
LM 10	OT (F)	14	102	7.29	22.32	22.36	0.009	34.19	753.35	-0.818	10.52	66.16	1.273	1.123
LM 11	LV (F)	19	156.4	8.23	21.98	22.19	0.001	37.52	766.86	-0.154	10.52	66.16	1.216	1.138
LM 12	DR (F)	49	167.6	3.42	22.98	23.24	0.004	44.56	747.13	-0.467	10.52	66.16	1.127	1.082
LM 13	LV (N)	20	56.7	2.84	22.54	23.02	0.001	39.50	827.12	-0.267	10.52	66.16	1.182	1.094
El Viso														
EV 1	LV (O)	14	124.6	8.90	23.81	24.02	0.001	31.32	516.2	-0.375	13.8	41	1.232	1.12
EV 2	Gym (O)	13	47	3.62	22.22	22.27	0.005	35.58	631.56	0.25	13.8	41	0.971	1.213
EV 3	OT (F)	8	35	4.38	22.24	22.35	0.001	37.74	941.32	0	13.8	41	0.925	1.109
EV 4	OT (F)	9	35	3.89	22.56	22.57	0	42.02	1388.7	0	13.8	41	0.897	1.1
EV 5	DR (F)	12	54.3	4.53	22.21	22.43	0.008	42.35	565.16	-0.1	13.8	41	1.035	1.1
EV 6	LV (F)	6	124.6	20.77	21.94	22.05	0	22.62	425.66	-0.546	4.5	67.6	1.123	1.067
EV 7	LV (F)	12	124.6	10.38	24.78	24.78	0.002	20.72	551.75	-0.6	4.5	67.6	1.123	1.067

Table 4: Continued.

Case ID	Room & ventilation type	Occupancy (pers)	Area (m^2)	Occ. dens. (m^2/pers)	T_{op} (°C)	T_a (°C)	V_a (m/s)	RH (%)	CO_2 (ppm)	TSV	T_{out} (°C)	RH_{out} (%)	Icl (clo)	M (met)
Colmenar Viejo														
CV 1	Gym (F)	14	47.14	3.37	22.14	22.20	0.002	35.22	810.89	0.167	6.11	59.95	0.813	1.333
CV 2	LV (F)	25	103.7	4.15	22.07	22.43	0.05	21.42	489.05	-0.333	4.8	59.38	1.029	1.071
CV 3	OT (F)	32	97.5	3.05	22.79	22.96	0.02	23.25	664.96	0	4.8	59.38	0.97	1.096
CV 4	LV (F)	28	103.7	3.70	26.27	25.44	0.03	20.05	516.75	0	4.8	59.38	1.067	1.123
CV 5	LV (F)	25	103.7	4.15	22.32	22.59	0	25.32	485.78	-0.091	3.42	70.33	1.086	1.092
CV 6	OT (F)	7	97.5	13.93	22.96	22.92	0.01	25.71	548.66	0	3.42	70.33	1.034	1.035
CV 7	OT (F)	23	97.5	4.24	23.64	23.88	0	26.02	704.59	-0.063	3.42	70.33	1.053	1.037
CV 8	LV (F)	15	103.7	6.91	23.73	24.03	0.05	22.43	506.2	-0.125	3.42	70.33	1.052	1.14
Alameda														
AL 1	Gym (F)	12	61	5.08	24.07	24.13	0.009	27.35	510.22	0.429	8.03	61.2	0.93	1.32
AL 2	OT (F)	30	65.4	2.18	23.43	23.51	0.013	28.67	888.46	-0.08	8.0	61.2	1.03	1.024
AL 3	DR (F)	31	81.1	2.62	23.83	24.10	0.003	30.81	634.04	-0.167	8.0	61.2	1.134	1.111
AL 4	OT (F)	28	65.4	2.34	23.67	23.84	0.012	28.77	503.72	-0.053	8.0	61.2	1.114	1.084
AL 5	Gym (F)	10	61	6.10	18.63	18.58	0.01	23.46	524.51	-0.75	2.47	62.29	1.29	1.291
AL 6	OT (F)	20	65.4	3.27	19.19	19.35	0	25.44	670.16	-0.158	2.47	62.29	1.217	1.05
AL 7	DR (F)	22	81	3.68	23.03	23.44	0	29.14	871.68	0.16	2.47	62.29	1.193	1.143
AL 8	OT (F)	25	65.4	2.62	22.48	22.66	0	22.84	727.86	0.308	2.47	62.29	1.035	1.114
AL 9	Gym (F)	11	61	5.55	22.5	22.83	0.01	25.68	553.72	-0.9	7.53	66.7	1.182	1.08
AL 10	OT (F)	22	65.4	2.97	23.13	23.31	0.01	27.75	709.52	-1.571	7.53	66.7	1.015	1.113
AL 11	DR (F)	23	81	3.52	23.13	23.50	0.01	31.39	747.61	0.091	7.53	66.7	1.02	1.035
AL 12	OT (F)	36	126.4	3.51	24.51	24.78	0	31.94	775.36	-0.95	7.53	66.7	1.008	1.03

OT: occupational therapy room; DR: dining room; LV: living room; F: forced; N: natural; O: off; LR: Las Rozas; EV: El Viso; AL: Alameda; CV: Colmenar Viejo; Occ: occupancy; RH: indoor relative humidity; V_a: air speed; CO_2: carbon dioxide; T_{out}: outdoor dry temperature; RH_{out}: outdoor relative humidity; T_{op}: operative temperature; TSV: thermal sensation vote; met: metabolic rate; clo: level of clothing (including chairs).

Table 5: Minimum, maximum, average, and deviation of the monitored variables.

	Occ. (pers)	Area (m^2)	Occ. dens. (m^2/pers)	T_{op} (°C)	T_a (°C)	V_a (m/s)	RH (%)	CO_2 (ppm)	TSV	T_{out} (°C)	RH_{out} (%)	Icl (clo)	M (met)
Min	6.00	35.00	1.70	18.63	18.58	0.00	20.05	425.66	-1.57	2.47	41.00	0.81	1.02
Max	49.00	172.50	20.77	26.27	25.47	0.05	44.56	1388.70	0.43	14.80	71.41	1.39	1.33
Average	21.98	93.25	5.20	22.96	23.21	0.01	30.02	672.48	-0.28	7.81	60.52	1.08	1.10
Deviation	10.82	36.31	3.43	1.33	1.29	0.01	5.99	164.02	0.42	3.71	9.00	0.13	0.07

and models to account for these differences. Therefore, understanding these factors and developing location-specific thermal comfort models can help improve indoor environments and promote thermal comfort for older adults in different climatic zones.

The broad thermal comfort zone within nursing homes allows accepting broader ranges of comfort temperatures with the consequent reduction of heating prevalence and energy consumption. However, indoor temperatures higher than 26°C are associated with an increase in respiratory distress, emergencies, and significant aggravation of dementia symptoms, some of the most common morbidities in older people [80], while temperatures below 18°C increase blood pressure and cardiovascular disease risk (Public Health England, 2017). Collins et al. [81] also found that an indoor temperature under 15°C affected the cardiovascular system in older people. Therefore, not only should subjective comfort temperatures be used to determine setpoint temperatures of occupied rooms but the impact of these thermal comfort ranges on health should also be assessed.

3.3. Comparison of the Field Thermal Comfort and the Existing Thermal Comfort Models. The predicted mean vote (PMV) model developed by Fanger in the late 1960s is the

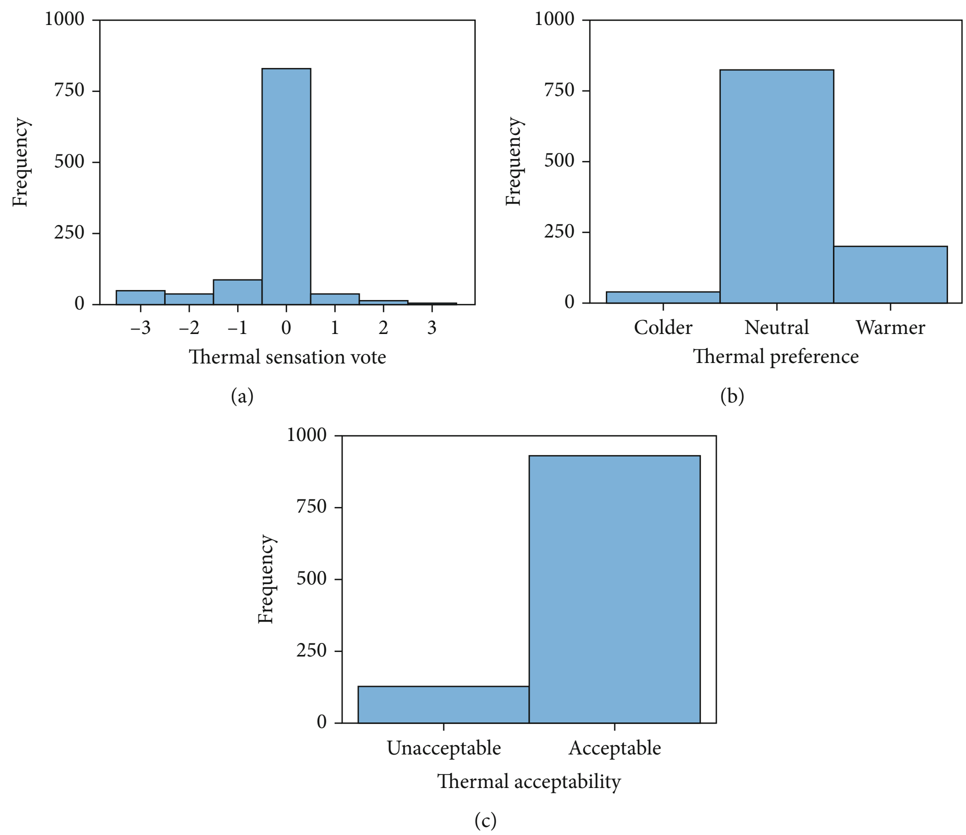

FIGURE 4: Histogram of occupants' (a) thermal sensation vote, (b) thermal preference, and (c) thermal acceptability.

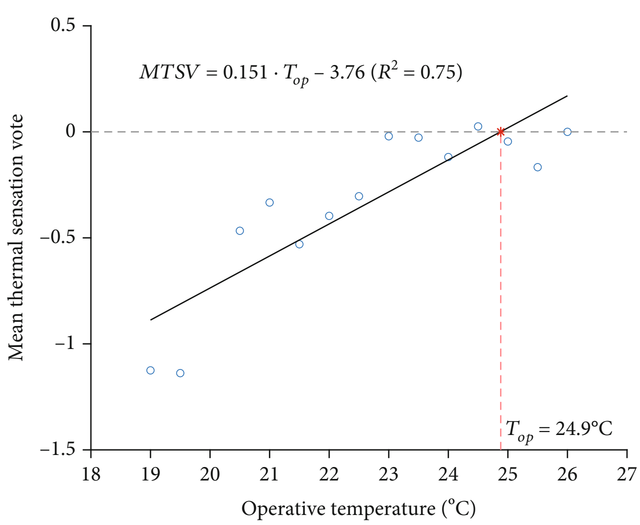

FIGURE 5: Linear regression between mean thermal sensation vote (MTSV) and operative temperature (T_{op}).

most used worldwide for assessing indoor thermal comfort (Equation 4). The suitability of the PMV model was analysed for older people in Continental Mediterranean climate heated indoor environments by a linear regression model comparing MTSV (Equation (3)) and PMV (Equation 4) on T_{op} (Equation (1)), depicted in Figure 6. A big difference of around 2.3°C is found between neutral temperatures, which would be lower in the PMV model (22.6°C) than obtained in the experimental campaign (24.9°C). Thus, based on this experimental campaign, the PMV model cannot predict correctly the thermal comfort of the older people.

$$\mathrm{PMV} = 0.168 T_{op} - 3.79, \quad R^2 = 0.87. \tag{4}$$

These results agree with other similar studies that compared the thermal comfort of older people with the PMV model and found that older adults have lower thermal sensation than predicted by the current thermal comfort model in winter and found it unsuitable for older adults in heated environments [9, 45, 73, 75]. For example, Jin et al. [32] found that the neutral temperature predicted by PMV was 2.7°C lower than the actual TSV in nursing homes in Scotland (Cfb climate) in winter.

Some authors stated that the most underestimated factor in the PMV model might be the metabolic rate that is usually assumed and not measured, due to the low physical activity levels of older adults [9, 82] and physiological changes that affect their metabolism apart from cases of people taking certain medications for chronic diseases that may affect them [43]. On the other hand, some attempts to correct the PMV model to adapt it to older people have been assessed [9], but no common model has already been accepted.

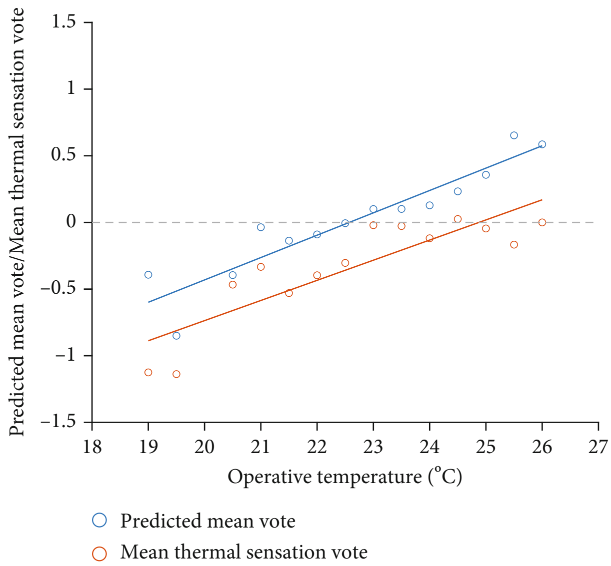

Figure 6: Comparison between predicted mean vote (PMV) and mean thermal sensation vote (MTSV) related to operative temperature (T_{op}).

Table 6: Metabolic rate (met), clothing insulation (clo), and thermal sensation vote by gender.

Gender	Parameter	Metabolic rate (met)	Clothing insulation (clo)	Thermal sensation vote
Women	Mean	1.04	1.08	-0.12
	SD	0.12	0.32	0.95
	Min	0.8	0.43	-3
	Max	1.6	2.17	3
Men	Mean	1.04	1.14	-0.18
	SD	0.11	0.23	0.79
	Min	0.8	0.57	-3
	Max	1.4	1.69	3

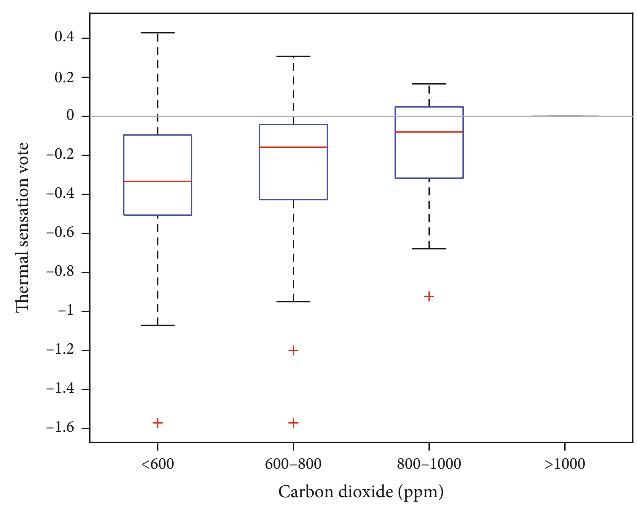

Figure 7: Boxplot of mean thermal sensation vote (MTSV) by IAQ category.

3.4. Factors Affecting the Thermal Comfort of Elder People in Nursing Homes. Apart from the recognised factors affecting the thermal comfort of elderly people such as age and health conditions, the influence of indoor and outdoor environmental conditions and the impact of personal characteristics are analysed to determine good practices to improve the thermal comfort of this population group.

To evaluate the influence of gender in thermal comfort, the chi-square test highlighted significant differences ($p < 0.05$) in TSV between men and women. 72% of women and 82.5 % of men felt the environment as "neutral," while women had a warmer (6%) and cooler (17%) thermal sensation than men. Mean values are elucidated in Table 6.

On the other hand, significant differences were found between gender and clothing insulation (clo). In the analysed nursing homes, men wore more clothes than women (Table 6). However, no differences between genders were found for the metabolic rate (met) and thermal sensation vote (TSV).

In fact, gender plays a role in perceiving the thermal environment. In general, females are more sensitive to cold conditions than males and frequently prefer higher temperatures [44]. However, thermal comfort differences in gender can also be a consequence of some physiological variations such as sweating, hydration levels, and cardiovascular diseases [19].

To evaluate the relation between metabolic rate and clothing insulation, a Pearson test was used. A significant correlation was found between both parameters because when doing programmed activities such as in a gymnasium, caregivers help residents adjust their level of clothing according to the activity they perform [65]. Clothing insulation (Icl) was found to decrease with increasing metabolic rate (M), according to regression studies conducted on the two variables ($\text{Icl} = -0.383 \cdot M + 1.507, R^2 = 0.682$).

Moreover, clothing insulation (Icl) was also found to be significantly correlated ($p < 0.05$) with operative temperature (T_{op}). When the operative temperature rises, occupants reduce their level of clothing, according to the regression studies performed ($\text{Icl} = -0.045 \cdot T_{op} + 2.167, R^2 = 0.639$).

Besides, further analysis confirmed that the thermal sensation vote (TSV) had a significant relation with the CO_2 levels, as observed in Figure 7.

This result highlights the influence of the indoor air quality (IEQ) of the room on the thermal comfort of the occupants. The surveyed older adults tend to feel more thermally comfortable (TSV = 0) in rooms where the CO_2 levels are higher.

As expected, the CO_2 level has a significant correlation with the occupation density ($r = -0.408$, $p < 0.01$), as stated by authors such as Meyn et al. [83], Mendes et al. [27], and Serrano-Jiménez et al. [37]. Moreover, a significant relation ($p < 0.05$) was found between CO_2 levels and indoor environmental (V_a and RH) and outdoor environmental parameters (T_{out} and RH_{out}).

Table 7: Mean thermal sensation, vote, mean CO_2 levels, and mean metabolic rate by type of room.

	Dining room	Gymnasium	Living room	Occupational therapy room
Mean thermal sensation vote (MTSV)	-0.15	-0.12	-0.75	-0.07
Mean CO_2 (ppm)	745.1	621.5	565.7	755.9
Mean metabolic rate (met)	1.08	1.2	1.1	1.09

The analysis by nursing home and by type of room revealed that both the thermal comfort (TSV) and the IAQ (CO_2 level) were not affected by the nursing home but by the type of room. Table 7 summarizes the mean thermal sensation vote (MTSV) of the residents, the mean CO_2 levels, and the mean metabolic rate (M), split by the type of room.

It is noteworthy that, although the operative temperature is somewhat static in each nursing home (22.8°C ± 0.5°C), there are significant differences in the thermal perception of the residents depending on the type of activity performed in each room. So, even though residents tend to feel colder rather than warmer, the most thermally neutral sensation is found in the dining room (DR), the gymnasium (gym), and the occupational therapy room (OT) (Table 7). These findings meet a sociological explanation; in this sense, the thermal perception of occupants may be influenced by factors such as the fact of being accompanied [84], or other factors named "forgiveness factors" as pointed by Deuble and De Dear [85], that broaden the users' tolerance to thermal environmental conditions. The dining room (DR) is a space devoted to eating, which causes a change in their metabolic rate, as well as provokes the residents to be highly distracted and, thus, contributes to having a neutral thermal sensation. Likewise, the activities performed in the occupational therapy room (OT), such as crosswords or reading, also strengthen their thermal neutrality sensation. On the contrary, spaces such as the living room (LR) tend to present less monitored activities, thus leading to older people being more aware of the environment of the room. As a result, lower thermal sensation vote (TSV) is found in those spaces. This relation is also explained mainly due to the differences of the occupation density, the type of activity that occurs in each typology of the room, and the CO_2 levels present in each room. The occupational therapy room (OT) and the dining room (DR) have a low occupancy density (5.1 m^2/pers and 3.2 m^2/pers, respectively) in comparison with the other analysed rooms (6.2 m^2/pers in average).

In addition, the type of ventilation is also a determinant factor when determining the IAQ of a room, as observed in Figure 8. As expected, natural ventilation was found to be less effective in maintaining an adequate IAQ level compared to forced ventilation. Moreover, considering the occupancy density of the different rooms, when forced ventilation is present, a weak relationship is found between CO_2 levels and the occupancy density ($r = -0.293$, $p < 0.01$). On the other hand, when natural ventilation is the main source of fresh air, the relationship ascends to $r = -0.554$ ($p < 0.01$), suggesting that forced ventilation is a more effective system to renew and bring fresh air to the room. Moreover, the metabolic rate (M) plays an important role when analysing the levels of CO_2 per occupancy density ($r = -0.408$, $p < 0.01$). These findings allow concluding that implementing more monitored activities in nursing homes, such as those in the occupational therapy room (OT), will make residents feel more comfortable, also in terms of thermal comfort.

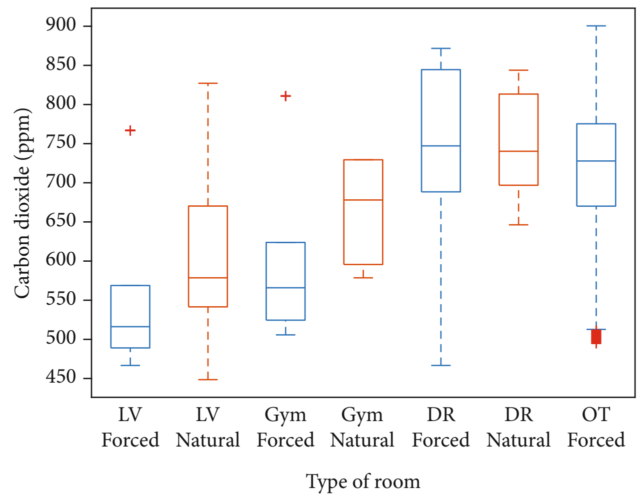

Figure 8: Boxplot of CO_2 levels by type of room and ventilation method. DR: dining room; Gym: gymnasium; LV: living room; OT: occupational therapy room.

Finally, a significant positive correlation between CO_2 levels and relative humidity ($r = 0.533$, $p < 0.01$) was found in the Pearson test. The humidity in a room is affected by the number of people present in the space. People release moisture into the air through breathing and the skin, which increases humidity levels in a room. However, it is important to note that the relative humidity in a room is also affected by other factors such as the ventilation rate or the presence of moisture-generating activities or appliances.

It can be observed that in some monitored rooms, neither the indoor relative humidity (RH) nor the CO_2 fulfilled the regulations (the levels of RH were lower while the levels of CO_2 were higher than those recommended). Results also showed that in certain cases, natural ventilation did not allow meeting the minimum required air renovation, as CO_2 levels were significantly higher compared to the forced ventilation system. These conditions can lead to health threats to older people. Therefore, for rooms, air-handling units incorporating forced ventilation and humidifiers should be implemented.

4. Limitations and Further Research

This study contributes to current research in several ways. It provides insights into the thermal comfort and preferences of older adults living in nursing homes in a Continental

Mediterranean climate during winter, since the predictive models established in the standards are not applicable to this group of populations. This information is important because the older population is growing worldwide, and it is crucial to understand their needs and preferences to improve their quality of life. The study provides valuable information for policy makers and nursing home facility managers. The modification of temperature setpoints based on the study's results could influence energy use, and the findings suggest that indoor air quality must be controlled for older adults to feel more comfortable. However, it also presents some limitations and issues that are beyond the scope of this study, such as the following:

(i) This study, like many others in the field, considers the metabolic rate values reported in ISO 7730 [59], although physiological changes in older people affect their normal metabolic rate, so this could affect the calculation of the predicted mean vote (PMV) index overestimating the metabolic rate. Further studies might consider this for a better estimation of PMV in older people

(ii) The on-site survey focused on the thermal comfort perception of older adults but not on their general air quality perception. Moreover, indoor air quality assessment is a complex process involving several factors that were beyond the scope of this study's measurements, such as air pollutants, level of toxicity of building materials, and outdoor air quality. Further research might include users' overall perception of air quality as well as measuring the factors related to indoor air quality. However, this was not the aim of this study

(iii) Finally, individual factors such as health status, medication use, and activity level can also affect users' thermal comfort. For example, older adults with chronic medical conditions or on certain medications may have a different thermal perception than those who are healthy and medication-free. In this study, due to privacy policies, it was not possible to obtain this information. Further investigation might be conducted to include all possible user variables that were difficult to measure and control

5. Conclusions

In this study, the factors affecting the thermal comfort of older adults in a cold winter climate have been analysed. The study also determined the thermal comfort conditions and the suitability of the PMV model for older people under this climate. Five nursing homes located in Madrid (Spain) were selected as case studies and monitored from October 2021 to February 2022. Simultaneously, field thermal surveys were conducted on 1065 residents. The main findings are the following:

(i) Results of this study affirmed that climate is one of the most relevant factors affecting thermal comfort. For the cold winter climate, the neutral temperature was found to be 24.9°C and the comfort zone between 18.3°C and 26.3°C, different from the field studies in other climates

(ii) The suitability of the predicted mean vote (PMV) model was analysed for the case of older people in the monitored cold winter climate. The neutral temperature predicted in the PMV model (22.6°C) differed 2.3°C from that obtained in the experimental campaign (24.9°C). These results show that the PMV model is not suitable for predicting the thermal comfort of older people under this climate

(iii) The results also showed that older adults are thermally more comfortable in rooms with higher CO_2 concentrations

(iv) Three factors were found to be the most relevant affecting the thermal comfort of the older adults: (a) the type of room, which indirectly implies the metabolic rate of the occupants, the type of ventilation, and the CO_2 level; (b) the occupancy density; and (c) the relative humidity of the room

Both the broader thermal comfort zone and the better thermal comfort in spaces with high CO_2 in cold winter climates allow to reduce temperatures in some periods with the consequent reduction of heating prevalence and energy consumption. However, the impact of indoor environments on the health of older people should also be considered, and further analysis considering the limitations of the study in terms of determining the users' metabolic rate and the assessment of the indoor air quality and determining individual factors of the residents should be done.

In a world where the number of older people is increasing, more nursing homes are needed. Considering future extreme climate scenarios and the need to find energy-efficient models for thermal conditioning and air renovation, the results of this study might lead to accurate indoor thermal comfort and environmental quality standards for older people.

The results of this study can help nursing homes' managers organise and plan the monitored activities and establish ventilation protocols specifically adapted to the activities carried out in each room to ensure the well-being of older people.

The implementation of the results of this study will contribute to a better quality of life for occupants of nursing homes and reduce energy consumption and CO_2 emissions due to a reduction of heating. The results of this study carry significant policy implications for regulatory bodies to develop standards to operate buildings occupied by older people such as nursing homes. The adaptation of HVAC design and operation standards based on these results would not only improve the occupant's comfort and well-being but also significantly reduce the energy consumption of the buildings.

Data Availability

Data is confidential but can be reached by contacting the corresponding authors (nuria.forcada@upc.edu or roger.verges.eiras@estudiantat.upc.edu).

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Acknowledgments

This research was supported by the Spanish Ministry of Economy, Industry and Competitiveness under R&D project Thecoelen, reference no. PID2019-106777RB-C21. Additionally, thanks are due to Sanitas Mayores and especially Eng. Marc Vallet and Eng. Albert Ayala for providing their nursing homes and helping to collect all required data. The authors would also like to extend their appreciation to all caregivers, maintenance staff, and elderly people who participated in this project. This work was also supported by the Catalan agency AGAUR through its research group support program (2021 SGR 00341). Open access funding was enabled and organized by CRUE-CSUC Gold.

References

[1] European Commission, "Proposal for a directive of the European Parliament and of the council on the energy performance of buildings (recast)," *Official Journal of the European Union*, vol. 426, pp. 10–27, 2021.

[2] Building Performance Institute Europe, *97% of buildings in the EU need to be upgraded*, BPIE, Brussels, 2017.

[3] European Commission, "Directive (EU) 2018/844 of the European Parliament and of the council of 30 May 2018 amending directive 2010/31/EU on the energy performance of buildings and directive 2012/27/EU on energy efficiency," *Official Journal of the European Union 2018*, pp. 75–91, 2018, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0844&from=EN.

[4] K. J. Chua, S. K. Chou, W. M. Yang, and J. Yan, "Achieving better energy-efficient air conditioning – a review of technologies and strategies," *Applied Energy*, vol. 104, pp. 87–104, 2013.

[5] W. Chung, "Review of building energy-use performance benchmarking methodologies," *Applied Energy*, vol. 88, no. 5, pp. 1470–1479, 2011.

[6] Eurostat, *Energy consumption in households*, Eurostat, 2021.

[7] Instituto Nacional de Estadística, *Proyecciones de Población 2016-2066*, Notas de Prensa, 20, 2016, https://www.ine.es/prensa/np994.pdf.

[8] European Commission, *Indoor air pollution: new EU research reveals higher risks than previously thought*, European Commission, 2003.

[9] C. Hughes, S. Natarajan, C. Liu, W. J. Chung, and M. Herrera, "Winter thermal comfort and health in the elderly," *Energy Policy*, vol. 134, article 110954, 2019.

[10] G. Havenith, "Temperature regulation and technology," *Geron*, vol. 1, no. 1, pp. 41–49, 2001.

[11] F. Salata, I. Golasi, W. Verrusio, E. de Lieto Vollaro, M. Cacciafesta, and A. de Lieto Vollaro, "On the necessities to analyse the thermohygrometric perception in aged people. A review about indoor thermal comfort, health and energetic aspects and a perspective for future studies," *Sustainable Cities and Society*, vol. 41, pp. 469–480, 2018.

[12] World Health Organization, *Did you know that when you have climate change strategies, you are improving your health?*, WHO, 2008.

[13] J. Díaz, R. Carmona, and C. Linares, *Temperaturas umbrales de disparo de la mortalidad atribuible al calor en España en el periodo 2000-2009*, Escuela Naional de Sanidad. Ministerio de Economía y Competitividad, Madrid, 2015.

[14] J. Díaz, R. Carmona, I. J. Mirón, C. Ortiz, and C. Linares, "Comparison of the effects of extreme temperatures on daily mortality in Madrid (Spain), by age group: the need for a cold wave prevention plan," *Environmental Research*, vol. 143, no. -Partt A, pp. 186–191, 2015.

[15] C. Linares, J. Diaz, A. Tobías, R. Carmona, and I. J. Mirón, "Impact of heat and cold waves on circulatory-cause and respiratory-cause mortality in Spain: 1975–2008," *Stochastic Environmental Research and Risk Assessment*, vol. 29, no. 8, pp. 2037–2046, 2015.

[16] A. Tobias, B. Armstrong, I. Zuza, A. Gasparrini, C. Linares, and J. Diaz, "Mortality on extreme heat days using official thresholds in Spain: a multi-city time series analysis," *BMC Public Health*, vol. 12, no. 1, pp. 12–133, 2012.

[17] D. T. Novieto and Y. Zhang, "Thermal comfort implications of the aging effect on metabolism, cardiac output and body weight," in *Adapting to Change: New Thinking on Comfort*, London, 2010.

[18] N. R. Ryti, Y. Guo, and J. J. Jaakkola, "Global association of cold spells and adverse health effects: a systematic review and meta-analysis," *Environmental Health Perspectives*, vol. 124, no. 1, pp. 12–22, 2016.

[19] H. Van and J. Hensen, "Thermal comfort and older adults," *Geron*, vol. 4, no. 4, pp. 223–228, 2006.

[20] V. Soebarto, H. Bennetts, A. Hansen et al., "Living environment, heating-cooling behaviours and well-being: survey of older south Australians," *Building and Environment*, vol. 157, pp. 215–226, 2019.

[21] M. Bentayeb, M. Simoni, D. Norback et al., "Indoor air pollution and respiratory health in the elderly," *Journal of Environmental Science and Health, Part A*, vol. 48, no. 14, pp. 1783–1789, 2013.

[22] P. Carreiro-martins, J. Gomes-Belo, I. Caires et al., "Chronic respiratory diseases and quality of life in older people nursing home residents," *Chronic Respiratory Disease*, vol. 13, no. 3, pp. 211–219, 2016.

[23] Y. Chen, H. Zhang, H. Yoshino et al., "Winter indoor environment of elderly households: a case of rural regions in Northeast and Southeast China," *Building and Environment*, vol. 165, article 106388, 2019.

[24] S. F. Ferng and L. Li-Wen, "Indoor air quality assessment of daycare facilities with carbon dioxide, temperature and humidity as indicators," *Journal of Environmental Health*, vol. 65, no. 4, pp. 14–18, 2002.

[25] M. Jantunen, J. J. K. Jaakkola, and M. Krzyzanowski, *Assessment of exposure to indoor air pollutants*, WHO Regional Office Europe, 1997.

[26] A. Marengoni, S. Angleman, R. Melis et al., "Aging with multimorbidity: a systematic review of the literature," *Ageing Research Reviews*, vol. 10, no. 4, pp. 430–439, 2011.

[27] A. Mendes, C. Pereira, D. Mendes et al., "Indoor air quality and thermal comfort—results of a pilot study in elderly care centers in Portugal," *Journal of Toxicology and Environmental Health, Part A*, vol. 76, no. 4-5, pp. 333–344, 2013.

[28] S. A. Mende, A. L. Papoila, P. Carreiro-Martins et al., "The impact of indoor air quality and contaminants on respiratory health of older people living in long-term care residences in Porto," *Age and Ageing*, vol. 45, no. 1, pp. 136–142, 2016.

[29] H. Thomson, S. Thomas, E. Sellstrom, and M. Petticrew, "Housing improvements for health and associated socio-economic outcomes," *Cochrane Database of Systematic Reviews*, vol. 2, 2013.

[30] O. Seppänen, W. Fisk, and M. Mendell, "Association of ventilation rates and CO_2 concentrations with health and other responses in commercial and institutional buildings," *Indoor Air*, vol. 9, no. 4, pp. 226–252, 1999.

[31] L. Fang, G. Clause, and P. Fanger, "Impact of temperature and humidity on the perception of indoor air quality," *Indoor Air*, vol. 8, no. 2, pp. 80–90, 1998.

[32] Y. Jin, F. Wang, M. Carpenter, R. B. Weller, D. Tabor, and S. R. Payne, "The effect of indoor thermal and humidity condition on the oldest-old people's comfort and skin condition in winter," *Building and Environment*, vol. 174, article 106790, 2020.

[33] P. Wolkoff, "Indoor air humidity, air quality, and health – an overview," *International Journal of Hygiene and Environmental Health*, vol. 221, no. 3, pp. 376–390, 2018.

[34] M. Bentayeb, D. Norback, M. Bednarek et al., "Indoor air quality, ventilation and respiratory health in elderly residents living in nursing homes in Europe," *European Respiratory Journal*, vol. 45, no. 5, pp. 1228–1238, 2015.

[35] M. Guo, M. Zhou, B. Li et al., "Reducing indoor relative humidity can improve the circulation and cardiorespiratory health of older people in a cold environment: a field trial conducted in Chongqing, China," *Science of the Total Environment*, vol. 817, p. 152695, 2022.

[36] J. Hou, Y. Sun, X. Dai et al., "Associations of indoor carbon dioxide concentrations, air temperature, and humidity with perceived air quality and sick building syndrome symptoms in Chinese homes," *Indoor Air*, vol. 31, no. 4, pp. 1018–1028, 2021.

[37] A. Serrano-Jiménez, J. Lizana, M. Molina-Huelva, and A. Barrios-Padura, "Indoor environmental quality in social housing with elderly occupants in Spain: measurement results and retrofit opportunities," *Journal of Building Engineering*, vol. 30, article 101264, 2020.

[38] L. Bøkenes, J. B. Mercer, S. MacEvilly, J. F. Andrews, and R. Bolle, "Annual variations in indoor climate in the homes of elderly persons living in Dublin, Ireland and Tromsø, Norway," *European Journal of Public Health*, vol. 21, no. 4, pp. 526–531, 2009.

[39] S. Çağlak, "Evaluation of the effects of thermal comfort conditions on cardiovascular diseases in Amasya city, Turkey," *Turkey. Journal of Public Health*, pp. 1–10, 2022.

[40] R. Raymann and E. Van Someren, "Diminished capability to recognize the optimal temperature for sleep initiation may contribute to poor sleep in elderly people," *Sleep*, vol. 31, no. 9, pp. 1301–1309, 2008.

[41] G. Brooke, "Improving indoor thermal comfort, air quality and the health of older adults through environmental policies in London improving indoor thermal comfort, air quality and the health of older adults through environmental policies in London," *Journal of Physics: Conference Series*, vol. 2069, no. 1, 2021.

[42] F. Tartarini, P. Cooper, and R. Fleming, "Thermal perceptions, preferences and adaptive behaviours of occupants of nursing homes," *Building and Environment*, vol. 132, pp. 57–69, 2018.

[43] M. T. Baquero Larriva and E. Higueras García, "Confort térmico de adultos mayores: una revisión sistemática de la literatura científica," *Revista Española de Geriatría y Gerontología*, vol. 54, no. 5, pp. 280–295, 2019.

[44] J. Van Hoof, L. Schellen, V. Soebarto, J. K. W. Wong, and J. K. Kazak, "Ten questions concerning thermal comfort and ageing," *Building and Environment*, vol. 120, pp. 123–133, 2017.

[45] L. T. Wong, K. N. K. Fong, K. W. Mui, W. W. Y. Wong, and L. W. Lee, "A field survey of the expected desirable thermal environment for older people," *Indoor and Built Environment*, vol. 18, no. 4, pp. 336–345, 2009.

[46] P. Fanger, *Thermal Comfort: Analysis and Applications in Environmental Engineering*, Danish Tec, Copenhagen, 1970.

[47] Y. Wu, H. Liu, B. Li et al., "Thermal adaptation of the elderly during summer in a hot humid area: psychological, behavioral, and physiological responses," *Energy and Buildings*, vol. 203, article 109450, 2019.

[48] R. Bills, "Cold comfort: thermal sensation in people over 65 and the consequences for an ageing population," in *Proceedings of 9th Windsor Conference: Making Comfort Relevant*, Cumberland Lodge, Windsor, UK, 2016.

[49] N. Forcada, M. Gangolells, M. Casals, B. Tejedor, M. Macarulla, and K. Gaspar, "Field study on thermal comfort in nursing homes in heated environments," *Energy and Buildings*, vol. 244, article 111032, 2021.

[50] M. Giamalaki and D. Kolokotsa, "Understanding the thermal experience of elderly people in their residences: study on thermal comfort and adaptive behaviors of senior citizens in Crete, Greece," *Energy and Buildings*, vol. 185, pp. 76–87, 2019.

[51] G. Fan, J. Xie, H. Yoshino et al., "Investigation of indoor thermal environment in the homes with elderly people during heating season in Beijing, China," *Building and Environment*, vol. 126, pp. 288–303, 2017.

[52] R. Hwang and C. Chen, "Field study on behaviors and adaptation of elderly people and their thermal comfort requirements in residential environments," *Indoor Air*, vol. 20, no. 3, pp. 235–245, 2010.

[53] J. Yang, I. Nam, and J. R. Sohn, "The influence of seasonal characteristics in elderly thermal comfort in Korea," *Energy and Buildings*, vol. 128, pp. 583–591, 2016.

[54] P. Devine-Wright, W. Wrapson, V. Henshaw, and S. Guy, "Low carbon heating and older adults: comfort, cosiness and glow," *Building Research and Information*, vol. 42, no. 3, pp. 288–299, 2014.

[55] Comunidad de Madrid, "Actualidad," *La población la Comunidad Madrid creció un 1,1 % en 2017, Hast. 6.578.079 habitantes*, 2019, https://www.comunidad.madrid/noticias/2019/01/27/poblacion-comunidad-madrid-crecio-11-2017-6578079-habitantes#:~:text=Laspersonasmayoresde65,17%2C5%25deltotal.

[56] W. Koppen, E. Volken, and S. Brönnimann, "The thermal zones of the Earth according to the duration of hot, moderate and cold periods and to the impact of heat on the organic world," *Meteorologische Zeitschrift*, vol. 20, no. 3, pp. 351–360, 2011.

[57] Agencia Estatal de Meteorología de España AEMET, 2022, https://www.aemet.es/.

[58] American National Standards Institute, "ASHRAE STANDARD 55 – thermal environmental conditions for human occupancy," ANSI, Atlanta, 2020.

[59] International Standard Organization, "ISO 7730: Ergonomics of the Thermal Environment," in *Analytical determination*

and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, ISO, 2005.

[60] International Standard Organization, "ISO 7726: Ergonomics of the Thermal Environment," in *Instruments and methods for measuring physical quantities*, ISO, 1998.

[61] Gobierno de España, *Reglamento de instalaciones térmicas en los edificios (RITE)*, Boletín Oficial Del Estado, 2021, https://www.boe.es/buscar/act.php?id=BOE-A-2007-15820.

[62] CEN - Comité Européen de Normalisation, "EN 16798-1. Energy performance of buildings. Ventilation for buildings," in *Part 1: indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Module M1-6*, CEdN, 2019.

[63] CEN - Comité Européen de Normalisation, "CEN/TR 16798-2. Energy performance of buildings. Ventilation for buildings," in *Part 2: interpretation of the requirements in EN 16798-1. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Module M1-6*, CEdN, 2019.

[64] R. De Dear and G. S. Brager, "Developing an adaptive model of thermal comfort and preference," *ASHRAE Transactions*, vol. 104, pp. 145–167, 1998.

[65] N. Forcada, M. Gangolells, M. Casals, B. Tejedor, M. Macarulla, and K. Gaspar, "Field study on adaptive thermal comfort models for nursing homes in the Mediterranean climate," *Energy and Buildings*, vol. 252, article 111475, 2021.

[66] M. Jowkar, H. Bahadur, A. Montazami, and J. Brusey, "The influence of acclimatization, age and gender-related differences on thermal perception in university buildings: case studies in Scotland and England," *Building and Environment*, vol. 179, article 106933, 2020.

[67] M. Khoshbakht, Z. Gou, and F. Zhang, "A pilot study of thermal comfort in subtropical mixed-mode higher education office buildings with different change-over control strategies," *Energy and Buildings*, vol. 196, pp. 194–205, 2019.

[68] Z. Wang, R. DearDe, M. Luo et al., "Individual difference in thermal comfort: a literature review," *Building and Environment*, vol. 138, pp. 181–193, 2018.

[69] R. Bills, V. Soebarto, and T. Williamson, "Thermal experiences of older people during hot conditions in Adelaide," in *Revisiting the role of architectural science in design and practice: 50th International Conference of the Architectural Science Association*, J. Zuo, L. Daniel, and V. Soebarto, Eds., pp. 657–664, The Architectural Science Association and The University of Adelaide, Adelaide, 2016.

[70] R. De Dear and G. S. Brager, "The adaptive model of thermal comfort and energy conservation in the built environment," *International Journal of Biometeorology*, vol. 45, no. 2, pp. 100–108, 2001.

[71] H. Feriadi, N. H. Wong, S. Chandra, and K. W. Cheong, "Adaptive behaviour and thermal comfort in Singapore's naturally ventilated housing," *Building Research & Information*, vol. 31, no. 1, pp. 13–23, 2010.

[72] X. L. Ji, W. Z. Lou, Z. Z. Dai, B. G. Wang, and S. Y. Liu, "Predicting thermal comfort in Shanghai's non-air-conditioned buildings," *Building Research and Information*, vol. 34, no. 5, pp. 507–514, 2006.

[73] T. Kainaga, K. Sagisaka, R. Yamada, and T. Nakaya, "A case study of a nursing home in Nagano, Japan: field survey on thermal comfort and building energy simulation for future climate change," *Energies*, vol. 15, no. 3, p. 936, 2022.

[74] R. Bills, "Creating comfort and cultivating good health: the links between indoor temperature," in *Thermal Comfort and Health. 10th Windsor Conference. Rethinking Comfort, NCEUB 2018*, pp. 886–900, Windsor, UK, 2018.

[75] Y. Jiao, H. Yu, T. Wang, Y. An, and Y. Yu, "Thermal comfort and adaptation of the elderly in free-running environments in Shanghai, China," *Building and Environment*, vol. 118, pp. 259–272, 2017.

[76] Y. Tao, Z. Gou, Z. Yu, J. Fu, and X. Chen, "The challenge of creating age-friendly indoor environments in a high-density city: case study of Hong Kong's care and attention homes," *Journal of Building Engineering*, vol. 30, article 101280, 2020.

[77] M. Frontczak and P. Wargocki, "Literature survey on how different factors influence human comfort in indoor environments," *Building and Environment*, vol. 46, no. 4, pp. 922–937, 2011.

[78] S. Manu, Y. Shukla, R. Rawal, L. E. Thomas, and R. de Dear, "Field studies of thermal comfort across multiple climate zones for the subcontinent: India model for adaptive comfort (IMAC)," *Building and Environment*, vol. 98, pp. 55–70, 2016.

[79] M. T. Baquero Larriva, A. S. Mendes, and N. Forcada, "The effect of climatic conditions on occupants' thermal comfort in naturally ventilated nursing homes," *Building and Environment*, vol. 214, article 108930, 2022.

[80] S. Tham, R. Thompson, O. Landeg, K. A. Murray, and T. Waite, "Indoor temperature and health: a global systematic review," *Public Health*, vol. 179, pp. 9–17, 2020.

[81] K. J. Collins, C. Dore, A. N. Exton-Smith, R. H. Fox, I. C. MacDonald, and P. M. Woodward, "Accidental hypothermia and impaired temperature homoeostasis in the elderly," *British Medical Journal*, vol. 1, no. 6057, pp. 353–356, 1977.

[82] C. Yi, C. Childs, C. Peng, and D. Robinson, "Thermal comfort modelling of older people living in care homes: an evaluation of heat balance, adaptive comfort, and thermographic methods," *Building and Environment*, vol. 207, article 108550, 2022.

[83] S. Meyn, A. Surana, Y. Lin, S. M. Oggianu, S. Narayanan, and T. A. Frewen, "A sensor-utility-network method for estimation of occupancy in buildings," in *Proceedings of the 48h IEEE Conference on Decision and Control (CDC) held jointly with 2009 28th Chinese Control Conference*, pp. 1494–1500, Shanghai, China, 2009.

[84] E. H. K. Yung, S. Wang, and C. Chau, "Thermal perceptions of the elderly, use patterns and satisfaction with open space," *Landscape and Urban Planning*, vol. 185, pp. 44–60, 2019.

[85] M. P. Deuble and R. J. de Dear, "Is it hot in here or is it just me? Validating the post-occupancy evaluation," *Intelligent Buildings International*, vol. 6, no. 2, pp. 112–134, 2014.