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Field study on adaptive thermal comfort models for nursing homes in the Mediterranean climate

N. Forcada [a,*], M. Gangolells [b], M. Casals [c], B. Tejedor [d], M. Macarulla [e], K. Gaspar [f]

[a] Associate Professor, Department of Project and Construction Engineering (DPCE), Group of Construction Research and Innovation (GRIC), Universitat Politècnica de Catalunya (UPC), Colom, 11, Ed. TR5, 08222 Terrassa, Barcelona, Spain
[b] Associate Professor, Department of Project and Construction Engineering (DPCE), Group of Construction Research and Innovation (GRIC), Universitat Politècnica de Catalunya (UPC), Colom, 11, Ed. TR5, 08222 Terrassa, Barcelona, Spain
[c] Full Professor, Department of Project and Construction Engineering (DPCE), Group of Construction Research and Innovation (GRIC), Universitat Politècnica de Catalunya (UPC), Colom, 11, Ed. TR5, 08222 Terrassa, Barcelona, Spain
[d] Lecturer, Department of Project and Construction Engineering (DPCE), Group of Construction Research and Innovation (GRIC), Universitat Politècnica de Catalunya (UPC), Colom, 11, Ed. TR5, 08222 Terrassa, Barcelona, Spain
[e] Associate Professor, Department of Project and Construction Engineering (DPCE), Group of Construction Research and Innovation (GRIC), Universitat Politècnica de Catalunya (UPC), Colom, 11, Ed. TR5, 08222 Terrassa, Barcelona, Spain
[f] Associate Professor, Department of Project and Construction Engineering (DPCE), Group of Construction Research and Innovation (GRIC), Universitat Politècnica de Catalunya (UPC), Colom, 11, Ed. TR5, 08222 Terrassa, Barcelona, Spain

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A B S T R A C T

Nursing homes are designed and operated to meet general thermal specifications outlined by existing standards. This paper presents adaptive thermal comfort models for nursing homes based on the field survey administered in 100 common rooms of five nursing homes in the Mediterranean climate. The survey included simultaneous measurements of outdoor and indoor environmental parameters and an assessment of the occupants' thermal comfort sensations using questionnaires. In total, 1,921 subjective questionnaires were obtained. The analysis focused on: Building Operation Mode (naturally ventilated and air-conditioned mode (cooling and heating)); and type of occupant (residents and non-residents (caregivers and therapists)). In naturally ventilated rooms residents were found to be more adaptive than what EN and ASHRAE 55:2020 standards propose (T_c (naturally ventilated) = 0.26 T_{rm} + 18.83 (R^2 = 0.81)). Residents in air-conditioned rooms were found to be less sensitive to outdoor conditions (T_c (air-conditioned) = 0.16T_{rm} + 20.41 (R^2 = 0,91)) than in naturally ventilated rooms. Both adaptive thermal models fall in limits set by these standards but in the lower acceptable levels. These adaptive thermal comfort models for nursing homes will allow extending the use of natural ventilation and the adoption of setpoint temperatures when air-conditioning is needed with the consequent reduction of heating and cooling use.

1. Introduction

The current Covid-19 virus which is impacting massively in elderly people has manifested the deficiencies of existing nursing homes. Existing stock of buildings occupied by elderly should be revised while regulations for indoor conditions must be updated to focus on health and wellbeing of their occupants.

Considering that older people spend 80% of their time indoors, their health and comfort is significantly influenced by indoor thermal environment [123]. Although thermal comfort and HVAC design are important issues in nursing homes, existing stock of buildings occupied by elderly are designed and operated considering general regulations for all type of tertiary buildings.

The heat-balanced predicted mean vote (PMV) is the most commonly used model to evaluate if a thermal environment is acceptable [4]. PMV is expressed on the ASHRAE thermal sensation scale (from −3 cold to + 3 hot) and depends on the air temperature (T_a), the mean radiant temperature (T_r), the relative air velocity (v_a) the air humidity (HR_a), the occupant's activity level (met) and the occupant's clothing insulation (Clo). Based on experimental studies an empirical relationship between PMV and the predicted percentage of dissatisfied (PPD) was developed. The ISO 7730 [5], ASHRAE 55:2020 [6], EN 15251:2007[7] and EN 16798:2019 [8] standards which determine the comfort conditions for the majority of indoor occupants, adopt the PMV model. In general, PMV model is suitable

* Corresponding author.
E-mail address: nuria.forcada@upc.edu (N. Forcada).

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for air-conditioned buildings occupied by adults. However, there are uncertainties when adopting it in naturally ventilated buildings and for building occupied by elderly people [9].

Field studies suggest that regression methods representing the mean occupants' thermal sensation (MTSV) as a function of the operative temperature (T_{op}) with weighted 0.5 °C binned data allows obtaining the temperature of neutrality, the temperature at which participants reported their thermal perception of feeling "neutral" [10].

However, the neutral temperature obtained from simple regression analysis between T_{op} and TSV might not be suitable in field surveys where people adjust their environment including their clothing, metabolism, behaviour, and environment [11] such as in naturally ventilated or free-running buildings. In these cases, people have a natural tendency to adapt to changing conditions in their environment. Therefore, the comfort temperature is expressed in the adaptive approach to thermal comfort [12] in which the comfortable indoor temperature increases significantly in warmer climates, and decreases in colder regions [13 14]. Therefore, the use of the PMV model is usually associated to air-conditioned spaces with a more static thermal environment.

An alternative thermal comfort model based on the idea that people are not passive, but constantly interacting with and adapting to it adjusting the body's heat balance to maintain thermal comfort, such as changing the activity and clothing levels [15 12] was proposed by de Dear et al. [16] and Nicol and Humphreys [12 17]. Behavioural adjustments and adaptations increase occupants tolerance of temperatures in naturally ventilated buildings [9]. Adaptive comfort theory considers that the comfort temperature for occupants relates to the mean outdoor temperature, building types, [15] and climatic regions. The ASHRAE 55:2020 [6] includes adaptive thermal comfort models for natural ventilated buildings. EN 15251:2007[7] and EN 16798:2019 [8] do also consider adaptive thermal comfort models both for naturally ventilated and for mixed-mode buildings.

Existing thermal comfort models focus on office buildings, which tend to be occupied by adults aged less than 65 years old [18 19]. A nursing home is a 24-hour care and assistance residence for people who cannot stay alone and need daily living assistance and complex health care needs [20]. Therefore, in comparison to occupants in offices, the thermal sensation and adaptation of older people in nursing homes is different [212223]. The age affects the difficulty regulating the body temperature and affects the thermal comfort perception. Although existing standards are not developed considering these specific characteristics, ASHRAE 55:2020 [6] proposes two thermal comfort ranges (80% of satisfied people for adults and 90% for elderly) while EN 15,251 [7] and EN 16,798 [8] include three categories. The most restrictive category is for elderly occupants.

The adaptive thermal comfort theoretical concepts is well-established [1312]. However, there are uncertainties related to its use for elderly people and its proper application in existing standards [9].

To date, few studies evaluated the thermal comfort of elderly. Wu et al.[24], Yang et al. [25] and Hughes et al. [26] compared the thermal comfort of elderly people with existing static PMV comfort models and concluded that elderly people have lower thermal sensitivity than the PMV model used in many standards.

Tartarini et al.[27], Wong et al. [28], Hwang and Chen [29] and Forcada et al. [30 31] found that elderly people were more tolerant than non-elderly adults and preferred higher temperatures than adults.

The only adaptive thermal comfort model for elderly people was developed by Jiao et. al [32] in China. However, in their study, only naturally ventilated buildings were analysed and the climatic conditions were extreme with outdoor temperatures ranging from 0 to 30 °C.

Thus, there is research to be done, especially regarding the adaptive thermal comfort of elderly and its applicability in different climatic conditions and seasons: heating (winter season), cooling (summer season) and naturally ventilated (generally spring and autumn).

Thermal comfort indicators for elderly will allow design comfortable spaces, refurbish existing ones, improve elderly well-being and adopt new strategies of efficiency and energy saving.

Given the current pandemic which is impacting massively in elderly people in nursing homes, the thermal comfort and adaptation of older people is a topic of interest in all over the world today. Therefore, this study conducted a field survey on thermal comfort to 1,921 occupants in nursing homes in the Mediterranean climate.

The research objectives were as follows: 1) To develop adaptive thermal comfort models for nursing homes' occupants of the Mediterranean climate for the different air conditioning modes (heating, cooling and naturally ventilated mode) and (2) To evaluate the suitability of existing adaptive thermal comfort models to nursing homes' occupants.

This study is the continuation of previous analysis investigating the thermal sensation of elderly people during summer [30] and winter [31] seasons in nursing homes from the Mediterranean climate.

2. Method

Environmental parameters from 100 common areas (living room, dining room, occupational therapy room and gym) from five nursing homes located in the Mediterranean climate were collected in the same time that occupants were surveyed to obtain their thermal sensation.

The selected common areas were all from Sanitas Mayores' nursing homes, an elderly healthcare and residential company which is part of Bupa. It has 50 nursing homes throughout Spain and serves more than 6,000 residents.

All selected nursing homes have a traditional brick façade without air chamber and sliding double glazing windows. These nursing homes were selected because they all have the same HVAC system (an air–water system with fan-coils and air recovery units) manually controlled. All common rooms are operated similarly, heating / cooling is switched on from 8:00 to 21:00 during the summer / winter while windows are operated manually by caregivers. During heating and cooling periods, ventilation comes from heat recovery units through fan-coils while during spring and autumn when heating and cooling is not necessary, fresh air comes from natural ventilation by opening windows.

The experimental campaign was carried out from the 8th of February to the 1st of November 2019 and 1,921 questionnaire surveys were acquired both from residents and non-residents (caregivers and therapists) within the heating, cooling and naturally ventilated modes.

This study was approved by the ethics committee of Universitat Politècnica de Catalunya (2020.01 reference number) and respects the fundamental principles established in the Declaration of Helsinki. An informed consent form was signed by all participants during the experimental campaign.

2.1. Description of the climatology

The selected nursing homes were located in the Mediterranean climate which is characterized by dry summers and mild, wet winters [33].

Under this climate, the minimum and maximum monthly outdoor temperatures are very changeable along the year. In winter temperatures vary between 4 °C and 15 °C, in spring and autumn between 10 °C and 21 °C while in summer between 18 °C and 28 °C (Fig. 1).

However, the average humidity is very constant (between 64% and 70% along the year) [34].

2.2. Description of the sample

This study focused on two groups of data analysis:

- Building Operation Mode: naturally ventilated mode and air-conditioned mode (cooling and heating).
- Type of occupant: residents and non-residents (caregivers and therapists).

The heating mode was mainly in winter period, the cooling mode in summer period and the naturally ventilated mode along all the seasons.

From the 1,921 questionnaire surveys, 1,252 were during the naturally ventilated mode while 669 were during the conditioning mode (either cooling or heating) (see Table 1). The sample was divided into residents and non-residents to determine their particular characteristics.

2.3. Measurement of environmental variables

To measure indoor environmental parameters (air temperature (T_a), relative humidity (HR%), mean radiant temperature (T_r) and air velocity (v_a)) a portable Delta Ohm HD32.2 instrument was used.

The mean radiant temperature (T_r) was estimated from the globe temperature (T_g) and the air temperature (T_a) using the ISO7726 standard [35].

For the globe thermometer temperature (°C), a TP3276.2 probe with a ± 0.2 °C precision and a −10 °C to 100 °C tolerance was used.

To obtain the air speed (m/s), an AP3203.2 probe with a ± 0.0 5 m/s precision and a 0 m/s to 5 m/s tolerance was used.

For the indoor temperature and relative humidity, a HP3201.2 probe with a <±0,5°C precision and −30 °C to 60 °C and a HP3217.2 probe with a ± 3HR precision and 20% to 80% tolerance were used.

According to ASHRAE 55 [6], the instrument was located in the centre of the room and between 0.8 and 1.5 m above the ground depending on the position of the occupants. When the occupants were seated the instrument was located at 0.8 m while when they were standing it was located at 1.5 m. The equipment was stabilized for 10 min and measurements were recorded during approximately 40 min.

2.4. Thermal comfort surveys

At the same time of measuring environmental variables, nursing homes' occupants were surveyed to determine their thermal comfort.

Measurements and surveys were carried out in different common rooms (living room, dining room, gym and occupational therapy room). The occupants were surveyed along the different Building Operation Modes (heating, cooling, naturally ventilated).

Thermal perceptions and preferences of the occupants from nursing homes were obtained using an image-based questionnaire survey (Fig. 2) while the environmental parameters were collected.

The survey included the thermal sensation vote (TSV), preference (P) and acceptability (A). The TSV was assessed using the ASHRAE seven-point thermal sensation scale (−3 cold, −2 cool, −1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot) [6]. For the thermal preference (P) a three point scale (−1 cooler, 0 without change,+1 warmer [7]) was used. And for the thermal acceptability (A) a two-point scale (1 acceptable, 0 unacceptable) was used.

Standard procedures were used to ensure accurate and consistent data collection throughout the study.

For the thermal comfort survey, ISO 10,551 [36] standard procedures were used to provide consistency and reliability of results and meaningful comparison of data obtained from investigations internationally.

All surveys were conducted in the daytime when residents were in the common areas. Only one researcher with the help of caregivers collected the residents' comfort evaluation. The question-

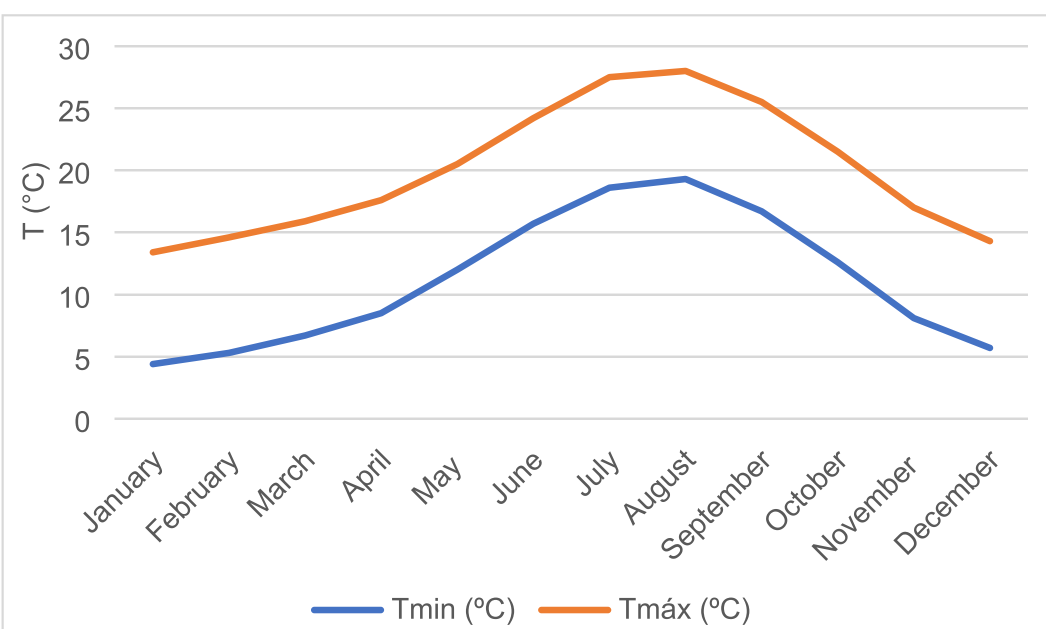

Fig. 1. Mean T_{min} and T_{max} in a typical Mediterranean climate.

Table 1
Sample characteristics.

		Cooling	Heating	Naturally ventilated	Total
Non-residents	N	64	95	280	439
	%	3.3	4.9	14.6	22.8
Residents	N	182	328	972	1482
	%	9.5	17.1	14.6	77.1
Total	N	246	423	1252	1921

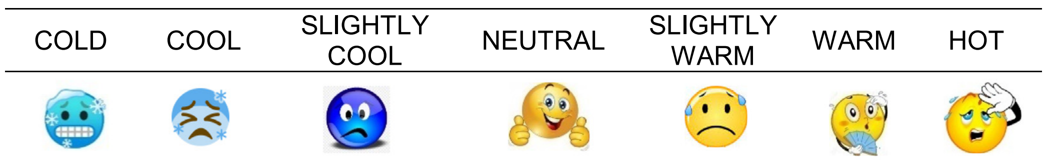

Fig. 2. Image-based evaluation of thermal sensation.

naire was designed to take less than two minutes to complete, and consisted of simple questions supported by figures to facilitate their understanding of the thermal scales.

To monitor the survey progress and detect errors, quality checks were carried out monthly. These quality checks comprised respondents coding and analysis of the TSV, P and A including average, maximum, minimum and deviation. When inconsistent responses and/or outliers were found, they were deeply analysed and deleted, if considered.

2.5. Estimation of the comfort temperature and adaptive comfort models

The comfort temperature is defined as the operative temperature in which the average person will feel thermally comfortable [6].

The Griffith method proposes to calculate the comfort temperature of the occupants by using function based on the average sensitivity (known as the Griffith constant) (Equation 3) [37].

$$Tc = Tg - \frac{TSV}{G}$$

where T_c is the comfort temperature, T_g is the globe temperature, TSV is the occupants' thermal sensation vote and G is the Griffith constant.

The Griffith constant is commonly referred as thermal sensitivity and represents the rate of change of the comfort vote with the indoor temperature when without adaptation processes [37]. Generally, at higher values of G, there is a better correlation between comfort temperature and outside temperature [38].

Although Rupp et al. [39] found that the thermal sensitivity differs between building typologies, modes of ventilation, outdoor climatic types, and genders, no specific values for the Griffith's constant under these conditions are suggested.

Humphreys et al. [40] and Rijal et al. [41], de Dear and Brager [16] and Nicol and Humphreys [15] found that the correlation between the running mean temperature and the indoor comfort temperature was the highest using G = 0.5. Therefore, the comfort temperature calculated with the coefficient 0.5 was used for this analysis. However, future studies to validate the use of this value in nursing homes of the Mediterranean climate are planned.

3. Results

3.1. Outdoor conditions during the experimental campaign

Daily maximum and minimum outdoor temperature and relative humidity were collected from the closest meteorological stations for each nursing home [27] with the aim to calculate the running mean outdoor air temperature which considers the influence of the thermal inertia of the previous days [16426].

$$T_{rm} = \left(\begin{array}{c} T_{ed-1} + 0.8\hat{A} \cdot T_{ed-2} + 0.6\hat{A} \cdot T_{ed-3} + 0.5\hat{A} \cdot T_{ed-4} + 0.4\hat{A} \cdot T_{ed-5} \\ + 0.3\hat{A} \cdot T_{ed-6} + 0.2\hat{A} \cdot T_{ed-7} \end{array} \right) / 3.8$$

where T_{ed-1} is the daily mean outdoor temperature for the previous day and T_{ed-2} is the daily mean outdoor temperature for the day before that, and so on.

Table 2. presents the outdoor conditions during the experimental campaign.

The range of outdoor temperatures under the Heating Operation Mode was from 12.1 to 23.5 °C, for the Cooling Operation Mode, from 24.7 to 28.2 °C and for the Natural Ventilation Mode from 12.1 to 28.2 °C (Table 2).

The average humidity was around 65% while the running mean temperature was a bit lower than the outdoor temperature in the cooling mode and a bit higher for heating mode and naturally ventilated rooms.

Temperatures remained, on average, above 20 °C but show seasonal variation There were cold seasons below 18 °C and others warmer exceed 22 °C, the typical characteristic of the Mediterranean climate.

3.2. Indoor conditions during the experimental campaign

Table 3. shows the indoor environmental variables monitored in the experimental campaign of the study split by those indoor conditions in naturally ventilated rooms, those rooms in cooling mode and those in heating mode.

The mean operative temperature in naturally ventilated and cooling mode was similar (24.5 and 24.6 °C) while for the heating mode was nearly one degree lower (23.5 °C). However, the maximum operative temperature in naturally ventilated rooms was much higher (28.4 °C) than in cooling mode (25 °C). The same happened with the minimum operative temperature. In average, the air velocity was higher in the cooling mode (0.13 m/s) than in

Table 2
Outdoor conditions during the experimental campaign.

		Average	Maximum	Minimum	Deviation
Naturally ventilated	T_{out} (°C)	19.2	28.2	12.1	4.5
	T_{rm} (°C)	19.6	27.4	13.3	4.1
	RH_{out} (%)	63.5	84.0	50.0	8.4
Cooling	T_{out} (°C)	26.3	28.2	24.7	1.1
	T_{rm} (°C)	26.1	27.4	25.4	0.6
	RH_{out} (%)	71.3	80.0	56.0	6.7
Heating	T_{out} (°C)	15.4	23.5	12.1	3.2
	T_{rm} (°C)	16.2	23.3	13.3	3.1
	RH_{out} (%)	57.1	74.0	49.0	7.5

Table 3
Indoor conditions during the experimental campaign.

		Average	Maximum	Minimum	Deviation
Naturally ventilated	T_g (°C)	24.5	28.5	19.7	1.8
	T_a (°C)	24.6	28.4	19.6	1.8
	RH (%)	54.9	68.7	42.8	6.9
	v_a (m/s)	0.02	0.07	0.00	0.01
	T_r (°C)	24.5	28.5	19.7	1.8
	T_{op} (°C)	24.5	28.4	19.6	1.8
Cooling	T_g (°C)	24.6	25.1	23.4	0.4
	T_a (°C)	24.5	25.0	23.3	0.4
	RH (%)	63.7	69.3	58.1	3.0
	v_a (m/s)	0.13	0.35	0.00	0.09
	T_r (°C)	24.6	25.3	23.4	0.4
	T_{op} (°C)	24.6	25.0	23.4	0.4
Heating	T_g (°C)	23.5	25.0	21.7	1.0
	T_a (°C)	23.6	25.3	21.7	0.9
	RH (%)	49.6	65.0	41.8	6.6
	v_a (m/s)	0.02	0.16	0.00	0.02
	T_r (°C)	23.5	25.0	21.6	1.0
	T_{op} (°C)	23.5	25.1	21.7	1.0

*$T_{op} = (T_a + T_r) / 2$

the heating mode (0.02 m/s). The indoor relative humidity was between 50 and 70% with the minimum relative humidity during the heating mode. Similar results were obtained in social housing for elderly [43].

3.3. Subjective thermal sensation, preference and acceptability

Results revealed that in cooling mode residents were more tolerant (61.5% TSV = 0) than non-residents which tended to be slightly cold (34.4%; TSV = -1) or slightly warm (37.5%; TSV=+1). However, in heating mode both residents and non-residents had a neutral thermal sensation or a slight warm thermal sensation (90.4% non-residents; 88.4% residents; TSV = 0 and + 1) (Table 4 and Fig. 3).

For naturally ventilated rooms, while the majority of residents had a neutral thermal sensation (69.4% TSV = 0), 69% of non-residents felt warm (TSV = 1 and 2).

To analyse the independence of the distribution of thermal sensation (TSV) for each group (residents-non-residents, Building Operation Mode) the Chi-square test was performed. The result showed that the TSV of residents and non-residents in the different air-conditioned modes was statistically different (p less than 0.05) (Table 5).

Table 6 and Fig. 4 show the thermal preference and acceptability of occupants by Building Operation Mode. For both the cooling and heating modes, the majority of residents did not want to change the temperature of the room (around 80%). However, 23.4% of non-residents preferred a cooler environment in cooling mode and 22.1% in the heating mode.

For the naturally ventilated rooms, surprisingly 40% of non-residents preferred a cooler environment, while only 16.8% of residents.

For the cooling mode and naturally ventilated mode ¾ of the residents accepted the thermal environment, while for the non-

Table 4
TSV by occupants and Building Operation Mode.

			−2	−1	0	1	2	3
Cooling mode	NR	N	0	22	10	24	6	2
		%	0.0	**34.4**	15.6	**37.5**	9.4	3.1
	R	N	7	34	112	16	11	2
		%	3.8	18.7	**61.5**	8.8	6.0	1.1
Heating mode	NR	N		4	53	33	4	1
		%		4.2	**55.8**	**34.7**	4.2	1.1
	R	N		28	221	69	10	0
		%		8.5	**67.4**	**21.0**	3.0	0.0
Naturally ventilated	NR	N	4	19	80	122	46	9
		%	1.4	6.8	28.6	**43.6**	**16.4**	3.2
	R	N	2	99	675	122	70	4
		%	0.2	10.2	**69.4**	12.6	7.2	0.4

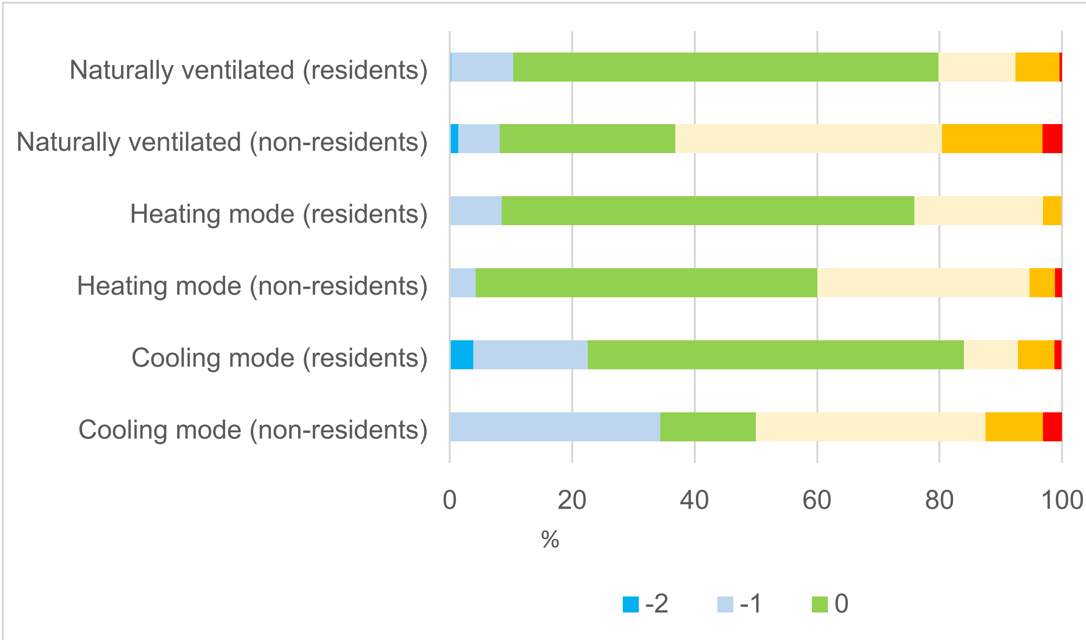

Fig. 3. TSV by occupants and Building Operation Mode.

Table 5
Chi square test between the TSV, the type of user and Building Operation Mode.

	Value	df	p: Asymptotic significance (2-sided)
Conditioned			
Pearson Chi-square	43.169[b]	5	0.000
Likelihood ratio	42.869	5	0.000
N of valid cases	669		0.000
Naturally ventilated			
Pearson Chi-square	213.419[c]	5	0.000
Likelihood ratio	198.557	5	0.000
N of valid cases	1252		0.000
Total			
Pearson Chi-square	231.676[a]	5	0.000
Likelihood ratio	217.440	5	0.000
N of valid cases	1921		0.000
2 cells (16.7%) have expected count less than 5.			
2 cells (25.0%) have expected count less than 5.			
2 cells (25.0%) have expected count less than 5.			

residents this proportion was lower. For the heating mode the acceptability was higher (4/5) for both residents and non-residents.

3.4. Comfort temperature

Fig. 5 shows the TSV plotted against the T_{op} for both naturally ventilated and conditioned rooms and for residents and non-residents.

Regression equations representing the mean occupants' thermal sensation (MTSV) as a function of the operative temperature (T_{op}) with weighted 0.5 °C binned data were obtained to evaluate the sensitivity and to obtain the neutral temperature for both Building Operation Modes and type of occupants.

Regression equations for both residents and non-residents and air-conditioned (AC) and naturally ventilated (NV) rooms are shown below (Equation 3 to 6 and Fig. 6):

$$\text{MTSV R (AC)} = 0.10T_{op}\text{-}2.3\ (R^2 = 0.84);\ T_n\ (\text{TSV} = 0) = 22.7 \circ \text{C} \quad (3)$$

$$\text{MTSV R (NV)} = 0.12T_{op}\text{-}2.8\ (R^2 = 0.84);\ T_n\ (\text{TSV} = 0) = 22.7 \circ \text{C} \quad (4)$$

$$\text{MTSV NR (AC)} = 0.30\ T_{op} - 6.84\ (R^2 = 0.73);\ T_n\ (\text{TSV} = 0) = 22.9 \circ \text{C} \quad (5)$$

$$\text{MTSV NR (NV)} = 0.32\ T_{op} - 6.95\ (R^2 = 0.83);\ T_n\ (\text{TSV} = 0) = 21.8 \circ \text{C} \quad (6)$$

Table 6
Thermal preference and acceptability by occupant and Building Operation Mode.

			Thermal preference			Thermal acceptability	
			Cooler	Without change	Warmer	Unacceptable	Acceptable
Cooling mode	NR	N	15	39	10	20	44
		%	23.4	**60.9**	15.6	31.3	68.8
	R	N	18	147	17	46	136
		%	9.9	**80.8**	9.3	25.3	74.7
Heating mode	NR	N	21	70	4	17	78
		%	22.1	**73.7**	4.2	17.9	**82.1**
	R	N	48	264	16	53	275
		%	14.6	**80.5**	4.9	16.2	**83.8**
Naturally ventilated	NR	N	112	149	19	108	172
		%	**40.0**	**53.2**	6.8	38.6	61.4
	R	N	163	761	48	252	720
		%	16.8	**78.3**	4.9	25.9	74.1

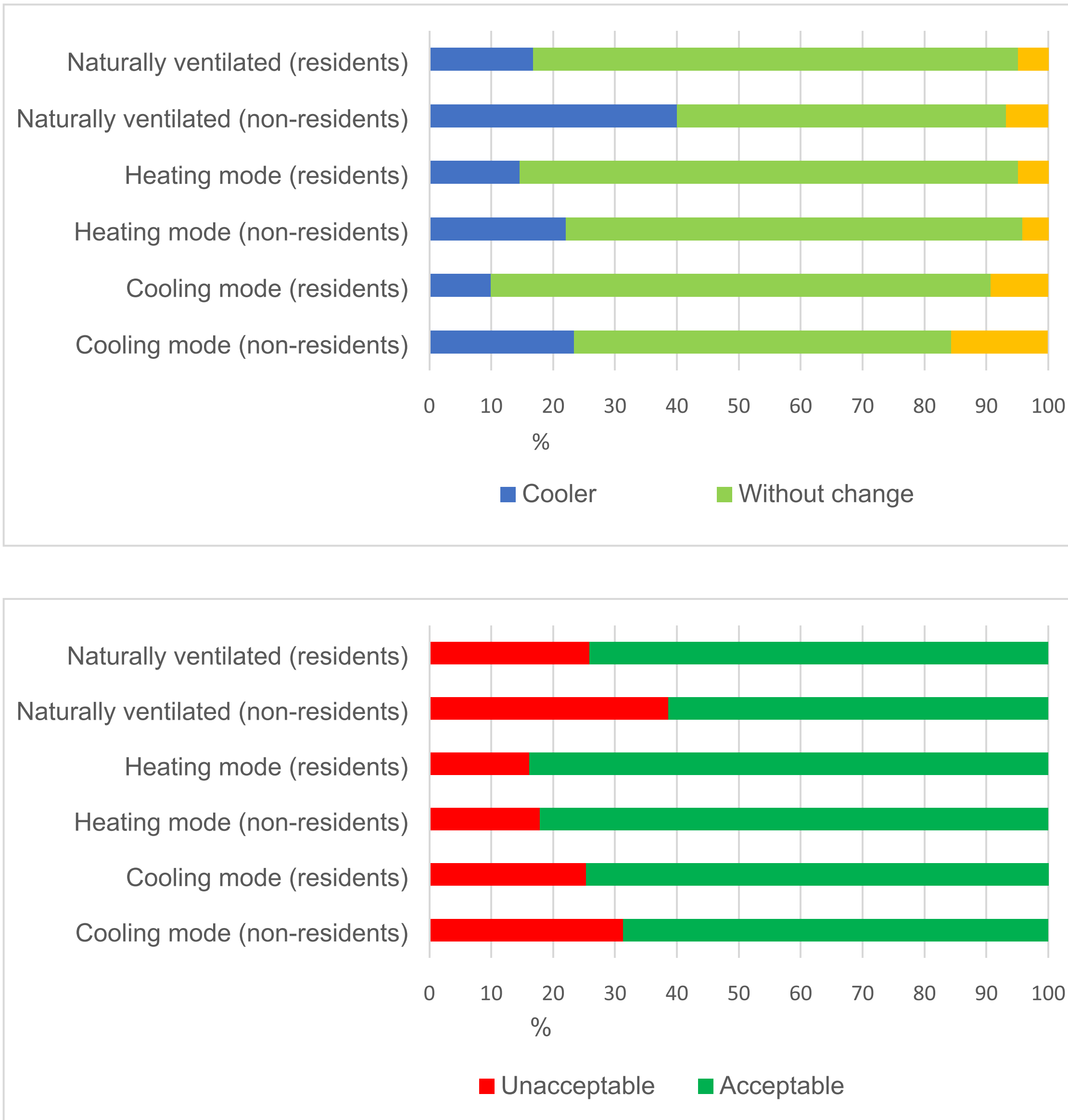

Fig. 4. Thermal preference and acceptability by occupant and Building Operation Mode.

All regression equations passed the goodness-of-fit (R^2 > 0,5). Results highlight that residents had a lower thermal sensitivity (the slope of the equations) than non-residents, both for conditioned and naturally ventilated rooms. A larger regression coefficient implies that a smaller change in temperature is required by thermal sensation to change one scale, indicating higher thermal sensitivity [16].

The neutral temperature (TSV = 0) was exactly the same (22.7 °C) for conditioned and naturally ventilated rooms for residents. However, results revealed that non-residents had different neutral temperature when rooms were conditioned (22.9 °C) and when they were naturally ventilated (21.8 °C). Their temperature of neutrality was lower in naturally ventilated rooms but the thermal sensitivity was higher.

3.5. Adaptive thermal comfort models

The comfort temperature based on the Griffiths method was calculated. Table 7 presents the comfort temperature for the different air-conditioned modes.

The comfort temperature ranged between 23.0 and 24.6 °C. Residents' comfort temperature was higher than non-residents for both naturally ventilated rooms and those rooms with cooling or heating. The difference was higher in naturally ventilated rooms.

For naturally ventilated rooms residents' comfort temperature was 1.1 °C higher than non-residents. Fig. 7 shows the comfort temperature plotted against the running mean temperature for naturally ventilated rooms and air-conditioned rooms (both for residents and non-residents).

Detailed information on the regression equations is shown below. It can (Fig. 8) be seen that all the regression equations have passed the goodness of fit (R^2 greater than 0.5) for residents, both for air-conditioned rooms and for naturally ventilated rooms but not for non-residents. We, thus obtain two models for residents (naturally ventilated rooms and air-conditioned rooms) (Equations 7 and 8):

$$T_c\ R\ (AC) = 0.16T_{rm} + 20.41\ (R^2 = 0.91)\ (7)$$

$$T_c\ R\ (NV) = 0.26\ T_{rm} + 18.83\ (R^2 = 0.81)\ (8)$$

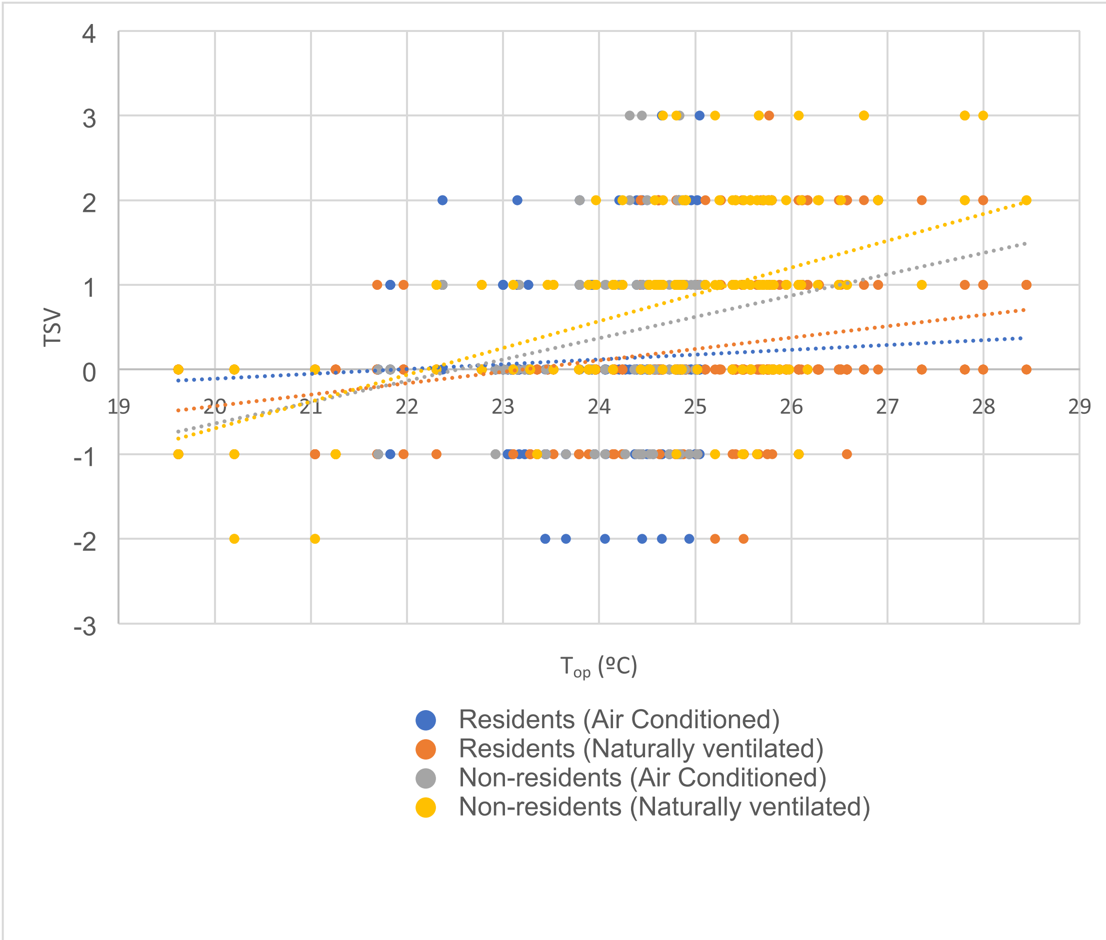

Fig. 5. TSV vs. T_{op} for both naturally ventilated and conditioned rooms for both residents and non-residents.

Indoor comfort temperature was found to be relatively static in air-conditioned rooms, but the thermal adaptation occurred in all indoor climatic environments, regardless of conditioning strategy [44].

The difference in the comfort temperature between naturally ventilated and air-conditioned rooms ranged from 0.5°for a range of lower external temperatures up to more than two degree for higher external temperatures.

For naturally ventilated rooms in winter period (temperatures around 13 °C and 23 °C) comfort temperatures for residents were found to be between 22.5 and 24.5 °C while for the summer period (temperatures around 25 to 27 °C) comfort temperatures ranged 25.5 to 26 °C. In air-conditioned rooms residents preferred lower temperatures both in winter and in summer than in naturally ventilated rooms. Considering that in the Mediterranean climate the summer is longer than the winter and outdoor temperatures in winter are not extreme, a reduction of cooling demand would allow energy savings.

In Europe, the current standards for determining the indoor thermal comfort zone of an indoor environment when using the thermal adaptation model are the ASHRAE 55:2020 [6] and the EN16798:2019 [8] which has substituted the EN15251:2007 [7].

Field study data was used to validate the different adaptive thermal comfort standards for older people in the Mediterranean climate in naturally ventilated rooms and in air-conditioned rooms.

Fig. 7 shows the lower and upper limits of the comfort temperatures based on the running mean temperature for EN 16798:2019 and EN 15251:2007 Category I (for older people) and ASHRAE 55:2020 standards with 90% acceptability.

Category I of the EN16798:2019 and EN 15251:2007 Category I European Standards coincide with the upper limit and just differs 1 °C in the lower limit.

Both ASHRAE 55 and European Standards narrow the comfort temperatures for spaces occupied by weak and sensitive people with special requirements, such as handicapped, sick, very young children and the elderly. However, although both are based on a huge database measurement taken primarily in office buildings, ASHRAE 55 propose lower comfort temperatures.

$$T_c\ (\text{ASHRAE-55 90\% acceptability (lower limit)}) = 0.31T_{rm} + 15.3$$

$$T_c\ (\text{ASHRAE-55 90\% acceptability (upper limit)}) = 0.31T_{rm} + 20.3$$

$$T_c\ (\text{EN 15,251 Cat I (lower limit)}) = 0.33T_{rm} + 16.8$$

$$T_c\ (\text{EN 15,251 Cat I (upper limit)}) = 0.33T_{rm} + 20.8$$

$$T_c\ (\text{EN 16,798 Cat I (lower limit)}) = 0.33\ T_{rm} + 15.8$$

$$T_c\ (\text{EN 16,798 Cat I (upper limit)}) = 0.33\ T_{rm} + 20.8$$

The adaptive model for residents within naturally ventilated rooms and air-conditioned rooms were also included in Fig. 9.

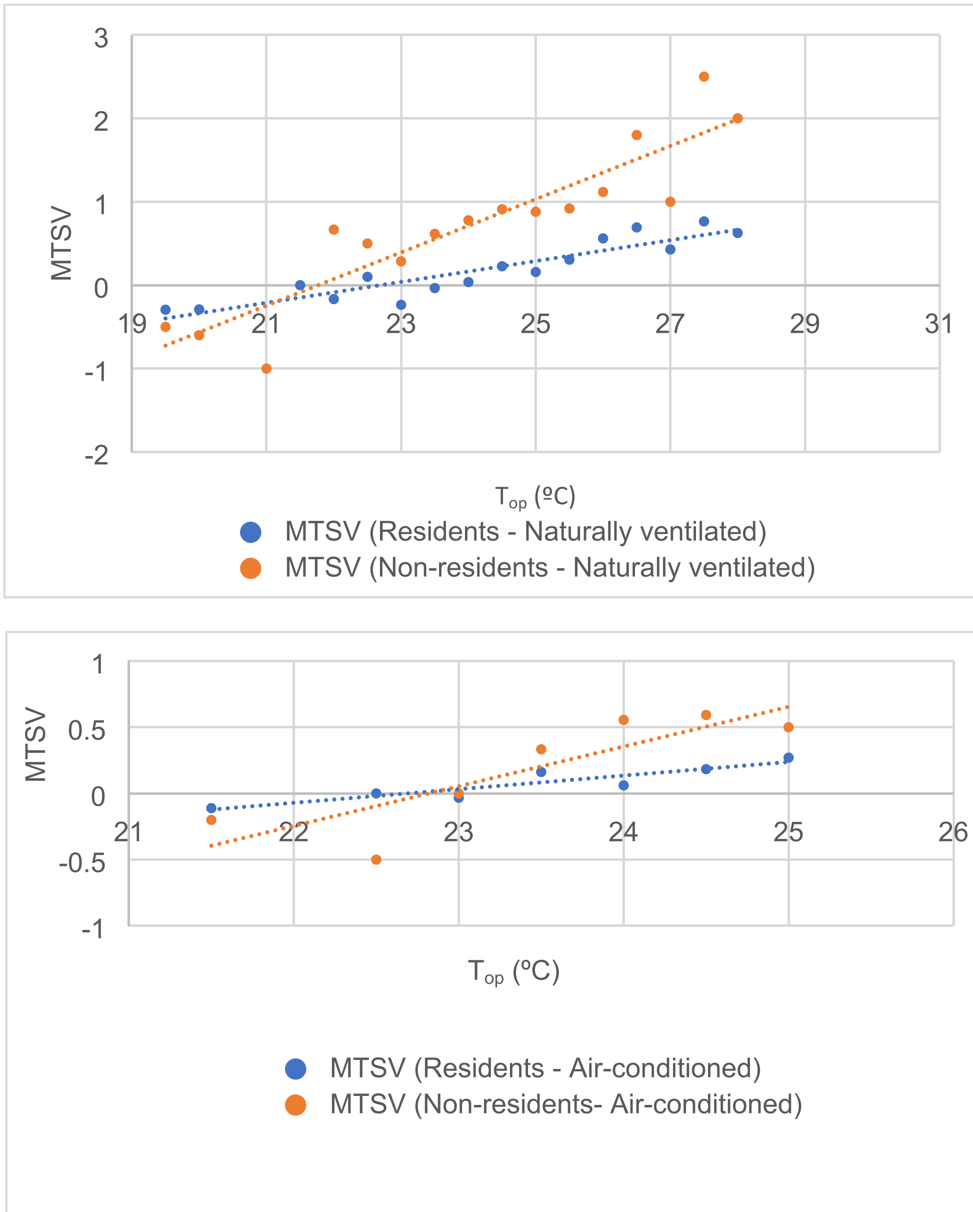

Fig. 6. Regression equations (MTSV vs T_{op}).

Table 7
Comfort temperature for the different Building Operation Modes.

		T_c (°C) Average	Maximum	Minimum	Deviation
Naturally ventilated	NR	23.0	28.0	18.6	1.7
	R	24.1	29.5	19.7	1.9
Cooling	NR	23.9	27.0	18.3	2.2
	R	24.6	29.0	18.7	4.7
Heating	NR	22.8	25.0	18.4	1.3
	R	23.1	27.0	18.3	1.4

The suitable indoor temperature conditions for the thermal adaptation model ranges from 10 °C to 30 °C in the EN 16798:2019 and EN 15251:2007 standards and from 10 °C to 33.5 °C. The prevailing mean outdoor temperature of this study ranged 12.1 °C to 28.2 °C. Therefore, all field data felt into the acceptable outdoor conditions to apply these standards.

For those rooms with natural ventilation, the slope of the model was lower to that of both the ASHRAE 55:2020, EN 16798:2019 and EN 15251:2007 standards. However, the comfort model for residents in nursing homes in the Mediterranean climate was within the limits set by these standards but in the lower limit.

In the case of those air-conditioned rooms, the slope of the thermal comfort model confirmed that occupants in air-conditioned

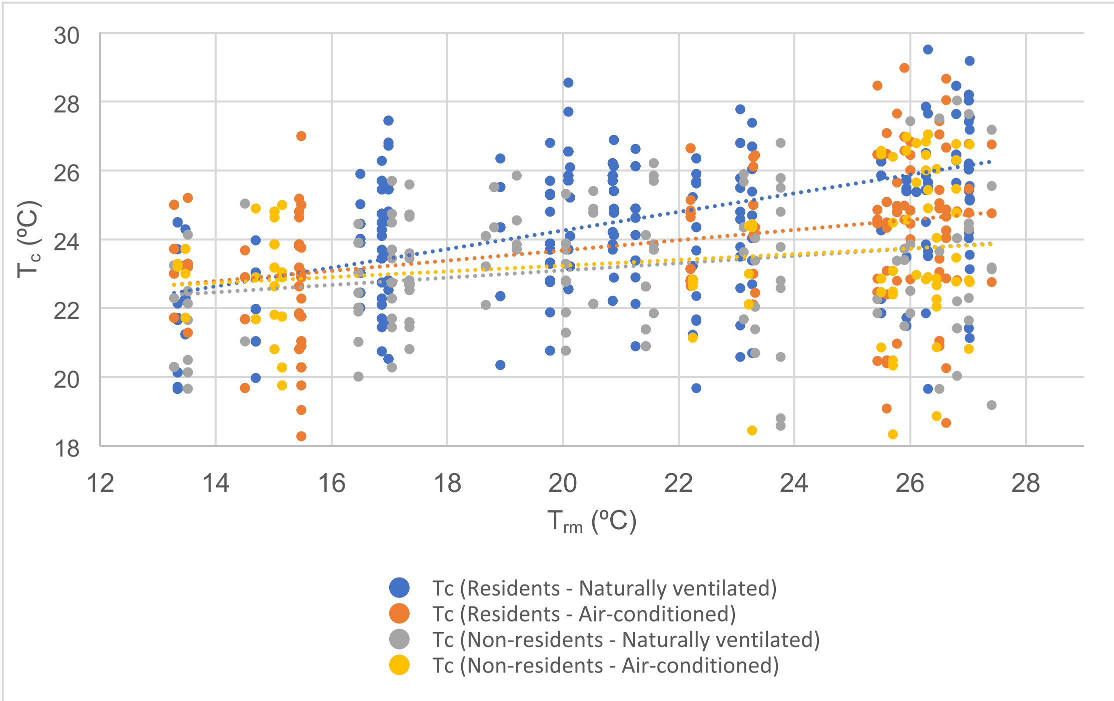

Fig. 7. T_c vs T_{rm} for both naturally ventilated and air-conditioned rooms for both residents and non-residents.

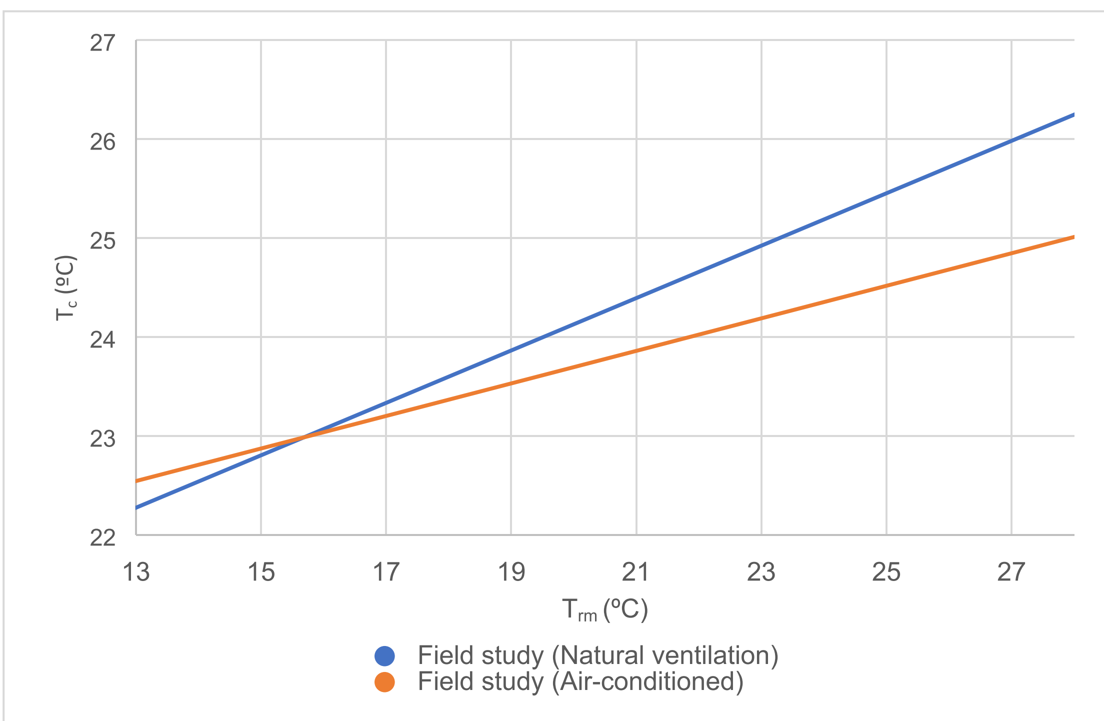

Fig. 8. Adaptive thermal comfort models for residents for naturally ventilated and air-conditioned rooms.

rooms are less sensitive to outdoor conditions and comfort temperature remains fairly constant along the different seasons.

For running mean outdoor temperatures higher than 21.7 °C, the air-conditioned comfort model for residents did not fulfil EN 15251:2007 lower limit but EN 16798:2019. Regarding the most appropriate comfort temperature, ASHRAE 55:2020 remains the most rational choice.

Field data confirmed that air-conditioned buildings are often operated at much cooler temperatures than comfortable. In Spain, the typical design temperatures are set between 21 °C and 23 °C

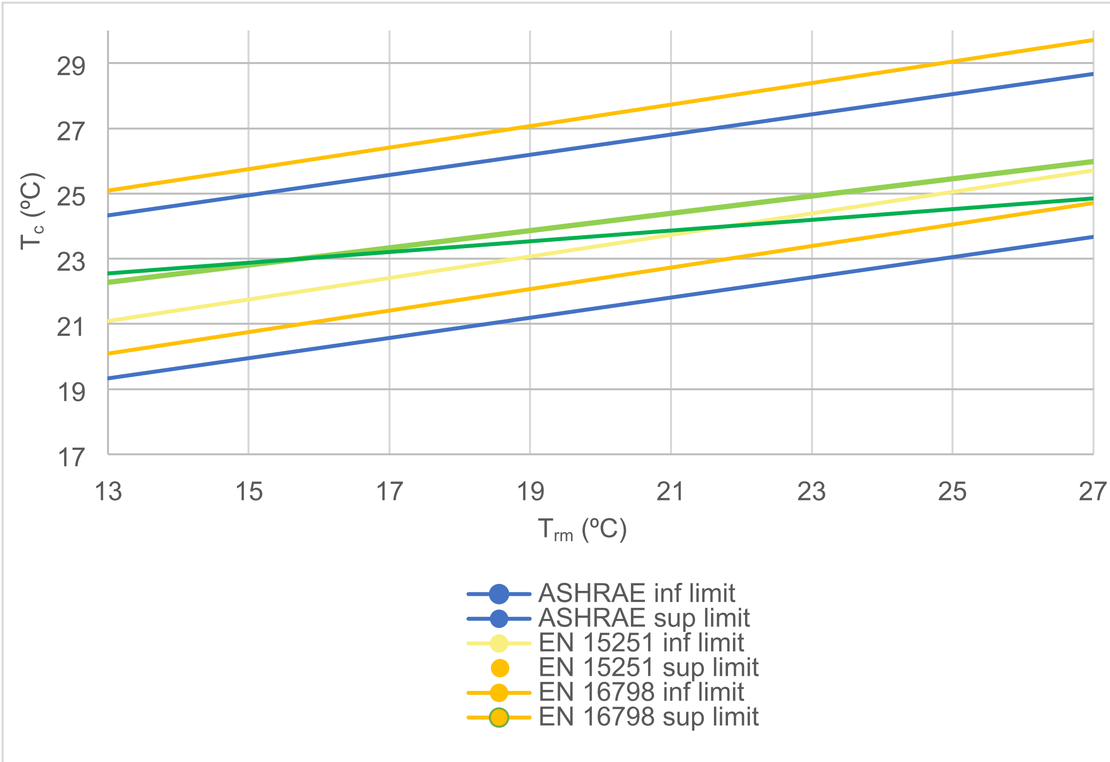

Fig. 9. Comparison of the adaptive thermal comfort model and the models from existing standards.

and 40% to 50% relative humidity in winter while 23 °C to 25 °C and 45% to 60% in summer [45]. This adaptive thermal comfort model for nursing homes will allow adapt setpoint temperatures within these ranges with the consequent reduction of cooling use.

Note that while the current study uses the running mean temperature to represent the outdoor conditions, the ASHRAE 55:2020 refers to outdoor running mean temperature as prevailing mean outdoor air temperature.

4. Discussion

The results of this study showed that residents have lower thermal sensitivity than non-residents which might be attributed to both physiological debility with aging [21] and psychological factors such as lower comfort expectations or avoiding expressing discomfort to caregivers to be engaged with them [23 46]. Previous field studies on nursing homes also found differences in thermal sensitivity with elderly preferring higher temperatures [282947].

The Building Operation Mode was found to be decisive on the thermal adaptation of residents [48]. In fact, in natural ventilation building occupants adapt and utilize several available measures such as windows, fans or clothing adjustment to make the conditions more comfortable for them [30]. However, in common zones of nursing homes windows are centrally controlled and no fans are installed. Therefore, clothing adjustment and adaptation of the physical activity are the most important adaptive strategies for residents [31].

The adaptive thermal comfort model for residents under the natural ventilation operation mode (T_c = 0.26 T_{rm} + 18.83) was found to be within the limits set by ASHRAE-55:2020, EN 16798:2019 and EN 15251:2007 but with a lower slope. However, the comfort temperatures obtained by Jiao et. al [32] T_c = 0.840-T_{rm} + 6.935) were much lower than the comfort temperatures predicted by the EN15251:2007 model and the ASHRAE-55:2020 while the thermal sensitivity was higher. Outdoor extreme conditions of Jiao et. al [32] study might influence this result. In fact, climate is found to be an influential factor of indoor comfort temperature [14]. For naturally ventilated buildings, the comfortable temperature increases in warmer climates, and decreases in colder climate regions [15]. Thus, specific adaptive comfort models for different climates need to be further explored.

For the air-conditioned building operation mode, a significant (R^2 = 0.91) adaptive thermal comfort model was obtained (T_c = 0.16-T_{rm} + 20.41) confirming that air-conditioned buildings can be operated using adaptive thermal comfort models.

In the case of those air-conditioned rooms the slope of the thermal comfort model for residents (T_c = 0.16T_{rm} + 20.41) confirmed that air-conditioned rooms are less sensitive to outdoor conditions.

Current nursing homes owners and facility managers in Spain focus on maintaining setpoint temperatures (around 23 °C in winter and 25 °C in summer) [49] by using heating or cooling. The results of this study and the research literature on adaptive thermal comfort suggest that accommodating the natural adaptability of occupants within the building operation mode imply a reduction of energy consumption in HVAC. More than 30% HVAC energy savings can be obtained by adapting setpoint temperatures to adaptive comfort temperatures [50]. Adapting the use of heating and cooling to outdoor conditions is then a viable solution to both occupants comfort and energy efficiency [51]. The different building operational modes can be selected by a building management system (BMS) using real outdoor and indoor environmental data.

Moreover, considering the climate change, the implementation of thermal adaptive models in the Mediterranean climate can greatly reduce energy consumption due to HVAC [5253].

The adaptive thermal comfort models obtained in this study can be implemented easily in nursing homes by implementing HVAC control systems and adapting setpoint temperatures to outdoor conditions. However, the results of this study highlight significant thermal comfort variations between residents and non-residents. Therefore, adaptive measures such as clothing or activity adaptation both for residents, therapists or caregivers, might be a good solution when both groups of occupants coexist in the same rooms.

Nevertheless, adaptive thermal comfort models for non-residents couldn't be obtained due to the low sample size of therapists and caregivers. In a nursery home there are always less therapists and caregivers than residents. Therefore, the proportion in whatever study will be similar to the one presented in this analysis. Future steps will include analysing a bigger sample size of non-residents.

Another limitation is related to the climate. Adaptive models depend on the climate and outdoor conditions. Therefore, this study is only applicable to nursing homes of the Mediterranean climate. Future steps include analysing the thermal comfort of elderly in other climates such as the continental or Atlantic climates

5. Conclusion

The aim of this study was to develop an adaptive thermal comfort model for elderly people and check the applicability of existing standard for nursing homes' occupants in both naturally ventilated rooms and air-conditioned rooms.

Following results were observed.

- This study demonstrated that residents have a lower thermal sensitivity than non-residents. For naturally ventilated rooms the neutral temperature for residents was found to be 22.7 °C, higher than the obtained for non-residents (21.8 °C) indicating that elderly prefer higher indoor temperatures.
- This study also demonstrated that elderly adapt most strongly to prevailing indoor temperatures in naturally ventilated rooms than in air-conditioned rooms. Considering the thermal adaptation of residents within naturally ventilated rooms, the use of cooling systems might be reduced in favour to natural ventilation, resulting with a less energy consumption through air conditioning.
- We developed an adaptive comfort model for naturally ventilated rooms (T_c (naturally ventilated) = 0.26 T_{rm} + 18.83 (R^2 = 0.81)) and for air-conditioned rooms T_c (air-conditioned) = 0.16T_{rm} + 20.41 (R2 = 0.91)). The slope of the naturally ventilated comfort model was more similar to ASHRAE's adaptive model (0.31) than the slope of the air-conditioned comfort model. This study manifest that the adaptive comfort model is applicable both in naturally ventilated rooms and in air-conditioned rooms.
- This study confirmed that the ASHRAE 55:2020 adaptive model with a 90% of acceptance is valid in approximating occupants' comfort response in naturally ventilated rooms for residents in nursing homes using prevailing outdoor conditions in the Mediterranean climate. However, the comfort temperatures obtained from the field study were in the lower band of the proposed ranges defined by the ASHRAE 55:2020 model and the EN 16798:2019 and EN 15251:2007.
- For non-residents (caregivers and therapists) no significant model was obtained. Future analysis will enlarge the sample size of non-residents to develop an adaptive model for this group of occupants within the nursing homes.

This analysis will allow to determine adaptive measures of clothing and level of activity together with adapting setpoint temperatures acceptable to both groups of occupants.

These findings carry significant implications for regulatory bodies to develop guidelines to design and operate nursing homes. Current findings support a modification of HVAC design and operation standards, which should permit the use of the adaptive models for air-conditioning and naturally ventilated buildings to improve occupant's comfort and well-being. The use of these adaptive thermal comfort models can significantly reduce energy consumption in nursing homes.

In conclusion, the results of this study reveal that it would be possible to implement adaptive models in nursing homes that optimize the operation of conditioning systems and which would lead to greater energy efficiency in buildings without compromising occupant comfort.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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