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Unlocking thermal comfort in transitional spaces: A field study in three Italian shopping centres

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ABSTRACT

Shopping centres are commonly laid out as small individual stores connected by transitional spaces. Setpoint temperatures used to control transitional spaces are normally the same as in traditional indoor environments despite substantial differences in use, time of permanence and users' needs. Currently, there are no comfort guidelines for transitional spaces and the literature lacks relevant studies on the topic. There is an untapped potential for energy savings and improved indoor environmental quality. The main objective of this work is to evaluate the suitability of Fanger's comfort model and adaptive comfort model for transitional spaces. We assessed users' thermal perception and potential impacting factors in three Italian shopping centres. 724 customers were interviewed on their thermal comfort, thermal sensation, thermal preference, and clothing level while experiencing the transitional space. In addition, the thermal environment at the interview locations (dry-bulb temperature, globe temperature, relative humidity, and air speed at different levels) and the outdoor temperature were monitored. The study demonstrated that Fanger's model and the adaptive comfort model are not suitable for transitional spaces. Customers were inclined to adapt to a much wider range of indoor environmental conditions. An operative temperature of up to 27.5 °C was still deemed comfortable by more than 80% of the customers. These results unlock a large potential for energy savings and pave the way for passive solutions such as natural ventilation.

1. Introduction

Large shopping centres are based on a model of small individual stores connected by common areas that enable customers to move from a shop to another without exiting the centre. They can be shaped as gallery, atrium or ring and can be located on a single level or connect multiple levels.

The number of people in the common areas varies during the day. Observed users' activity is dynamic and the time of permanence differs, which creates highly variable occupancy.

Shopping centres are normally conditioned by an all-air HVAC system that handles both the individual stores and retail units or using an individual system per each retail unit. In either case, the temperature setpoints inside the single shops are controlled by managers, workers, or according to brand policies. Most of the time this results in temperatures that are different from the common areas, which exposes customers to several rapid changes in thermal conditions.

Moreover, indoor temperatures are generally controlled independently from outdoor conditions. Implemented setpoints are typically based on guidelines intended for other indoor environments or on the experience of the facility manager. The customers' clothing and their activity are not (or cannot be) taken into consideration and sometimes results in uncomfortable conditions or inefficient energy management. Due to their unique features, common areas may not require the same

Abbreviations: MEMO, Mobile Environmental Monitoring; PMV, Predicted Mean Vote; PPD, Predicted Percentage of Dissatisfied; TAV, thermal acceptability vote; TCV, thermal comfort vote; TPV, thermal preference vote.

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tight control as other indoor environments. A wider range of setpoints may still provide or even improve comfort.

Thermal comfort research traditionally focuses on either the indoor or the outdoor environment. Little has been discussed in previous work about people's thermal perception and comfort in indoor transitional spaces[1] with transient and dynamic conditions. Table 1 collects studies related to thermal comfort in transitional spaces in the last fifteen years. Only field studies have been included in the table because they are representative of the specific conditions in the transitional spaces. However, we briefly report on important findings from studies conducted in more strictly controlled environments such as labs and climate chambers. Zhang et al. [1] analysed psychological and physiological responses from thirty college students subjected to step changes of neutral-warm and neutral-cool in a climate chamber consisting of two adjacent rooms in China reproducing a hot-humid climate. As acceptable upper limits for transitional spaces and people naturally acclimatized to such a climate, air temperatures of 29.2 °C at 50% relative humidity and 28.0 °C at 70% relative humidity for 90% satisfied were reported. Despite the challenge to represent natural movement of people in transitional spaces within such a controlled environment, this study shows the high adaptation potential of people accustomed to a specific climate.

The common methodological approach is to combine objective measurements with subjective questionnaires. Most of the studies were conducted in the UK [4,8,10,11,13] and in the south-east of Asia [2,5–7,12,14–16]. No studies were found concerning transitional spaces in Southern Europe except for three papers focusing on the same hypermarket in Bari, Italy. In the first paper [17], the authors perform physical measurements as well as administer IEQ questionnaires to over 300 workers in the hypermarket. They found that Fanger's model [20] was less suitable to describe the thermal sensation in the naturally ventilated warehouses than in air-conditioned areas. Therefore, they suggested to investigate more suitable indexes for these environments. In the second paper by the same authors [18], they included further data collected after their earlier paper and investigated the influence of clothing distribution and local discomfort on the Fanger model's accuracy. As these studies focused on specific aspects, no upper limits for acceptable thermal conditions in such spaces during the hot season were reported. In the third paper [19], statistical techniques were applied to the data to derive, through a multiple regression, 'optimal ranges' for thermal conditions considered satisfactory by the workers, namely 13.7–21.8 °C (17.2–22.8 °C) in winter (summer) for operative temperature and 16.4–30.3 °C for floor temperature. The low operative temperature range for summer derived from the regression was lower than the measured values and may be due to the workers' activities, clothing, and individual preferences, and possibly the statistical method used, among potential other factors. Another paper dealing with transitional spaces in Southern Europe is the one of Albuquerque et al. [21]. I this case the focus was more on control strategies during closing time and related energy savings more than users' thermal comfort.

All above studies refer to Fanger's model and do not consider the adaptive thermal comfort model [22].

Most of the studies [2–4,7,8,11,14,16,12] concluded that people in transitional spaces can accept a wider range of comfort conditions than predicted by Fanger's model. In their view, the limitation of Fanger's model lies in the steady-state conditions under which it was developed, whereas transitional spaces have dynamic features making Fanger's model unsuitable. Some studies [8–11] also observed that users in transitional spaces have a higher adaptability, which might be influenced by the time spent within the transitional space and the previous thermal experience. All these studies concluded that further investigation on thermal comfort in transitional spaces at different times of the year is required to expand the database of evidences.

Current comfort standards do not specifically address transitional spaces, which are therefore treated by energy managers like other indoor environments (e.g. offices) [6]. According to Pitts and al. [4], the energy demand of transitional spaces per unit area or volume is three times that of the remaining of the building interior, and past studies [4,7–10] identified a high energy use intensity of transitional spaces for heating and cooling and thus a great energy saving potential linked to more relaxed setpoint settings.

The main objective of this work is to evaluate the suitability of Fanger's model and adaptive comfort model for transitional spaces. We also investigated the interrelationship of users' thermal acceptability, comfort, and preference as well as the range of operative temperatures considered comfortable by most users.

2. Methods

We conducted a field study in three Italian shopping centres in spring and summer 2016. Detailed outdoor and indoor environmental monitoring was performed while the customers were asked to complete a dedicated questionnaire on their perception over the indoor parameters. 724 customers answered questions about thermal comfort, thermal sensation, thermal preference, and clothing while being in a common area of the shopping centre.

2.1. Environmental monitoring

The measurement campaign considers the monitoring of both indoor and outdoor environmental variables as described in the following sections.

2.1.1. Indoor environmental monitoring

For this study, a cart named MEMO (Mobile Environmental MOnitoring) was made in the Eurac Research labs. MEMO can be easily moved on a flat floor and the height of the sensors can be modified as needed. MEMO was equipped with a globe thermometer and hygrometer to respectively measure globe temperature and relative humidity at 1.1 m above the floor. Sensors were placed at 1.1 m and 1.6 m to monitor air speed and dry bulb temperature (see Fig. 1).

The accuracy of the sensors meets the recommendations of the European standard EN ISO 7726 [23]. Air temperature is measured using radiation shielded Pt100 sensors. To measure the globe temperature, a 40 mm globe thermometer was built from a ping-pong ball painted in grey on the inside and opaque black on the outside. This setup closely approximates the operative temperature for limited air speed for indoor applications [24,25]. The mean radiant temperature was determined from the globe thermometer measurement as per European standard EN ISO 7726 [23]. Omnidirectional hot wire sensors were used to measure air speeds at the two heights. Indoor relative humidity was measured with a portable probe. All thermal parameters where measured and recorded every 10 s. Table 2 presents the characteristics of the used sensors.

Indoor measurements were performed in several locations within the building, mainly atriums and galleries between more frequented shops. Areas with direct sunlight were limited in the three case studies and anyway never used for the measurements.

2.1.2. Outdoor environmental monitoring

Outdoor dry bulb air temperature and relative humidity were measured every 10 s. To this aim, we used a MEMS (Micro-Electro-

[1] Referring to shopping centres, transitional spaces are all those conditioned areas open to the public that are within the building but are not the shops. It is the connection area between the different shops, which is made by elements like atriums, corridors, entrance, where customers can pass through or rest or do other activities while in the shopping centre. As expressed by Pitts et al. [4], these spaces are often perceived as some of the most important in architectural design terms since they also impact on a wide range of senses and perceptions of human occupants.

Table 1
Field studies related to transitional spaces.

Author	Building type	Research method	Location	Year	Ref.
Jitkhajornwanich et al.	Educational building Office	Questionnaire Physical measurements	Bangkok, Thailand	2002	[2]
Chun et al.	Lobbies, balconies, pavilions	Physical measurements (long & short term) Observation (activities)	Yokohama, Japan	2004	[3]
Pitts et al.	Educational buildings	Questionnaire Physical measurements	Sheffield, UK	2008	[4]
Hwang et al.	Entrance Atrium Service centre	Questionnaire Physical measurements	Taichung, Taiwan	2008	[5]
Kwong et al.	Lobby Educational building	Questionnaire Physical measurements CFD simulations	Serdang, Malaysia	2009	[6]
Hui and Jie	Lift, lobbies, corridors Educational building	Questionnaire Physical measurements Energy simulation tool	Hong Kong	2014	[7]
Kotopouleas A., Nikolopoulou	Airport terminal	Questionnaire Physical measurements	Manchester London, UK	2016	[8]
Mishra et al.	Museum	Questionnaire Physical measurements	Amsterdam, Netherlands	2016	[9]
Vargas	Lobby	Questionnaire Physical measurements	Sheffield, UK	2016	[10]
Hou	Atria, educational buildings, business centre	Questionnaire Physical measurements	Cardiff, UK	2016	[11]
Li et al.	Underground malls	Questionnaire Physical measurements	Nanjing, China	2018	[12]
Tse et al.	Shopping centre	Questionnaire Physical measurements	Cardiff, UK	2019	[13]
Du et al.	Shopping mall	Questionnaire Physical measurements	Beijing, China	2020	[14]
Kwok et al.	Shopping centre	Questionnaire	Hong Kong	2017	[15]
Pin Lu, Jin Li	Commercial building	Questionnaire Physical measurements	Guangzhou, China	2020	[16]
Martellotta et al.	Supermarket	Questionnaire Physical measurements	Bari, Italy	2012-2013-2016	[17–19]

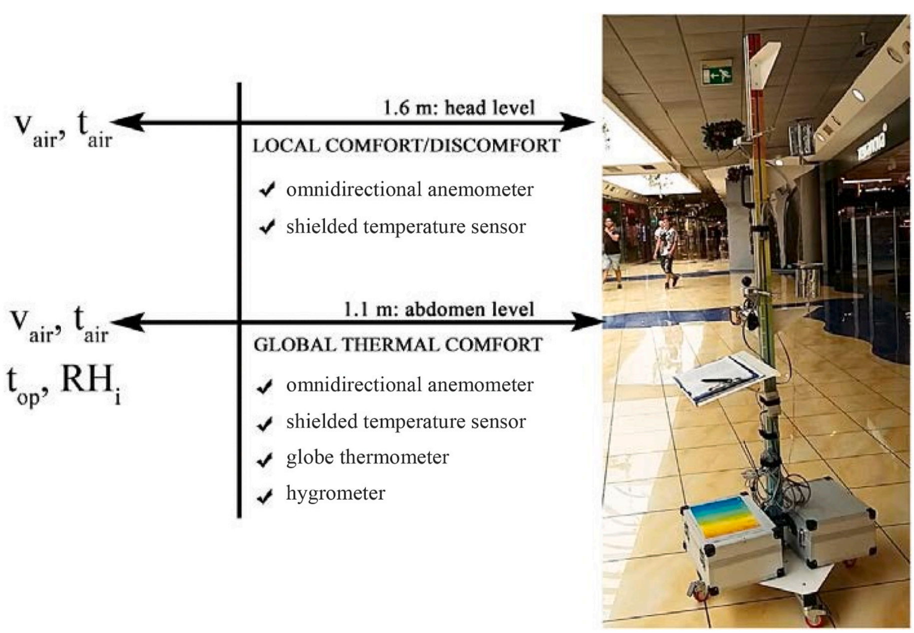


Fig. 1. Mobile environmental monitoring cart “MEMO” and parameters measured at different levels.

Mechanical Systems) integrated portable data logger whose features are listed in Table 3. Measurements were performed in outdoor parking areas of the three shopping centres.

2.2. Interviews

Customers passing by our equipment were randomly asked to participate in an interview. We filled their answers in a questionnaire structured into three main sections: background, thermal comfort, and clothing.

- **Background** - general questions about age, gender, health conditions, if they had eaten or drunk, and their previous activities.

Table 2
Measured indoor environment parameters and sensor characteristics.

Parameter	Sensor	Measuring range	Accuracy
Air temperature	Pt100 class A Radiation-shielded	−50 to 150 °C	±0.2 °C (−25 to 74.9 °C)
Mean radiant temperature	Pt100 class A and 40 mm diameter globe	−50 to 150 °C	±0.2 °C (−25.0 to 74.9 °C)
Air speed	Hotwire omnidirectional anemometer	0.05–5.0 m/s	0.02 m/s + 1.5% of reading
Relative humidity RH% (at ambient pressure)	EE08 series HC101 sensor	0–100%	±2% RH (0–90% RH) ±3% RH (90–100% RH)

Table 3
Measured outdoor environment parameters and characteristics of the MEMS integrated portable data logger.

Parameter	Sensor and brand type	Measuring range	Accuracy
Outdoor temperature	MEMS integrated portable data logger	−30.0 to 70.0 °C	±0.5 °C
Outdoor relative humidity	MEMS Integrated portable data logger	0–100%	±2%

Customers were also asked about the duration of their stay inside the building before taking the survey.

- **Thermal comfort** - customers were asked about their vote on thermal acceptability (TAV), sensation (TSV), preference (TPV), and comfort (TCV) while spending time in the common area. Thermal acceptability was assessed on a 2-point scale (acceptable or not acceptable). For thermal sensation, a 7-point scale was used according to PMV (Predicted Mean Vote) from −3 to +3 corresponding to the categories "cold," "cool," "slightly cool," "neutral," "slightly warm," "warm," and "hot". Thermal preference was surveyed using a 3-point scale: "right now I want the environment to be: cooler, no change, warmer". Thermal comfort was evaluated on a 6-point scale (very comfortable, comfortable, just comfortable, just uncomfortable, uncomfortable, and very uncomfortable) [26].
- **Clothing -** we asked the interviewees to report their clothing to estimate the thermal resistance according to the EN ISO 7730 standard [27]. Physiological parameters were not measured.

2.3. Case studies

The measurement campaigns were conducted in the transitional spaces of three Italian shopping centres. The main features of the shopping centres and climates according to the Köppen-Geiger classification [28] are presented in Table 4.

The first two centres (SC01 and SC02) are in the municipality of Trento in the north of Italy and the third centre (SC03) is in Catania in the south of Italy. Trento has a temperate, fully humid climate with hot summers (Cfa) whereas the climate of Catania is Mediterranean with dry, hot summers (Csa).

The first measurement campaign was conducted in SC1 on April 4th-6th and June 10th, 2016. The shopping centre was built in 2000 and has a floor area of 9′774 m^2 laid out over two floors with a total of 55 retail units. The common areas are mainly shop galleries. The main entrance atrium has a fully glazed, south-west-oriented façade coated with a sun control film. The field study was performed in different locations within the common areas including shop galleries and atria on the ground and first floor.

The second measurement campaign in SC02 was performed on June 21st - 22nd, 2016. The total floor area is laid over three floors with a total of 47 retail units. The common areas are mainly shop galleries. The main entrance is an atrium with a fully glazed, south-east oriented façade. The field study was performed in different locations within the shop gallery on the first floor.

The last measurements were conducted in Catania on six days between July 13th and 20th, 2016. SC3 was built in 2009 and contains a two-storey gallery with over 60 retail units, offering a gross leasable area of 27′521 m^2 of which 8′000 m^2 are dedicated to a hypermarket. The main building façade is oriented towards south-east. The field study was performed in different locations within the shop gallery at the second floor.

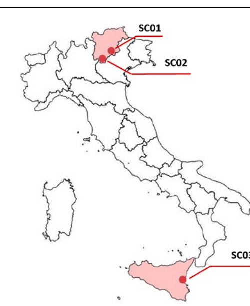
Before the measurement campaigns we had a one-day pilot study in August 2015 in SC1 to configure the monitoring devices, test the survey and refine the interview process.

2.4. Data analysis

A total of 724 randomly selected customers where interviewed on a voluntary basis during the three measurement campaigns. After a brief explanation about the content of the study, they could decide to be part of it or not. All interviews were included in the sample, also those resulting from customers who have eaten or drunk in the previous 20 min before the questionnaire. This to have a better representation of typical shopping centre customers, who are used to drink coffee or eat ice cream before or while shopping.

The survey results were compared against Fanger's model [20] and the adaptive comfort model. Fanger's model was considered because transitional spaces are typically mechanically conditioned. However, due to their peculiar conditions and use we decided to also evaluate the adaptive model suitable for free-running or naturally ventilated buildings. Specifically, we refer to the method presented by Nicol and

Table 4
Characteristics of the three shopping centres.

Shopping centre	Typology [29]	Municipality	Size [m^2]	Number of shops	Climate	Floors	Average time of permanence	Map
SC01	neighbourhood centre	Trento	9774	55	Cfa	2	25min - 1 h	
SC02	community centre	Trento	6898	40	Cfa	3	20min - 1 h	
SC03	super regional centre	Catania	27,521	70	Csa	2	25min - 1.5 h	

Humphreys [30] and included in the European standard EN 16798–1: 2019 [31].

Using data collected by the monitoring cart (MEMO) and the clothing ensembles recorded during the interview, it was possible to calculate PMV and PPD (Percentage of People Dissatisfied) for the indoor conditions experienced by the customers during the time they took the survey. The metabolic activity was assumed equal to 1.6 met (shopping) for all customers [27]. The R package "comf" [32] was used for the PMV-PPD calculation.

Because of the nature of the seven-point scale used to assess customers' thermal sensation, the TSV is a categorical variable, which is not directly comparable with a continuous variable such as the PMV. A direct comparison between TSV and PMV is however commonly done with a binning of the PMV by setting all values lower or equal −2.5 to −3, higher than −2.5 and lower or equal −1.5 to −2, and so on. This binning was realized with the function "cutTSV" of the R package "comf" [32].

Since we recorded outdoor conditions only during the measurement campaigns, data coming from weather stations located closer to the three case studies [33] were used to calculate the mean running temperature.

The evaluations of the thermal environment using the two thermal comfort models were compared with the real customers' satisfaction votes coming from the surveys.

In a second phase, customers perception of the thermal environment was deeply investigated by analysing their answers in connection with experienced indoor and outdoor parameters.

3. Results

3.1. Descriptive statistics

We were able to obtain an even distribution across case studies in terms of gender and age. 59% of the interviewees were female, 44% were less than 30 years old, 33% were between 31 and 50 years old, and 23% were older than 50.

Fig. 2 shows the distribution of the time of permanence by case study as indicated during the interviews. Looking at the total sample, 33.7% of the interviewees indicated less than 10 min of permanence, 26.8% had spent a period between 10 and 20 min, and 39.5% were inside the shopping centre for more than 20 min.

39% of respondents had drunk and 21% of respondents have eaten in the previous 20min. On the attempt to represent the entire population of shopping centre customers, in the following analysis we decided to consider the whole sample regardless of the time of permanence and the activities they were carrying on 20min before the interview.

Table 5
Indoor and outdoor environmental conditions for the three case studies. For each shopping mall, Mean, SD, Min, and Max denote the arithmetic mean, standard deviation, minimum value, and maximum value, respectively, of all measured values.

		Indoor			Outdoor		Average clothing level
		$T_{operative}$ (°C)	V_{air} (m/s)	RH (%)	$T_{dry\ bulb}$ (°C)	RH (%)	Clo
SC01	Mean	25.1	0.12	48	24.3	43	0.64
	SD	0.9	0.06	7	2.1	7	0.2
	Min	22.9	0.00	59	19.4	31	0.18
	Max	26.7	0.33	33	29.5	55	1.41
SC02	Mean	25.3	0.12	48	30.8	40	0.45
	SD	0.5	0.08	2.9	1.3	2	0.1
	Min	24.4	0.00	43	28.5	35	0.23
	Max	26.3	0.40	53	32.6	46	0.85
SC03	Mean	26.1	0.14	42	30.1	42	0.38
	SD	1.1	0.08	3	1.7	14	0.1
	Min	21.7	0.00	33	27.4	17	0.22
	Max	29.6	0.41	49	34.6	62	0.67

3.1.1. Indoor conditions

Table 5 shows basic descriptive statistics about the indoor and outdoor conditions in the three case studies during the measurements, as well as the average clothing level of the customers' interviewed. The operative temperatures recorded during the measurement campaigns ranged between 21.7 °C and 29.6 °C. Both extreme values of the range were recorded in SC03. Indoor relative humidity ranged between 33% and 59%. The air speed measurements generally showed very limited values typical of mechanically ventilated buildings. Outdoor dry bulb air temperature during interviews ranged between 19.4 °C and 34.6 °C. The lowest value was measured in SC01 during the mid-season campaign (April 2016) while the highest was recorded in SC03 in July 2016.

In SC01, the measurements took place in April and June. This justifies an average value of clothing higher than for SC02 and SC03 where the measurements were performed only in summer. The clothing level was often lower than 0.50 clo, which is the value used to estimate comfort temperatures under summer conditions [27].

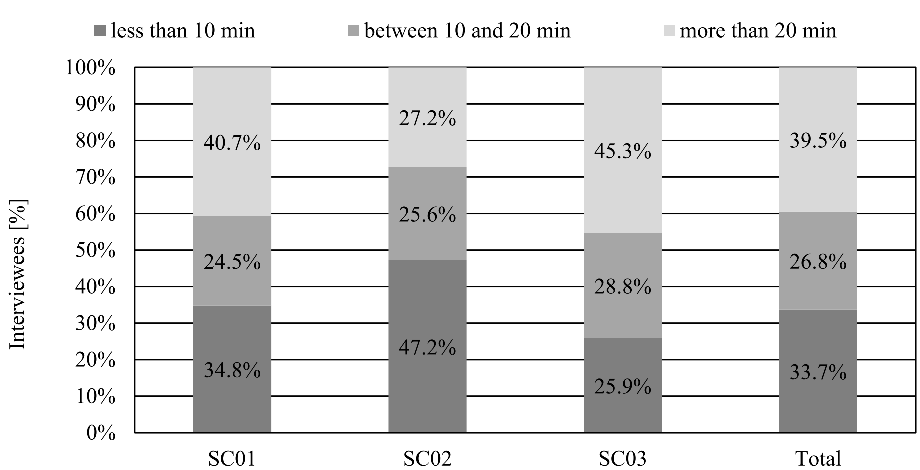


Fig. 2. Time of permanence within the three case studies and in total.

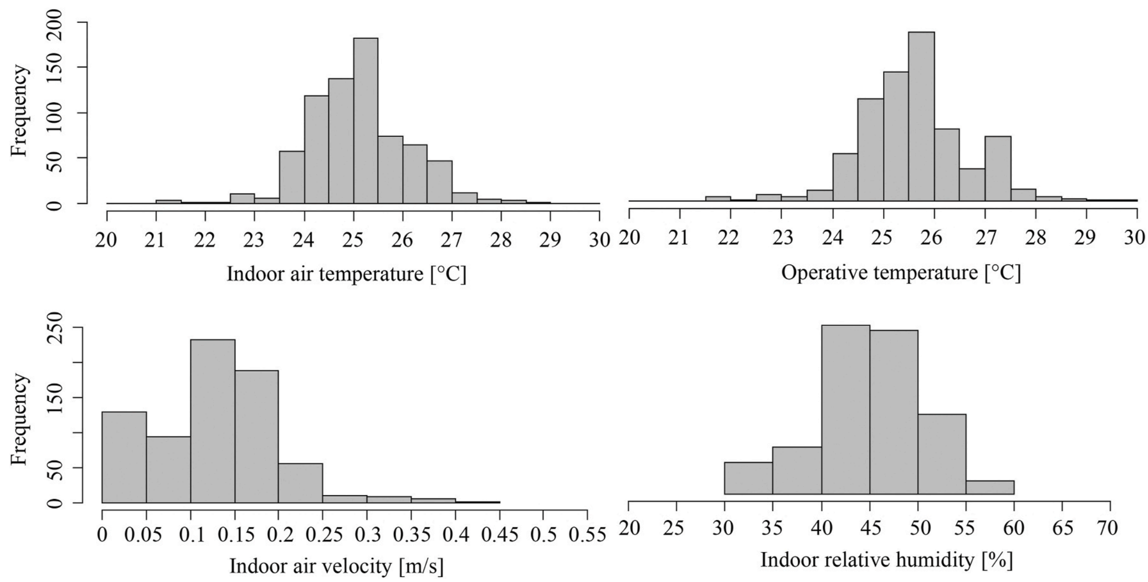


Fig. 3. Frequency distribution of the indoor parameters measured during the three campaigns: air temperature, operative temperature, indoor air velocity and relative humidity.

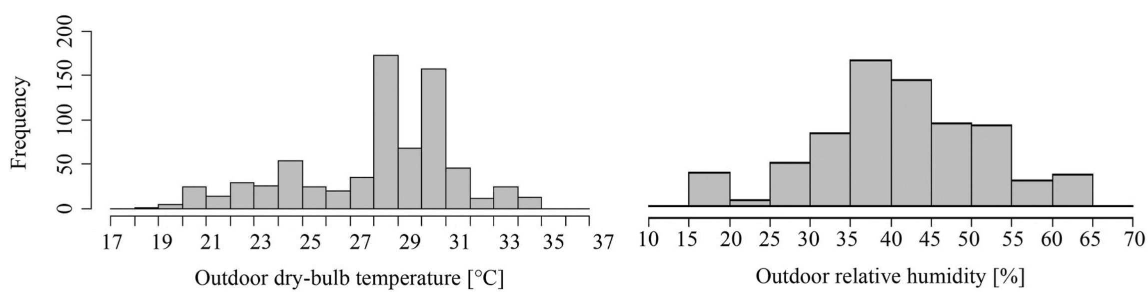


Fig. 4. Frequency distribution of the outdoor parameters measured during the three campaigns: dry-bulb temperature and relative humidity.

The data collected in the three shopping centres were aggregated to investigate the frequency distribution of the main environmental parameters. Fig. 3 reports the frequency distributions of the indoor parameters, while Fig. 4 shows the ones of the outdoor parameters.

The highest frequency of outdoor dry-bulb temperature distribution ranges between 28 °C and 31 °C (around 45% of the time). The indoor air temperature frequency distribution is centred between 24.5 °C and 25.5 °C, accounting for around 45% of the total. The highest frequency of the operative temperature distribution ranged between 25 °C and 26 °C, accounting for around 47% of the total. Most of the measured indoor air velocities were lower than 0.25 m/s. Measured indoor relative humidity is normally distributed with peak between 40% and 50%. Finally, the difference among the outdoor relative humidity distribution was relatively small, with the highest frequency ranging from 35% to 45%.

The distribution of indoor air temperatures is slightly different from the distribution of the operative temperatures. This is due to the radiant effect of internal gains such as lights and the effect of solar radiation passing through the wide glazed façades that characterize shopping centre transitional spaces.

The measurements were performed in both mid-season and summer conditions. This is the cause of the negative values of the outdoor-indoor temperature difference visible in Fig. 5.

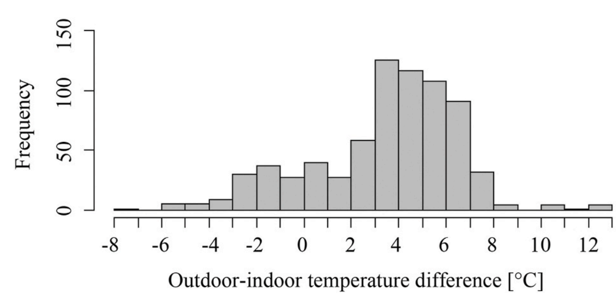


Fig. 5. Frequency distribution of the difference between outdoor and indoor temperature during the three campaigns.

3.2. *Investigation of customers' perception of the thermal environment*

In the following sections, the distribution of the customers' answers related to thermal acceptability (TAV), comfort (TCV), and preference (TPV) are presented and discussed.

Fig. 6 shows the interrelationship between thermal acceptability, comfort, and preference. Data related to a TSV equal to −3, −2, or 3 were removed because the number of respondents per each such TSV was less than 10.

Focusing first on the number of interviewed people, most people

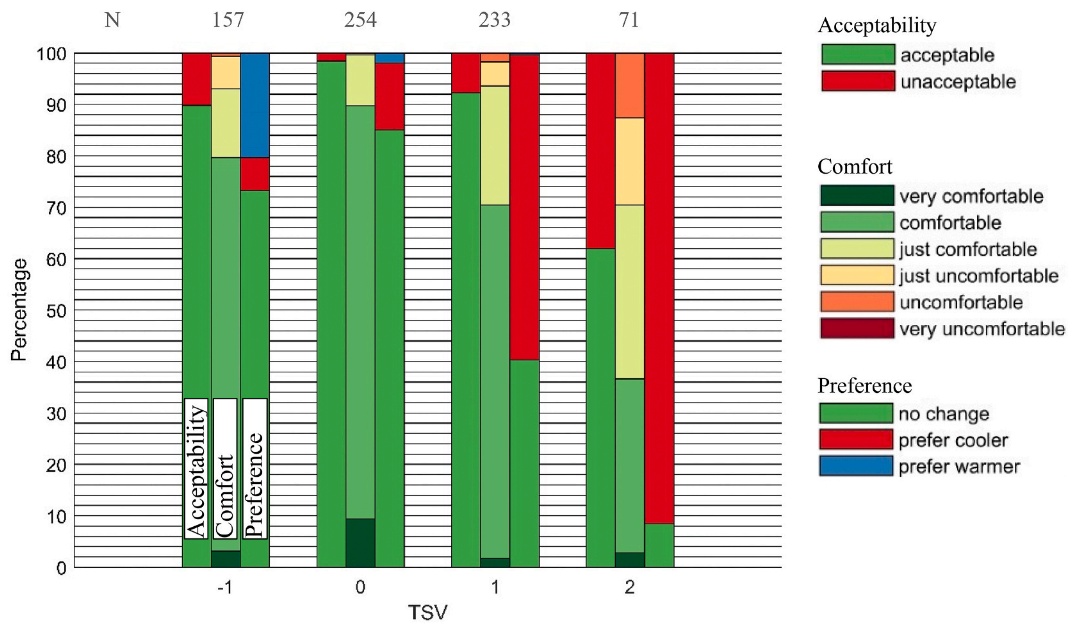


Fig. 6. Per each thermal sensation vote it is presented "Acceptability", first bar, "Comfort", second bar, and "Preference", third bar. On top, the number of responses per each TSV are reported.

reported a TSV between −1 (slightly cool) and 1 (slightly warm). More than 50 people reported a TSV of 2 (warm). Only very few people reported TSVs of −3, −2, or 3. Most people considered the environment thermally acceptable and comfortable. Nevertheless, when asked for their thermal preference, most people indicating a TSV of −1 or 0 stated that they would prefer a cooler environment. Expectedly, some people indicating a TSV of −1 or 1 stated that they would prefer a warmer or cooler environment, respectively.

Looking at the percentages, the strong link between thermal acceptability, comfort, and preference becomes clear, but important differences are observed as well. Acceptance is less difficult to achieve than the ensemble of "comfortable" and "very comfortable" conditions, and comfort is less difficult to achieve than a "no change" preference. The target "just comfortable" or a higher level of comfort is achieved in more cases than thermal acceptability, but the difference in the number of people between "acceptable" and "just comfortable" or a higher level of comfort is rather small, i.e., only very few people might state that the environment is "unacceptable" but nevertheless "just comfortable".

The strong link between acceptability, comfort, preference, and sensation also indicates a high coherence in the customers' answers.

To investigate the tolerance to a range of operative temperatures, thermal sensation votes were grouped into three categories.

- TSV (−1,0,1) stands for customers that are satisfied with the thermal environment.
- TSV (−3,-2) stands for customers that are cold dissatisfied
- TSV (+3,+2) stands for customers that are warm dissatisfied.

By grouping the thermal sensation votes in this way, for each

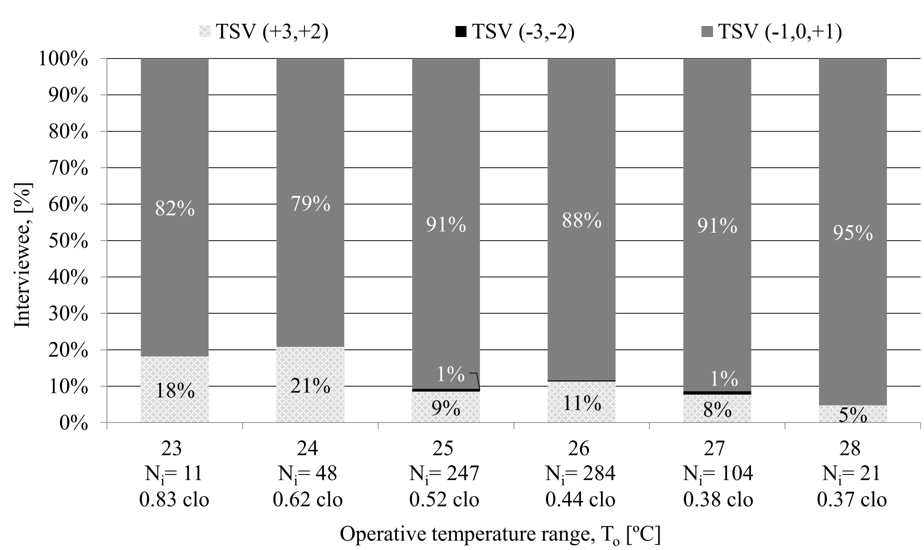


Fig. 7. Bar chart of the distribution of thermal sensation over operative temperature intervals [°C].

operative temperature interval, it was possible to identify the reason that generates discomfort (too cold or too warm).

A general satisfaction with the environment is observed, from 23 °C up to 28 °C (Fig. 7). A great tolerance to a wide range of operative temperature is hence demonstrated. During only three interviews the operative temperature was higher than 28.5 °C and the environment was perceived as too warm.

3.2.1. Customers thermal comfort

The customers were asked to rate their general state of comfort using a six-point scale. The results are reported in the bar chart in Fig. 8.

For most operative temperature intervals, people expressed their vote at the "just comfortable" to "very comfortable" side of the scale.

The results presented in Fig. 8 suggest that customers judge as comfortable a wide range of indoor operative temperatures. This result is in line with previous findings about acceptable temperatures in transitional spaces [2–4,7,8,11].

3.2.2. Generalizability of results

To assess whether these results are generalisable to the target population of shopping centre customers, we considered the interviews conducted within each operative temperature interval as separate trial with two possible outcomes per interview: (thermally) "comfortable" with probability p for answers "very comfortable" to "just comfortable" and (thermally) "uncomfortable" with probability 1-p for answers "just not comfortable" to "very not comfortable". The objective was to show that at least 80% of the customers were satisfied with the thermal environment. Using the sample proportion (i.e., the proportion of customers in the sample who felt thermally comfortable) as estimate for p, we thus deemed these results generalisable if the two inequalities showed in equations (2) and (3) were met.

$$n\hat{p}(1-\hat{p}) > 5 \tag{2}$$

$$\left(\frac{\hat{p}-0.8}{\Phi^{-1}(\alpha)}\right)^2 > \frac{\hat{p}(1-\hat{p})}{n} \tag{3}$$

where $\hat{p}$ denotes the sample proportion, Φ^{-1} the inverse of the standard normal cumulative distribution, and α the confidence level. The first inequality is a normal approximation condition while the second is equivalent to stating that the lower endpoint of the one-sided confidence interval for p is above 80%.

Table 6
Are the results in this study on thermal comfort of customers in shopping malls generalisable?

Operative temperature interval midpoint (°C)	Number (n)	Estimate for p	Is the result generalisable?
22	5	1.00	No
23	11	0.73	No
24	48	0.94	No
25	247	0.90	Yes***
26	284	0.84	Yes[a]
27	104	0.92	Yes***
28	21	1.00	No
29	3	0.66	No

[a] 95% (***99.9%) confidence level.

According to these results (Table 6), an operative temperature of up to 27.5 °C in summer is still deemed comfortable by at least 80% of the customers of a shopping centre that fits into the context of this study regarding parameters such as outdoor and indoor conditions, clothing,

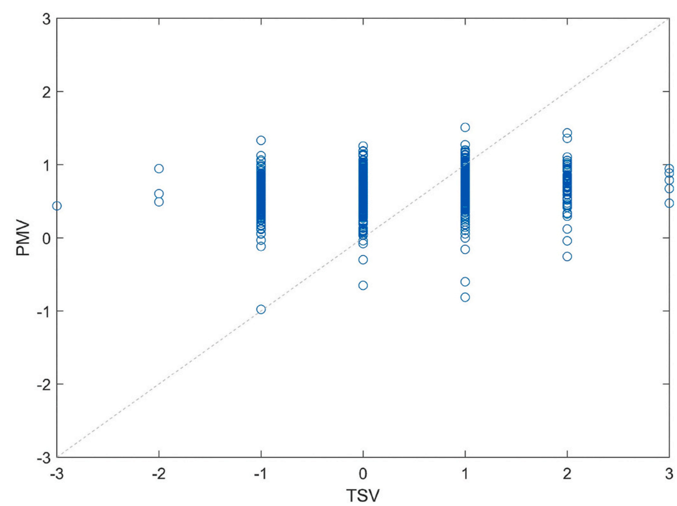


Fig. 9. PMV against TSV. The grey dashed line shows the diagonal.

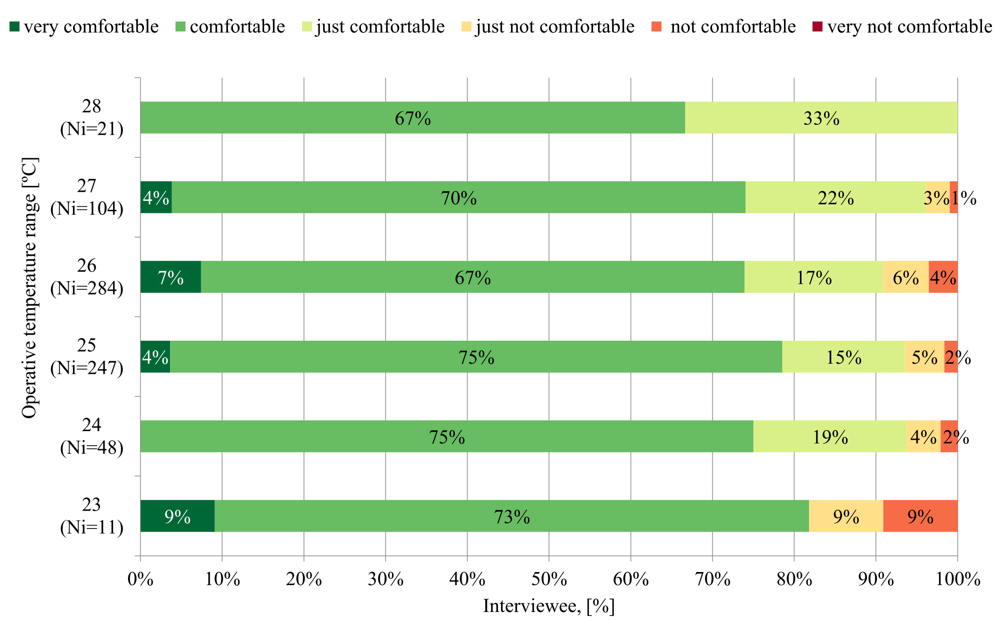


Fig. 8. Bar chart of the distribution related to the thermal comfort question.

customers' attitudes, cultural habits, etc.

3.3. Suitability of traditional thermal comfort models for transitional spaces

3.3.1. Fanger's model

We assessed the applicability of Fanger's model by comparing the PMVs calculated based on measured indoor conditions per each TSV level for the entire dataset (Fig. 9).

Clearly, the PMV is almost unaffected by the actual TSV. Although there is a very slight tendency for the PMV to increase with increasing TSV, we refrained from drawing a regression line, because the TSV is a variable of categorical nature and by rigorous standards of statistics does not allow interpolation.

This result shows that Fanger's model is not capable of capturing the thermal sensation reported by the customers. If Fanger's model was suitable in this context, the PMV would be a proxy for the TSV, and binning the PMV as described in Section 2.4 and equating it with the TSV would lead to the relationship between TSV and PPD shown by the grey line in Fig. 9. The narrow range of PMVs is the direct consequence of the narrow operation range for air conditioning in the spaces.

The inadequacy of Fanger's model in predicting thermal sensation for transitional spaces may find explanation in the assumptions at the base of this model. The method is indeed based on the assumption that people are in a steady-state condition, which is not the case of shopping centre transitional spaces. Subjects are under a constant thermal transient because of moving among different zones of the shopping centre (shops, common areas, food store, etc.). Furthermore, those interviewed right after entering the mall experience an initial thermal sensation overshoot due to the temperature difference between outdoor and indoor, a parameter that is not considered by Fanger's theory and model.

3.3.2. Adaptive comfort model

The adaptive comfort model was tested by verifying how far the average operative temperatures recorded during the measurement days were from the predicted comfort temperatures. The data were crossed-checked with the level of satisfaction of customers with respect to these temperatures.

For each day of measurement, the daily comfort temperature was calculated as shown in Equation (1):

$$Top = 0.33\ Trm + 18.8\ °C \qquad (1)$$

where Trm is the mean running temperature calculated as per EN16798-1: 2019 [31] and as introduced by Nicol and Humpreys [30].

As it is generally assumed, the customers were supposed to be satisfied when their TSV was within the range of slightly cool (−1) and slightly warm (1) [20].

Fig. 10 reports the results by day of measurement.

On April 4th, 5th and 6th the active cooling system was off in SC01. The mechanical ventilation system was providing just the minimum hygienic airflow rates.

For the measurement days in SC01 and SC02 the estimated comfort temperatures are in line with the actual average operative temperatures experienced by the customers. While for SC02 on summer period (June 21st- 22nd) these temperatures allow for over 90% of satisfied customers, for SC01 the percentage of satisfied customers exceeds the 80% just one day (April 6th). On April 5th, 60 customers were interviewed and just 50% of them were satisfied with the thermal environment although comfort temperature was close to average operative temperature. The almost same level of operative temperature is experienced on July 18th in SC03 by 52 customers and the percentage of them being satisfied reached 100%. There are two main possible reasons concurring in creating this difference on customers' thermal sensation:

- Clothing: on April 5th, customers of SC01 had an average level of clothing equal to 0.78 clo, which represents a mid-season situation. On July 18th, the average level of clothing in SC03 was equal to 0.38 clo. Therefore, experiencing the same operative temperature, the level of satisfaction was higher when the clothing level was lower.
- Outdoor-indoor temperature step: while in April the temperature increased from the outside to the inside, in July customers experienced the opposite. Therefore, customers experienced different outdoor temperatures before entering the shopping centre.

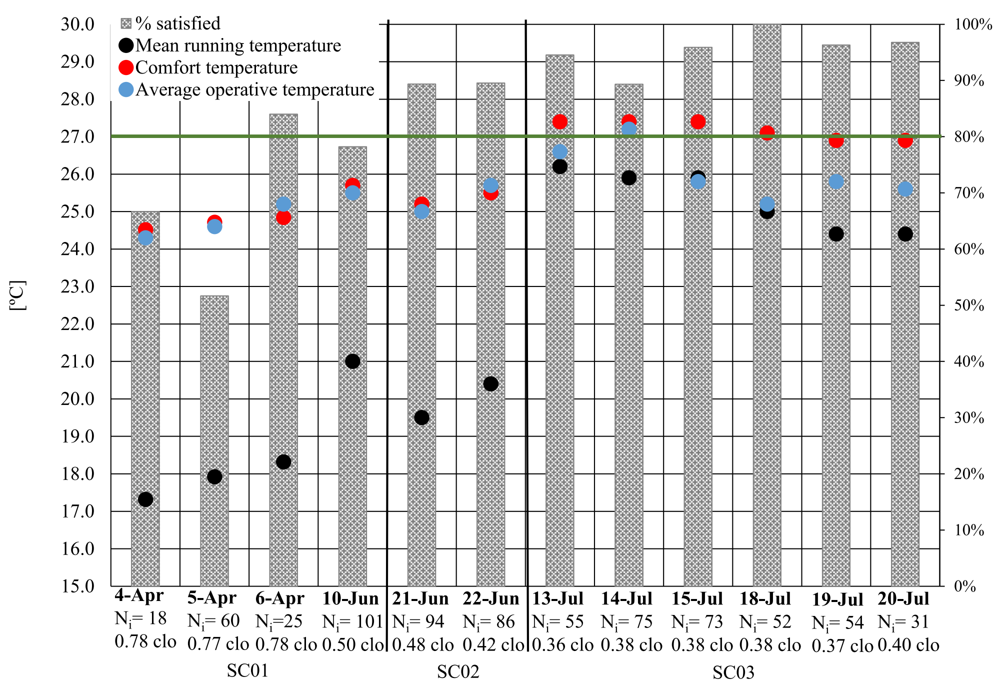


Fig. 10. Comparison between comfort temperature calculated according to the adaptive comfort model, average operative temperature, and percentage of satisfied customers over the day of measurement. The dark green line highlights the 80% threshold of satisfied customers. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The average operative temperatures recorded in SC02, which was mechanically conditioned during the measurements, were almost equal to the predicted comfort temperatures. The percentage of satisfied customers was around 90%. Looking at Fig. 10 and the data from SC03, the percentage of satisfied people was always above 80% but at lower average operative temperature than the one predicted by the adaptive comfort model.

Based on this analysis, the direct application of the adaptive thermal comfort model for transitional spaces is not recommended. This conclusion was reached especially for the conditions of dissatisfaction that the predicted comfort temperature can create in the mid-season period.

To derive a model to assess thermal comfort in shopping centre transitional spaces, it is first necessary to better understand the range of operative temperatures judged comfortable by the customers.

4. Discussion and study limitations

The methodology of the field study represents both advantages and disadvantages for research. Limitations arise from the lack of direct control over the environmental variables and from the difficulty to precisely assess human physiological conditions. On the other hand, field studies are of great importance to study thermal perception in a real environment under normal operation.

Physiological parameters of the customers were not directly measured. Therefore, the metabolic activity was assumed according to the recommendation of the European standard EN ISO 7730 [27], which suggest a value of 1.6 met for "shopping" activity.

Besides limitations related to the field study, another limitation can be found in the scale used in the questionnaire for the evaluation of the thermal sensation. It was not continuous, but discretized. The choice of a discrete scale was mainly due to the use of a paper-based questionnaire. The limitation showed up when directly comparing the PMV, a continuous value, with the actual thermal sensation of customers, which is an integer between −3 and +3. Within the study, a direct comparison was possible by categorizing the PMV. However, by doing so, a certain level of thermal sensation detail was lost.

In relation to the questionnaire, we need to consider a non-quantifiable bias due to the fact that the subjects were directly interviewed by the researchers. This may also affect the results as suggested by McIntyre [26].

The study was conducted entirely in Italian shopping centres during the warm season only. This means that it reflects the thermal perception and expectations of mostly Italian customers. The conclusions may vary if the study was conducted in another country. Measurements should be replicated also during the cold season to investigate the application of the Fanger comfort model in transitional spaces during winter. As highlighted in Section 1, the majority of previous studies took place in Asia or UK, and only one dealt with the Mediterranean climate [17–19] (three papers but the same case study), and even in this case the focus was the thermal comfort of workers and not customers. In line with the findings for other climates, this study shows that Fanger's model is not suitable to control indoor transitional spaces of shopping centres in the Mediterranean area. To extend the results on all transitional spaces located in Group C climates (according to Koppen categorization), a deeper analysis dealing with cultural habits and expectation is needed.

Another element that is worth to be discussed is the applicability of the adaptive comfort model. The peculiarities of transitional spaces may suggest treating them as a sort of hybrid areas in between a conditioned indoor environment (shop) and the outdoor. If that were the case, the adaptive comfort model could have fit the control needs of these spaces. Instead, the results strongly pointed toward a not applicability of the model in such spaces, with customers' answer that lacked to show that link between outdoor and indoor conditions typical of studies in naturally ventilated buildings (Fig. 10).

Furthermore, several literature studies involving human subjects revealed the occurrence of a phenomenon named thermal sensation overshoot. This event consists in a variation of the thermal sensation after experiencing a temperature difference while moving from outdoor to an indoor environment [34–36]. After moving from an environment to another that is cooler or warmer than the previous, thermal alliesthesia takes effect. Thermal alliesthesia relates to the thermal pleasure sensation and overshoot generated by the restoration of a thermal stress towards stable conditions [37,38].

Customers moving within the shopping centre go to and from the shops placed along the common areas where, most of the time, the thermal conditions are different. Therefore, customers are constantly subjected to a thermal transient and they can experience two different types of thermal sensation overshoot:

- A first overshoot due to outdoor-indoor temperature difference experienced when they first enter inside the shopping centre;
- Several overshoots due to the temperature difference between the shops and the common areas.

The thermal overshoot might generate an alliesthesial effect, which might result in a higher percentage of satisfied customers.

When a person moves from a warmer to a cooler environment, this is referred to as a down-step temperature difference. In the case of shopping centres, this is what happens in the summer season when customers enter the shopping centre. The link between down- or up-step temperature difference and thermal comfort perception and preference in the different seasons has been neglected in this study. Instead, we preferred to focus at parameters that impact the building operation like common areas temperatures and therefore setpoints. For what concern the down-set of temperature right after entering the building, this may impact with different extents the 33.7% of interviewees that has spent less than 10 min indoor. Nevertheless, our intent is to present thermal sensation and comfort level of a representative sample of the customers of a shopping centre, which is made by users who has been inside by different amount of time, and therefore provide indication on those parameters that an energy manager can actually control to operate the systems.

5. Conclusions and future work

In this study we assessed the thermal perception of over 700 customers through measurements and interviews performed in three Italian shopping centres. This study is one of the few works dealing with shopping centres on the Mediterranean area and compare with the work of Martellotta et al. [17–19] (also dealing with Mediterranean climate), we analysed customers instead of workers and their perceptions over the indoor environment. The main results of the study can be summarized as follows:

- The steady-state model of Fanger proved to be unsuitable in the estimation of the thermal sensation of the customers. It tends to overestimate the discomfort for higher operative temperature;
- The direct application of the adaptive thermal comfort model for transitional spaces is not recommended because of the discrepancy between predicted comfort temperature and satisfaction level in the mid-season period. The reasons for the high level of dissatisfaction were identified in the clothing level (average of 0.77 clo) combined with the up-step temperature difference experienced by the customers;
- The study showed the necessity of a tailor-made model to assess thermal comfort in transitional spaces. In order to expand the base of evidence, further field studies are required, gathering together a conspicuous number of data covering all seasons;
- Shopping centre customers judged operative temperatures between 23.5 and 27.5 °C as comfortable. Between 24.5 and 27.5 °C at least 88% of the respondents evaluated the indoor conditions with a TSV between −1 and 1, so they are satisfied with them;

- We proved statistically, at a confidence level of at least 95%, that the statement "at least 80% of the customers of a shopping centre deem an operative temperature between 24.5 and 27.5 °C comfortable" can be generalised to any shopping centre with comparable outdoor and indoor environmental conditions and customers' attitudes.

Within the increasing number of papers debating on the best indoor temperatures (and conditions in general) in shopping centres, this one is for sure in line with those providing evidences in favour of higher temperature setpoints. Even so, we believe that there is a fundamental issue that is rarely considered in literature that concern the difference between transitional spaces and the entire shopping mall (including also shops). Although within the same building, these spaces are physically divided, geometrically and aesthetically distinct, and customers used them in a radically different way. This main distinction in the analysis poses the validity of the results only for transitional spaces and highlight the need of a clear distinction in future works on this topic.

Concerning future work, this study should be replicated in other transitional spaces in different climatic and cultural contexts to extend its validity. Further, the issues mentioned in Section 4 (control over environmental variables; assessment of customers' physiological conditions; use of a continuous thermal sensation scale in the questionnaire) should be addressed in future studies by, e.g., refining the design of experiment and complementing the studies in the field with appropriate tests in controlled environments or the lab. Finally, the relationship between down- or up-step temperature differences and thermal comfort perception as well as potential thermal alliesthesia effects experienced by humans in transitional spaces should be investigated.

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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