Assessment of thermal comfort in shopping centre transitional spaces

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SUMMARY
In most modern consumer economies, large retail stores or shopping malls are laid out as small individual stores connected by open “transition” spaces. The set-point temperatures used to control these zones are normally the same used in traditional indoor environments despite the fact that they have quite different boundary condition and users’ needs.
The objective of this work is to find an alternative setpoint deadband for common areas in shopping center that can guarantee users’ thermal comfort, while saving HVAC energy.
We performed a field study in a shopping center during the summer of 2015. The thermal environment was characterized with physical measurements of indoor conditions (as prescribed by ASHRAE standard 55 (2013)) using a tailored mobile cart that can measure dry-bulb temperature, globe temperature, relative humidity (RH), and air speed. Customers were interviewed to assess their thermal comfort, thermal sensation, thermal preference and clothing level. Outdoor condition were also recorded during the study.
The results show that during summer costumers feel thermally comfortable between 24.5 and 27.5 °C., accomplishing 80% acceptability as prescribed by ASHRAE standard 55 (2013). A comparison between PMV values and the mean thermal sensation votes of the interviewee (MTSV) revealed that Fanger’s theory is not ideally suited to these zones, underestimating comfort temperature range and consequently the HVAC setpoint deadband.

PRACTICAL IMPLICATIONS
The implementation of a setpoint deadband, based on users’ real thermal sensation, that is significantly higher than conventional deadbands, has potential for substantial energy saving in new and existing shopping centres without negatively affect customers’ thermal comfort.

KEYWORDS
Thermal comfort, transitional space, HVAC setpoint deadband

1. INTRODUCTION

In most modern consumer economies, large shopping centers are based on a model of small individual stores connected by open “transition” spaces. These transition spaces represent a distinct type of indoor environment that borrow characteristics from outdoor spaces and from traditional indoor environments. Our study hypothesizes that an appropriate thermal conditioning of these spaces, which considers their distinct topologies and costumers’ thermal expectations, could potentially improve indoor thermal comfort and lead to energy savings.
Prior works (Belleri A., 2016) show that retail stores either use large HVAC systems, which handle both the individual stores internal loads and the common areas, or separate individual small systems for each of the retail units. The thermal conditioning of transitional spaces was found to use either set points that were based on guidelines intended for more traditional indoor environments, or set points that are based on the subjective judgment of the system manager.

No current guidelines on thermal comfort have been identified that are specific to retail transitional spaces.
According to previous studies ((Jitkhajornwanuch K., 2002) (Chun C., 2004)), transition zones can potentially improve occupants comfort. In extreme climatic conditions, they can help to relieve thermal shock to human and at the same time they aid to reduce energy losses.
Prior surveys of occupant thermal comfort in transitional spaces ((Ruey-Lung H. K.-H. Y.-P.-T., 2008), (Pitts A., 2008) indicate that thermal comfort of these types of spaces users' differs significantly from predictions based on the PMV model. Pitts A. (2008) observed that occupants of transition spaces react differently to the thermal stimuli than predictions based on the PMV model. He suggested that PMV limits for transitional spaces can be expanded beyond conventional indoor limit of ±0.5.
The focus of this study is to assess real costumer's thermal sensation within transitional spaces of shopping centres with the aim of defining new comfortable temperature ranges that will impact on the cooling set point dead band of transitional zones.

2. METHODS

2.1 Outline

A field study was conducted in the common areas of a shopping centre located in the northeast of Italy, between 10:00 am and 06:00 pm of August 5^{th} 2015. The centre was built in 2000 and has a total area of 9774 m², laid out over two floors. The common areas of the shopping centre are mainly shop galleries. The main entrance atrium has a fully glazed façade (with sun a control film) oriented towards south-west. The field study was performed in different locations within the common areas, which included shop galleries and atria on both the ground and first floor.
The field study procedures include both objective thermal environment measurements and structured interviews with close-ended questions.

2.2 Structured interviews

The interviews were designed to collect information about customers' physiological conditions, the amount of time they had spent in the shopping mall, thermal sensation, what items of clothing they were wearing at the time of interview, and preferences regarding any desired changes to the zone thermal conditions. We also collected background information such as age, gender, health conditions and prior activities.
We estimated the subjects clothing insulation level by summation of the partial insulation value for each item of their clothing, as specified in EN ISO 7730 (2005). The metabolic rate was determined by observing the current subjects' activity, which typically was shopping. According to EN ISO 7730 (2005), this activity level corresponds to a Metabolic Equivalent of Task (met) of 1.7.
Interviewees were asked to judge how they felt about the thermal environment on the ASHRAE 7-point Thermal Sensation Scale (TSS) (ASHRAE, 2013): cold '-3', cool '-2', slightly cool '-1', neutral '0', slightly warm '-1', warm '2' and hot '3'. We also asked them their preferences regarding indoor ambient temperatures on a 3-point preference scale ('Right now I want to be: "cooler", "warmer", or "no change'').
The sample for the analysis is composed by 89 interviewees (56 female and 33 male) distributed almost evenly among three age groups: 30 interviewees were less than 30 years old, 29 interviewees were between 31 and 50 years old and 30 interviewees were over 50 years old.
The average clothing level is 0.35 clo with a difference between male and female clothing level of about 0.04 clo. Detailed information about the sample are collected in Table 1.

Table 1. General information about the analysis sample

		Total sample	Female	Male
Number of Interviewees		89	56	33
Average clothing level [clo]		0.35	0.34	0.38
Age	Less than 30	30	19	16
	between 31-50 year old	29	23	6
	more than 50	30	14	16

2.3 Thermal Environment Measurements

For the scope of the measurement field, a tailor-made mobile cart (Figure 1) called MEMO (Mobile Environmental MOnitoring), was developed and equipped with the sensors needed to evaluate indoor thermal environments. MEMO can be easily moved within the indoor environment and the height of the sensors can be modified, resulting in a very flexible device applicable to indoor environment quality assessment in different building typologies (e.g. schools, offices, shops, etc.).

For this field study, MEMO was set up to measure all the parameters needed to assess global thermal comfort, at 1.1 m above ground as recommended by EN ISO 7730 (2005). .Table **2** lists the MEMO sensors equipment and their characteristics. The accuracy of the sensors used for MEMO meets the recommendations of the European standard EN ISO 7726 (1998). Air temperature is measured using radiation-shielded Pt100. Mean radiant temperature was determined by converting the globe temperature data measured using a 40-mm diameter globe thermometer (Simone A., 2007). We used an omni-directional hot wire sensor to measure air velocity and a portable probe to measure relative humidity. MEMO continuously measured and recorded the indoor thermal comfort parameters at 10 sec frequency between 10:00 am and 6:00 pm.

Figure 1 Mobile Environmental Monitoring cart.

Table 2. List of MEMO sensors equipment.

Parameter	**Sensor & Brand/Type**	**Measuring range**	**Accuracy**
Air temperature T_a	Pt100 class A Radiation-shielded	-50..+150°C	± 0.2 °C (-25..+74.9°C)

Mean radiant temperature T_{mr}	Pt100 class A and 40mm diameter globe (Simone A., 2007)	-50..+150°C	± 0.2 °C (-25..+74.9°C)
Air velocity V_a	Anemometer Sensor electronics SensoAnemo 5130LSF	0.05 to 5.0 m/s	0.02 m/s + 1.5% of reading
Relative humidity RH% (at ambient pressure)	EE EE08 series HC101 sensor	0-100%	±2% RH (0-90% RH) ±3% RH (90-100% RH)

2.4 Measurement of outdoor conditions

Outdoor dry bulb air temperature and the relative humidity were recorded at 10 sec frequency during the entire field study period using a portable data logger whose features are listed in Table 3. The outdoor temperature ranged from 30°C to 34°C and the relative humidity ranged from 35% to 42%.

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

Parameter	**Sensor & Brand Type**	**Measuring range**	**Accuracy**
Outdoor temperature T_{out}	MEMS Integrated portable data logger	-30...+70°C	± 0.5°C
Outdoor Relative Humidity RH%	MEMS Integrated portable data logger	0-100%	± 2%

3. RESULTS

3.1 Thermal sensation

The results are presented using box and whiskers diagrams. The box represents 50% of the total subject responses with the upper and lower whisker indicating maximum and minimum votes. Thermal sensation vote distribution was analyzed by binning the data by 1 K indoor temperature (temperature range between 24.5°C and 28.5°C). Results are presented in Figure 2.
The bold red horizontal line within the box represents the median, while white dots represent the mean values of the actual thermal sensation votes (MTSV) and the black triangles represent the PMV value, calculated using Fanger's equation.
For indoor air temperatures between 25.5°C and 28.5°C the subjects expressed the feeling of a neutral-slightly warm environment as defined by the ASHRAE thermal sensation scale, but still within thermal comfort zone.
The MTSV increased as indoor temperatures increased, nevertheless these values still fell within the thermal comfort zone. The difference between the MTSV and the average Fanger's PMV values vary between 0.56 and 0.91. We observed that the lower the measured indoor air temperature, the higher this differential was between MTSV and PMV values.

3.2 Thermal neutrality

Thermal neutrality refers to a specific indoor air temperature corresponding to a mean thermal sensation vote of "zero" on the thermal scale. Linear regression was performed between subjects' thermal sensation vote and corresponding indoor air temperature to assess the neutral temperature of the interviewee as represented in Figure 3. Assuming a linear regression model represented by Equation (1), the neutral temperature was found to be 24.5 °C.

$$(MTSV) = 0.22\ T_a - 5.4 \qquad (1)$$

where:

T_a is the Indoor Air temperature (°C)
MTSV is the thermal sensation vote

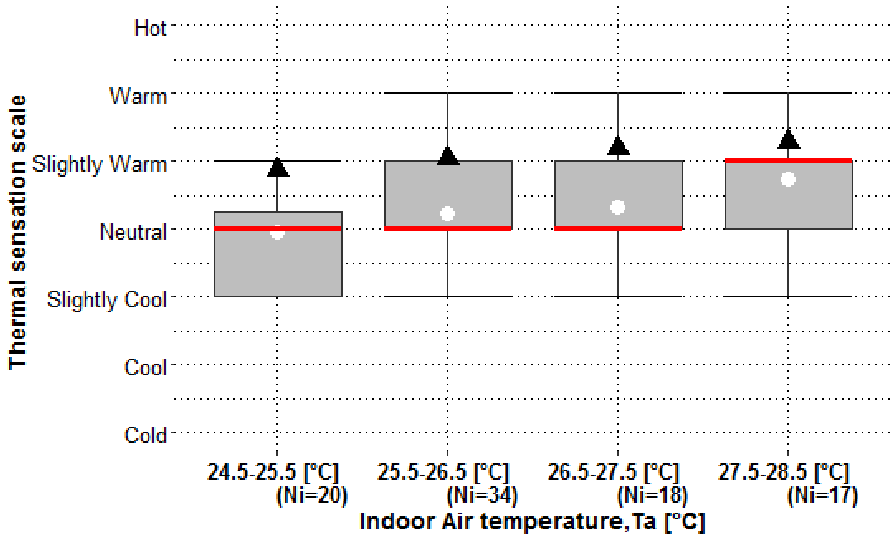

Figure 2. Box plot distribution of actual thermal sensation vote over indoor air temperature ranges.

The regression is however, not statistically significant (R^2= 0.0774) due to the small sample. The graph has been anyway presented to show the range of indoor temperature and respective actual thermal sensation vote during the field campaign.
It is important to point out that not all the customers were dressed in the same way at the same MET level (even if we assumed it constant and equal to 1.7 met in order to perform the analysis), so the neutral temperature is representative of the sample considered in this study. It does not refer to a specific clothing value while it refers to a defined MET level.

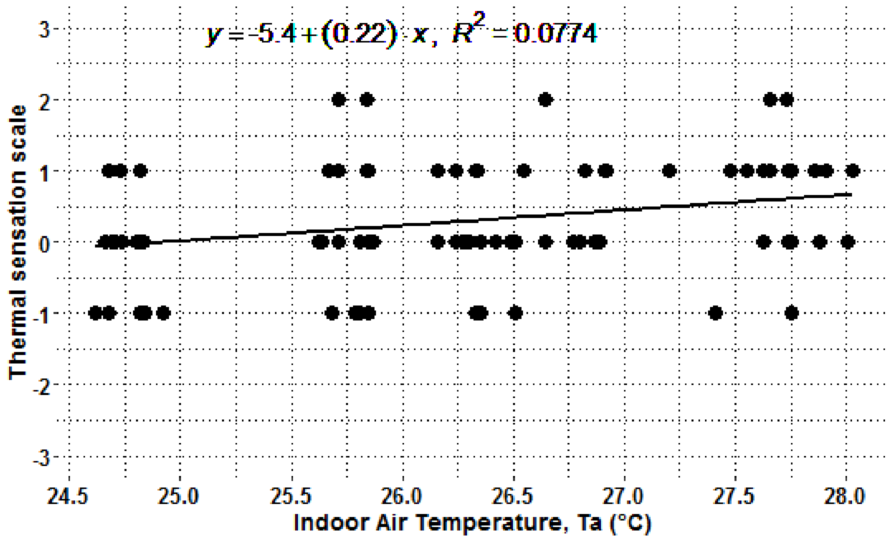

Figure 3. Regression plot between the actual thermal sensation votes and the indoor air temperatures

3.3 Thermal comfort and preferences

Table 4 shows thermal comfort and preference of interviewee at the 1 K indoor temperature intervals. Thermal comfort analysis revealed that the majority of the interviewees where comfortable with the air temperature they experienced during the test. The range of comfortable indoor temperatures was found to be from 24.5 °C up to 27.5 °C, where at least 80% of the respondents rated the thermal environment as "comfortable" (ASHRAE, 2013). Considering the thermal preference results, 75% of the interviewees stated their preference for "no change" in indoor operative temperature, while only 25% would prefer a cooler indoor operative temperature. Depending on the 1 K indoor air temperature intervals (Table 4), these percentage vary.

Table 4. Thermal comfort and preference of interviewee

Ni	Indoor air temperature	Operative temperature	Comfortable	Not comfortable	Want cooler	No change	Want warmer
	24.5 °C ≤ T_a < 25.5°C	25.1 °C ≤ T_o < 25.5°C	100%	0%	15%	85%	0%
	25.5°C ≤ T_a < 26.5°C	26.0 °C ≤ T_o < 27.0°C	88%	12%	24%	76%	0%
	26.5°C ≤ T_a < 27.5°C	26.9 °C ≤ T_o < 27.8°C	94%	6%	28%	72%	0%
	27.5°C ≤ T_a < 28.5°C	27.9 °C ≤ T_o < 28.3°C	76%	24%	35%	65%	0%

3.4 Influence of the indoor-outdoor temperature difference

Table 5 shows, for each indoor air temperature range, the effect of indoor–outdoor air temperature difference on each of the two thermal comfort parameters, Fanger's PMV and the mean of the actual thermal sensation vote (MTSV). The indoor-outdoor temperature differences were binned by increments of 2 K, starting from 3 K (the minimum recorded difference) up to 11 K (the maximum recorded). We also included the average clothing value.

The limited number of interviewees for each indoor-outdoor temperature difference did not allow us to derive robust models that describe the impact of this temperature difference on users' thermal sensation. Nevertheless, our analysis found that the PMV parameter overestimated the thermal comfort sensation. The PMV values were greater than the respective mean values related to the actual thermal sensation votes, for all the indoor temperature intervals and indoor-outdoor temperature differences. The difference between PMV and MTSV is reduced when the indoor temperatures are relatively high (27.5-28.5 °C) and the indoor-outdoor temperature difference is below 5 K.

4. DISCUSSION

Taking into consideration that data was collected in a single campaign, and that the sample analysed is relatively small, we were able still to identify trends in shopping centre customers' thermal sensation. Customers' responses indicated that the majority were thermally comfortable and wanted "no change" for the indoor air temperature. Significantly this was also observed when the recorded indoor air temperatures were higher than the upper temperature limit of the thermal comfort zone recommended by the standard EN 15251 (2008).

These results suggest that upper boundaries of comfortable temperature range, limited to summer period, are beyond the upper temperature limit recommended by EN ISO 7730 (2005) and ASHRAE 55 (ASHRAE, 2013).

It is worth mentioning, as a qualitative aspect arose during the field campaign, that most of the interviewees were satisfied with the "not too cold indoor climate" of the shopping centre, this was identified as one of the factors that influenced their decision to shop at this particular shopping center, as opposed to other local centers where "the indoor temperature were too low compared to the outside temperature".

The shopping centre energy manager, took an active role in determining the cooling set-point, considering both outdoor condition and occupancy frequency of the centre. This resulted in setpoints that differed from current guidelines, potentially improving shopper comfort compared to other stores, and energy savings. However, this set-point control is done without guidelines, based on his own experience. Further work will include other field campaigns, in winter and mid-season period, allowing us to perform more robust analysis, and to derive a detailed algoritm to control HVAC set-points, improving costumers comfort and potentially allowing for energy savings.

Table 5. Variation of MTSV, PMV and clothing level according to indoor air temperature ranges and temperature differences between indoor and outdoor temperature (ΔT).

Indoor Air Temperature		3K ≤ ΔT < 5K	5K ≤ ΔT < 7K	7K ≤ ΔT < 9K	9K ≤ ΔT < 11K
24.5 °C ≤ T_a < 25.5°C	N_i	0	0	8	12
N=20	MTSV ± sd			0.13 ± 0.83	-0.17 ± 0.72
	PMV ± sd			0.89 ± 0.12	0.85 ± 0.27
	CLO ± sd			0.39 ± 0.12	0.34 ± 0.14
25.5°C ≤ T_a < 26.5°C	N_i	7	25	0	0
N =34	MTSV ± sd	0.43 ± 0.53	0.19 ± 0.88		
	PMV ± sd	1.12 ± 0.09	0.99 ± 0.11		
	CLO ± sd	0.4 ± 0.11	0.33 ± 0.09		
26.5°C ≤ T_a < 27.5°C	N_i	4	10	4	0
N= 18	MTSV ± sd	0.5 ± 1.0	0.29 ± 0.61	0.50 ± 1.29	
	PMV ± sd	1.21 ± 0.08	1.17 ± 0.07	1.18 ± 0.06	
	CLO ± sd	0.38 ± 0.12	0.35 ± 0.09	0.4 ± 0.08	
27.5°C ≤ T_a < 28.5°C	N_i	17	0	0	0
N=17	MTSV ± sd	0.71 ± 0.77			
	PMV ± sd	1.29 ± 0.08			
	CLO ± sd	0.37 ± 0.09			

5. CONCLUSIONS

This paper presents results of a unique field study of transitional space thermal comfort conducted in a shopping centre in the northeast of Italy during a hot summer day. The field survey procedures include both thermal environment measurements (indoor and outdoor) and structured interviews with close-ended questions.

The results suggest that Fanger's model tends to overestimate thermal comfort sensation with respect to the actual thermal sensation of interviewees. The observed difference between the PMV and the mean thermal sensation vote (MTSV) was at its greatest during periods of low indoor air temperature (24.5 -25.5 °C). This results in an underestimation of HVAC temperature set points in the cooling season.

The linear regression found between subjects' thermal sensation vote and indoor air temperature reveals a neutral temperature of 24.5 °C. The thermal comfort analysis showed how a comfort temperature range between 24.5 and 27.5 °C complies with the ASHRAE 55 (2013) standard. When indoor air temperature falls within this range indeed, there is 80% of satisfied people. This results suggest that cooling set-point temperatures can be softened up to a maximum of 27.5 °C with an important impact on the energy consumption to cool the shopping centre transitional zones, still guarantying users' comfort.

The limited number of interviewees did not allow us to derive a robust model relating the indoor-outdoor temperature differences to users' thermal sensation. More data needs to be collected at different outdoor conditions in order to establish a robust correlation between climatic condition and comfort temperatures, and to define then complete guidelines for HVAC set-point controls.

The present study can play an important role in the definition of the comfort temperature range in shopping centre transitional spaces and as a consequence can help designers, engineers and energy managers to design and operate shopping centres more efficiently.

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7. REFERENCES

EN ISO 7726:1998. (s.d.). *Ergonomics of the thermal environment.Instruments for measuring physical quantities.*

ASHRAE. (2013). *ANSI/AHSRAE Standard 55- Thermal Environmental Conditions for Human Occupancy.* Atlanta.

Belleri A., A. M. (2016). *Ventilative cooling.* under revision: Deliverable D3.3, CommONEnergy project.

Chun C., K. A. (2004). Thermal comfort in transitional spaces—basic concepts: literature review and trial measurement. *Building and Environment 39*, 1187 - 1192.

EN 15251:2008. (2008). *Indoor Environmental input parameters for design and assessent of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acustics.*

EN ISO 7730: 2005. (s.d.). *Ergonomics of the thermal environment.*

Jitkhajornwanuch K., P. A. (2002). Interpretation of thermal responses of four subject groups in transitional spaces of Buildings. *Building and Enviroment, 37*, 1193-1204.

Pitts A., S. J. (2008). Building transition spaces, comfort and energy use. Dublin: 25th Conference on Passive and Low Energy Architecture.

Ruey-Lung H., K.-H. Y.-P.-T. (2008). Subjective responses and comfort perception in transitonal spaces for guests versus staff. *Building and Environment, 43*, 2013-2021.

Ruey-Lung H., T.-P. L. (2011). Thermal Comfort Requirements for Occupants of Semi-Outdoor and Outdoor Environment in Hot-Humid Regions. *Architectural Science Review, 50:4*, 357-364.

Ruey-Lung Hwang, Tzu-Ping Lin. (2007). Thermal Comfort Requirements for Occupants of Semi-Outdoor and Outdoor Environments in Hot-Humid Regions. *Architectural science review, 50:4*, 357-364.

Shop Center Valsugana. (s.d.). Tratto da http://www.shopcentervalsugana.com/

Simone A., B. J. (2007). Operative temperature control of radiant surface heating and cooling systems. Helsinki: Clima 2007 Wellbeing Indoors.

Woods A., F. S. (2004). Tension Between Natural and Mechanical Ventilation in a Large Shopping Complex. Eindhoven: PLEA 2014- The 21th Conference on Passive and Low Energy Architecture.