# Thermal Comfort in Supermarket's Refrigerated Areas:

# an Integrated Survey in Central Italy

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## ABSTRACT

Thermal comfort conditions in supermarkets have been barely investigated in the past and only few meaningful studies have been carried out involving customers and staff. In this paper, the results of an integrated investigation on thermal conditions of customers and staff in refrigerated areas of four supermarkets in Central Italy are presented and discussed. Microclimatic surveys demonstrated that thermal comfort conditions for staff were generally consistent with ISO 7730 requirements. To the contrary, considering worn clothes, the thermal sensation predicted for customers was generally turned towards the cold both in autumn and summer with PMV values often below -2.

The analysis of the local microclimatic parameters revealed low floor temperatures and a meaningful cold air stratification characterized by air temperature vertical differences measured between head and ankles up to 8-9 °C in case of open cabinets. In summer, due to the lower air temperature values (compared to the outdoor) combined with the usual low thermal insulation of clothes, the thermal environment is cold and the IREQ model revealed dangerous conditions for customers in three of the investigated areas with DLE (Duration Limit of Exposure) of about 40 minutes. In autumn, DLEs largely exceeded one hour. Results of the subjective investigation carried out in two sales points for 35 customers were consistent with the objective survey and revealed higher percentages of dissatisfied in case of women. Finally, local discomfort due to cold feet effect seemed to be more consistent for women due to the low clothing distribution in lower parts of the body.

**Keywords**

Thermal comfort, supermarkets, refrigerated cabinets, individual differences, ergonomics, cold aisle

## 1. INTRODUCTION

Due to the impact on energy demand [1, 2], performance and productivity [3-7], the scientific community has addressed significant efforts aimed at measuring, characterizing and optimizing Indoor Environmental Quality (IEQ) in occupied spaces [8, 9] especially from the perspective of thermal comfort [10-12] and Indoor Air Quality [13-15]. Regarding thermal comfort, the literature is mostly focused on residential and office buildings, whereas only relatively few research concerns retail trade buildings [16-31] as supermarkets, hypermarkets, department stores and shopping malls which strongly affect global energy consumptions. According to available data, yearly energy demand of supermarkets varies in the range from 400-500 kWh/m$^2$ (in Netherland [32], UK [33], USA [32] and Italy [34]) to 700 kWh/m$^2$ (in USA and Canada [32]) with an incidence of refrigerating equipment of about 45% [33, 35, 36] which correspond to about 4% of global electricity consumption [23, 37, 38]. In addition, it is accepted that using doored refrigerated cabinets results in 30% of energy saving with respect to open vertical refrigerated displays [39, 40]. The spread of large shopping malls and hypermarkets and the increase in average time spent therein by consumers require an in-depth analysis of the thermal comfort conditions. In fact, as stressed by Lindberg et al. [19, 22, 23, 26], besides the specific requirements of goods (especially refrigerated food) two different categories of people with different needs should be considered: staff and customers. Particularly, staff spends almost the entire work shift indoors and can adjust the dress-code according to the actual environment and performed activity (also in respect to the applicable safety rules). To the contrary, customers always spend shorter periods of time in refrigerated areas of supermarkets if compared to staff and they are dressed according to outdoor conditions. That means that during summer (and also in mid-seasons under mild climates) light clothes are not effective to protect people against cold temperatures in these spaces.

The presence of refrigerated areas is one of the most important issues of supermarkets, especially near display cabinets [41, 42]. Near open refrigerated vertical cabinet a big amount of cold air is pushed outside the cabinet and also in the presence of curtains providing a separation between the cabinet and the external ambient, a portion of cold air is poured to the floor [42] with negative effects on thermal comfort of customers due to the ‘cold feet effect’ [26]. As a consequence, customers are forced to reduce the time spent in sale areas with unforeseen effects on sales volume.

Over the past years, the scientific research has devoted meaningful efforts in identifying effective solutions to reduce the energy demand of retail stores and supermarkets with special interest to the refrigerating equipment [43-48]. To the contrary, thermal comfort conditions in these environments have not been adequately investigated despite their impact on residence times of customers and sales volume. In addition, few investigations are focused on the benefits related to the retrofit of existing open refrigerated cabinets by means of the installation of doors (e.g. improvement of comfort conditions due to the increase of operative temperature values and the reduction of cold aisle phenomenon [40]).The only meaningful and systematic studies on thermal comfort in refrigerated areas were carried out in Sweden being focused on customers and staff [19, 20, 22, 24, 26] and in Italy only on the staff in few refrigerated positions in a large hypermarket [17, 27, 28, 30].

Lindberg et al. [19, 20, 22, 24, 26] discussed subjective investigations according to ISO 10551 Standard [49] on a sample of about 1200 interviewed (staff included) in summer and winter combined with microclimatic surveys near vertical open cabinets in three different supermarkets. The questionnaires contained judgments about perception (on a 7-poles scale), evaluation (5-poles scale) and preference (7-poles scale). Concerning local discomfort, they observed temperature differences between ankle and head higher than 5 K with a percentage of dissatisfied calculated according to ISO 7730 Standard [50] exceeding 20%. Due to light worn clothes, customers perceived the temperature as more uncomfortable in summer compared to winter, whereas staff generally voted close to neutrality. In addition, customers did not report the preferred temperature to be neither warmer nor colder, whereas a larger variation of the preferred temperature for the staff was found depending on the season and the different measurement position. Finally, customers gave higher votes in both seasons than did the personnel to a specific question about the perception of the indoor environment. In a recent paper, Lindberg et al. [26] also investigated the correlation between the thermal sensation votes (TSV) from subjective survey (questionnaires) and objective one (PMV). Particularly, they obtained PMV values (varying in the range from -1.1 to -0.1) greater than TSV in winter (about 5 decimals), whereas in summer PMV (varying in the range from -3.5 to -1.1) largely underestimated the thermal sensation (up to one point) on the ASHRAE thermal sensation scale [51]. Moreover, they related such inconsistency to the uncertainties of clothing insulation values used for the calculation of the PMV (1.4 clo in winter and 0.5 clo in summer with no correction of basic insulation values due to body movements [50, 52]), the reference metabolic rate and the exposure time [53-55]. Lindberg et al. [21] also investigated the benefits related to the installation of doors to the vertical cabinets. From the surveys carried out in winter, they revealed a reduction of 1.5 K of the difference of temperature measured at ankles (0.1 m above the floor) and head (1.7 m above the floor) in front of doored cabinets and a general increasing in the percentage of people who felt a neutral thermal sensation and an improved perception of the indoor environment.

A second group of on field studies focused on IEQ levels perceived by the staff of a large hypermarket (17000 $m^2$ in surface) has been recently carried out in Southern Italy [17, 27, 28, 30]. Concerning global thermal comfort aspects, the authors did not find meaningful differences in subjective responses as a function of residence time of the staff [17]. In addition, they obtained a very good correlation between TSV votes and PMV in air-conditioned areas. To the contrary, PMV seemed to be less suitable in naturally ventilated areas as the warehouses. However, it is important to stress that only three out of 27 different investigated positions in the supermarket, were represented by refrigerated areas (i.e. fruit and vegetables, fish shop). As far local thermal discomfort, the authors recorded higher values of the percentages of dissatisfied due to draught rate from subjective investigation (from 25% to 40% depending upon the season and the task) with respect to that predicted by DR model [50]. In addition, the percentages of dissatisfied due to cold/warm floor and vertical radiant asymmetry measured according to ISO 7730 [50] were well correlated with the percentages of individuals indicating cold in the lower limbs as a cause of discomfort. Finally, they found a significant effect of the clothing distribution of the lower part of the body which resulted in a cold sensation on the lower limbs in the presence of low temperature of the floor and radiant asymmetries. This kind of discomfort seemed also affect the global vote for thermal sensation and satisfaction [27].

Based upon the analysis of the state of the art in the field, systematic research papers focused on the microclimatic characterization of refrigerated areas with different typologies of cabinets (i.e. horizontal, vertical, open, doored) and on the effect of their disposition inside sale areas are still not available in literature. In addition, the objective analysis of thermal comfort for customers has not been carried out considering the clothing really worn and the effects of body movements on its thermophysical properties whose effects can be significant [50, 52, 55, 56]. Finally, there are no systematic subjective investigations on local discomfort involving individual differences (e.g. gender) and questions on different judgments scales (e.g. perception, evaluation and preference).

To provide further information about comfort conditions in supermarkets, this study has been mainly addressed to investigate global and local thermal comfort conditions for customers and staff through a microclimatic monitoring of refrigerated areas in different supermarkets in Central Italy. The choice of the experimental site (i.e. Mediterranean climate) and seasons (i.e. summer and autumn) was aimed at assessing the influence of doored and open refrigerated cabinets both on male and female customer's perception of thermal comfort in periods when people do not wear heavy clothes (which help to not feel cold). The analyses will include the measurement of all the variables responsible for the local and the global thermal sensation, comfort (PMV) and stress (IREQ) indices and the assessment of cold stress risk as required by standardized strategies [57, 58]. In two supermarkets, objective analyses have been also integrated with subjective investigations (conducted at the same time on a sample of 35 customers) based upon the administration of special questionnaires prepared according ISO Standard 10551 and specifically adapted to the environments under investigation.

## 2 METHODS

This study is based on a large experimental survey carried out in 2018 in four supermarkets located in the Central Italy in the Region of Lazio within the district of Cassino. Lazio is the second-most-populous region of Italy and hosts Rome. Located in the Middle part of the Italian Peninsula, with the Mediterranean Sea to the west, it exhibits a typical Mediterranean climate along the coast, whereas in the inner zones it is more continental, with very low temperatures in winter due to the presence of high mountains (up to 2451 m). In table 1 further details are reported.

Main details about HVAC systems installed in the four stores can be summarized as follows:

- Supermarket A is provided with a multizone HVAC system with two air handling units and a heat pump generation system;
- Supermarket B is hosted in a mall and it is provided with a) water ring centralized system supplied by an air-water heat pump; b) three autonomous rooftops for the control of the different zones; c) air handling unit for the primary air.
- Supermarkets C and D are provided with a centralized whole air system with constant flow rate.

Set point temperatures have been settled at 20 ±1 °C in autumn (23 ±1 °C in summer) and fresh air flow rates used in all investigated sales point were about 5.5 l/s person [59]. Finally, operating times have been set up to the opening times with nocturnal attenuation and free cooling in summer season.

The measurement of thermo-hygrometric parameters was carried out according to ISO 7726 Standard [60]. For the evaluation of the metabolic rate and the clothing insulation of the customers and the staff, ISO 8996 [61] and ISO 9920 [62] have been considered, respectively. The measurements campaign has been carried out based on a special protocol for the assessment of the Indoor Environmental Quality (IEQ) [63] taking into account both thermal comfort measurements and subjective evaluations (only in two supermarkets). On field measurements have been carried out in summer (supermarkets A and C) and in autumn (supermarkets B and D) to stress possible criticalities also in midseason in the most representative positions as sketched in figures 1 and 2.

In supermarkets C and D, a subjective investigation has been also carried out at the same time of on field measurements by means of a special questionnaire compliant with ISO 10551 [49]. In table 2 a schematic description of measurement points and cabinets' arrangement is summarised.

PMV index was calculated from measurement results. On the basis of the index value the thermal environment was defined moderate or severe in agreement with ISO 15265 [57, 64]. In the first case the assessment of the thermal environment quality has been carried out by comparing the measured PMV values and the indices of local thermal discomfort with limit values suggested by ISO 7730 [50] as in table 3.

The evaluation of cold stress has been carried out by means of the IREQ model [65] and the calculation of the duration limit of exposure (DLE).

## 2.1. Measurement of physical and personal parameters affecting thermal comfort

As for the measurement of microclimatic quantities, a Comfort Data Logger Delta OHM HD 32 provided with sensors for air temperature, plane radiant temperatures, air velocity, aspirated wet bulb temperature and globe temperature compliant with ISO 7726 requirements [60, 66, 67] has been used (see Figure 3). Before the experimental campaign, all measuring devices have been calibrated at LAMI, the Industrial Measurements Laboratory of the University of Cassino and Lazio Meridionale, accredited by ACCREDIA, the Italian Accreditation Body. All measurements have been carried during a period of 30 min with a sample rate of 1 s for each investigated position. In some cases, they have been repeated in different period of the day and in different days of the same week in both seasons.

The calculation of comfort and discomfort indices has been carried out by means of the TEE package [68-70], a special software designed for the assessment of the thermal environment in agreement with the whole standardization in the field.

The evaluation of the basic thermal insulation of the clothing has been carried out according to ISO 9920 [62] on the basis of the clothing ensembles that customers declared to wear during the surveys and indicated on a special questionnaire and the dress worn by the staff. Used questionnaire (see below) contains a special section containing the pictures of the single garment. In this way the interviewed has only to select the picture of the i-th worn garment. Then the intrinsic clothing insulation of each subject in the sale point, $I_{cl,j}$ has been calculated according to the following equation:

$$I_{cl,j} = \sum_{i=1}^{n} I_{clu,i} \tag{1}$$

Finally, the intrinsic mean clothing insulation associated to the sale point $I_{cl}$ has been calculated by averaging $I_{cl,j}$ according to the following equation [62]:

$$I_{cl} = \frac{1}{m}\sum_{j=1}^{m} I_{cl,j} \tag{2}$$

According to ISO 7730 [50] before calculating the PMV values, the intrinsic clothing insulation values have been finally corrected by the effect of body movements by means of special correlations as a function of the relative air velocity and walking speed [50, 56, 62, 65, 68]. To allow the calculation of comfort and stress indices also in supermarket A and B (where no subjective investigation has been carried out), the same clothing insulation values measured respectively in C and D have been considered. This is because surveys in the two couples of supermarkets (A/C and B/D) have been carried out in the same season in days when outdoor conditions were similar. In table 4 a summary of mean basic clothing insulation values calculated according to equations (1) and (2) with related standard deviations is reported.

Finally, the reference value used for the metabolic rate in this study was 1.60 met for customers [64] and 1.85 for the staff [17, 61, 71].

## 2.2 Subjective investigations

A special questionnaire designed with the assistance of a team of psychologists and doctors [63] and specifically designed to allow a quick and easy filling has been administered to customers (18 in supermarket C and 17 in D as summarized in table 4). The questionnaire is divided into two sections: personal information (among other information customers have to describe their worn clothing at the moment of the survey) and thermal comfort.

Questions in the second section have been formulated in compliance with the recommendations of ISO 10551 Standard [49] and are related to the thermal state in terms of perception, evaluation and preference scale. The eleven questions (see details in figure 4) also deal with humidity, overall thermal conditions, local discomfort (draughts and temperature perception at head, hands and feet levels), tolerance and preference. Based on the answers, the following indicators of the subjective thermal comfort have been considered:

- *TSV*: Thermal Sensation Vote obtained by questionnaires expressed on the typical 7-point scale [51] and calculated as a mean value of the votes attributed to the environment;
- $PD_F$: percentage of dissatisfied obtained by the questionnaires and in compliance with the Fanger's definition [50, 72] (percentage of those who have voted ±2 or ±3 on the scale of the thermal perception).

## 3 RESULTS AND DISCUSSION

### 3.1. Global thermal comfort assessment

In table 5 the results of the microclimatic monitoring in the 16 measurement positions in the four investigated supermarkets are reported together with corresponding PMV values. Operative temperature has been calculated by means of the following equation [60]:

$$t_o = \frac{h_c t_a + h_r t_r}{h_c + h_r} \tag{3}$$

Based upon data summarized in table 5, the interaction between cabinets and environmental conditions resulted in a meaningful reduction of air temperature values with respect to the HVAC systems setpoint. Mean seasonal values of air temperature recorded in the different measurement points were 19.1±2.9 °C in summer and 17.6±1.5 °C in autumn that is about 3 °C below the HVAC setpoint in both seasons. This is also the case of mean radiant temperature (20.5±2.9 °C in summer and 18.0±2.0 °C in autumn), whereas relative humidity values were close to 50% (48.8% in summer and 52.6% in autumn). It is important to emphasize that the microclimatic conditions are also affected by the different characteristics of the building envelope, the arrangement of cabinets and

HVAC terminal units. Therefore, the effect of cabinets on the cold aisle phenomenon cannot be exactly quantified. To this aim more specific numerical CFD studies [74, 75] or experimental analyses based on the Particle Image Velocimetry (PIV) technique under laboratory conditions [40, 42] are required. However, this kind of investigations can only provide general information because laboratory results do not consider that the cabinets modify comfort conditions based only upon temperature and velocity values of HVAC supply air. This implies a case-by-case analysis also based upon the characteristics of the building envelope, the arrangement of cabinets in sale areas, the typology of HVAC system and its terminal units.

Concerning the evaluation of overall comfort conditions for customers, data in table 5 clearly demonstrate that in all monitored areas the typical thermal sensation was of non-thermal neutrality ($PMV \neq 0$) with only five situations consistent with comfort conditions (4 in category C and only one in B according to ISO 7730). Most critical situations occurred in summer (mean PMV value of -1.53) near vertical open cabinets (A1, A5 and A6) where systematically resulted $PMV<-2$. Such conditions are mainly due to very low air temperature values, sometimes compensated by a higher mean radiant temperature especially in supermarket A in hour of maximum solar radiation in summer conditions due to the poor thermal insulation of the roof. Due to so low PMV values, the class of risk shall be evaluated according to ISO 15265 [57, 75] as reported in table 6.

In autumn, probably due to clothing insulation values higher than those observed in summer (see table 4), PMV values for customers were higher and generally consistent with cold discomfort conditions (mean PMV value of -1.01).

Despite a different arrangement and the presence of long closed cabinets, microclimatic conditions in the supermarket B were close to those observed in A with only one position consistent with comfort conditions (B1) in summer and in autumn. It was surprising that the presence of closed cabinets in B6 and B7 did not result in the improvement of predicted comfort conditions being PMV values lower than those observed in B1 and B2 where cabinets are open. This was likely due to the proximity of exit which favour the air circulation inside the aisles (see figure 2).

Therefore, the higher air velocity values favour convective heat exchanges from the human body and the surrounding environment with the consequent worsening of the thermal sensation predicted by the PMV.

Mainly due to the higher operative temperature values, in the other two supermarkets (C and D) microclimatic conditions were better. Particularly, in supermarket D in autumn comfort conditions (PMV=-0.30) have been registered, whereas in summer PMV value was close to the lower limit for category C (PMV=-0.72).

As far the staff, due to higher clothing insulation and metabolic rate values, thermal sensation predicted by PMV index was always close to the neutrality. The only situations of high discomfort were found in summer in A1 (PMV=-0.72), A5 (PMV=-0.80) and A6 (PMV=-0.99) which already exhibited PMV values less than -2 for customers due to the low operative temperature values.

3.2 Cold discomfort assessment

As summarized in table 6, ISO Standard 15265, and also ISO 15743 – that is specific for cold workplaces [58] – do not require further analyses in case of cold discomfort (e.g. -2<PMV<-0.5). To account the onset of dangerous conditions especially for workers [75], the analysis of these situations has been carried out by applying the IREQ model [65, 69] and calculating related duration limit exposure DLE consistently with microclimatic data in table 5. It is noteworthy observing that in principle, IREQ model [65, 69] should not be applied in investigated areas being air temperature and clothing insulation (table 4) values over its validation ranges ($t_a$<10 °C and $I_{cl}$>0.5 clo). This apparent inconsistency is because, at the present, IREQ is the only index able to provide the assessment of working condition in cold environments.

In table 7 IREQ values and the DLEs calculated according to ISO 11079 [65, 69] have been reported. Obtained results clearly demonstrated that most of investigated positions (13 out of 23) are consistent with cold stress for customers being worn clothes unable to keep the thermal homeostasis ($I_{cl,r}$<$IREQ_{min}$). Despite this, DLEs values (105±45 min) largely exceed mean residence times spent in sales area. Better conditions can be found in autumn where critical positions were still 6 but with even higher DLEs revealing safe exposures also in this case. In case of staff, worn clothes are enough to avoid any uncontrolled cooling ($IREQmin<I_{cl,r}<IREQ_{neu}$) with higher DLEs values (182±52 min) and no risks for workers [65].

3.3. Local thermal discomfort

In table 8 the measured values of the variables responsible for local thermal discomfort phenomena and related percentages of dissatisfied are reported.

Obtained results showed a meaningful stratification of cold air at ankle level in all measurement points (the mean value of the air temperature vertical difference between 1,7 m and 0,1 m above the floor is higher than 6 °C in both seasons) with high values of the percentage of dissatisfied (mean value above 39% with peaks even over 80%). Particularly, the difference of the air temperature measured at head and ankle levels reached 8-9 °C in the meat department (A3) and in cured meat department (B1, B2). In the other departments, air temperature vertical differences are generally lower, more evident in summer and in agreement with Lindberg et al.'s studies [23] for the same typologies of cabinets (5.2-8.0 °C in summer and 5.7-9.0 °C in winter). The presence of doored cabinets in B6 and B7 measuring points undoubtedly softened stratification phenomena with lower ($t_h$-$t_{an}$) values (about 5.0 °C) than those recorded near vertical open cabinets (7.4 °C in B3 and to 9.0 °C in B2).

Based upon PD values reported in table 8, most critical positions are those near OVCs (mean PD values of 62.9% and 50.2% in autumn and summer, respectively). To the contrary, OHCs and CVCs result in more acceptable conditions: OHCs exhibit mean PD values of 22.3% (24%) in autumn (summer) instead of 18.5% in case of CVCs. Anyway, it is important to point out that all percentages of dissatisfied could be overestimated as the PD model reported in ISO 7730 can be applied only for seated persons with sedentary activity [50].

The meaningful stratification of cold air not only resulted in local discomfort at ankle level but also in local discomfort due to cold floor as the values of floor temperature recorded in the four supermarkets did not exceed 18.6 °C and in 17 out of 23 cases it was lower that the suggested value for environments in class C (see table 2). The presence of OVCs results also in this case in higher percentage of dissatisfied with respect to OHCs and CVCs (mean values of PD were 25.2%, 16.7% and 14%, respectively) in autumn.

Such a phenomenon also favoured a certain vertical radiant asymmetry (up to 5.2 °C in C1) but with PD values within the ranges suggested by ISO 7730 in most cases. The horizontal radiant asymmetry appeared less meaningful, especially near counterposed refrigerated cabinets and cabinets with lateral bodies (as in A1, A3 and C1). To the contrary, for cabinets without lateral bodies, in case of counterposed cabinets one of which was not-refrigerated (as in A6) or in case of counterposed cabinets one of which horizontal (as in A4 and A5), the radiant asymmetry was more significant especially in summer and always within the ranges suggested by ISO 7730. Finally, the local discomfort due to the draught rate, is generally negligible except for the supermarket B in those positions characterized by high air velocity values (B4, B5, B6 and B7).

## 3.3. Subjective investigation

### 3.3.1. Global comfort

The analysis of the subjective investigation on global comfort condition summarized in figure 5 and in table 9 with special reference to the question on the perceptual scale revealed a typical perceived sensation of cold in both supermarkets (TSV<0).

Despite there were no significant differences between mean thermal sensation votes (TSV) expressed by men and women, from the analysis of the distribution of votes and the percentage of dissatisfied calculated according to Fanger's approach (percentage of persons who voted ±2 and ±3 [11, 73]) women appeared more unsatisfied. Particularly, in C1 (D1) $PD_F$ value for women was 10% (22%) instead of 0% (13%) in case of men. Unlike Lindberg's team findings [26], TSV values from subjective investigation appeared quite in agreement with PMV. This was because microclimatic conditions in C1 and D1 are not excessively cold being operative temperature over 20 °C in both seasons while in Swedish sale points varied in the ranges from 4.0 °C to 14.6 °C in autumn and 7.2 to 16.4 °C in summer [23]. In addition, Lindberg et al. [26] neither evaluated clothing insulation levels (set at 0.5 clo in summer and 1.4 clo in winter) nor considered the effect of body movements [56, 62] which can be responsible of highest uncertainties in the evaluation of the PMV [52-55].

The answers given on the evaluation (Do you find this) and preference scale (How you would prefer to be now?) were consistent with low discomfort levels in both sales points. Most of answers was placed between comfort or slightly discomfort conditions with a meaningful gender related difference in C1 where 91% of women found their conditions as comfortable instead of 43% of men. The judgment on the preference scale was in agreement with that assigned on the evaluative scale as most of interviewed did not ask for variations or would prefer only little warmer conditions. In this case gender related differences were meaningful only in C1 and quite negligible in D1.

Answers given on the thermal and overall tolerance scales confirmed all findings as above, being most of interviewed in perfectly bearable or bearable conditions. Gender-related differences were less meaningful except for position C1 (summer) where only 30% of women found perfectly bearable conditions (overall state) instead of 56% of men. Finally, as for humidity, due to values near to 50% (see table 5) no critical conditions were found. Women perceived slightly dry conditions in both sales points whereas men in D1 perceived a more humid microclimate (38% humid and 13% dry).

3.3.2. Local discomfort

The results of the subjective investigation focused on local discomfort are summarized in figure 6.

Due to the low air velocity values recorded in both the measurement points, local discomfort related to the draught rate was perceived only by about 1/3 of the investigated sample (36% in C1 and 37% in D1) with a certain predominance of men. As for the question on the perceptual scale (how do you feel draught?), in C1 the judgment was neutral with a symmetric distribution in case of women (33% for each choice) whereas 100% of men declared draughts neither pleasant nor annoying. To the contrary, in D1, probably due to a lower air temperature value (20.9 °C instead of 22.7 °C in B1), quite 75% of those perceived draughts found them as annoying.

Finally, in perfect agreement with objective analysis that revealed high cold air stratification phenomena, subjective investigation showed increasing cold perceptions in the lower parts of the body. Particularly as far the head, the perceived thermal sensation is of neutrality, whereas in the case of feet most of interviewed perceived a sensation of cold, with a predominance of women (89-90%) with respect to men (63-67%). This is consistent with the lower distribution of clothes in the lower parts of the body of women as stressed by Simone et al. [27] who correlated the cold sensation of lower extremities with the high non-uniformity of clothing in these parts of the body.

In the following Table 10 the main findings of the present research have been briefly summarized.

## 4 CONCLUSIONS

Making sales spaces comfortable environments is a necessity for customers and salesmen, since the more the environment is pleasant, the greater customers will spend their time inside it, with increased possibilities of purchases, even unscheduled. In this context human factors and ergonomic approach play a crucial role bot at design and assessment stages.

The authors investigated four supermarkets placed in Central Italy through an experimental campaign highlighting critical thermo-hygrometric conditions for customers in sale areas characterized by the presence of refrigerated cabinets. This phenomenon appeared more significant in summer due to the low thermal insulation of clothes worn by customers. As far overall thermal comfort for customers, the microclimatic survey revealed systematically negative PMV values (based upon real worn clothes) both in summer and in autumn season. Except for 5 cases out of 23, generalized discomfort conditions (PMV<-0.7) and in some cases the onset of cold stress (PMV<-2) have been found. To the contrary, due to the higher activity combined with a dress code more adequate for tasks in refrigerated areas, quite comfortable conditions for staff have been found.

The implementation of the IREQ stress index revealed in summer cold stress conditions in five areas (dairy products, cured meats, yoghurt, fish and vegetables) with estimated DLE greater than mean residence times of customers in sale areas. In autumn, although in several positions clothing insulation values were below the minimum value required, DLE values largely exceeded one hour. No stress conditions were found for staff in both seasons.

As far local discomfort, the typology of cabinets (especially vertical open) and their arrangement inside the sale area (e.g. counterposed cabinets) favour a meaningful stratification of cold air at ankle level with low floor temperature values, resulting in percentage of dissatisfied even greater than 80% which seemed to be reduced in case of closed cabinets (20% at most).

In two investigated supermarkets, also a subjective investigation has been carried out only for customers and related results were quite in agreement with the objective analysis. This is probably due to microclimatic conditions more favourable to comfort. In particular, as far global discomfort, the judgements given on perceptual, evaluative and tolerance scale were consistent with slightly cold conditions as confirmed by the thermal sensation votes (TSV=-0.61 in summer and TSV=-0.77 in autumn). Although TSV values seemed to be not affected by gender-related issues, higher percentages of dissatisfied (according to Fanger's criterion) were found for women. The subjective assessment of local discomfort confirmed the onset of the cold feed effect especially for women (about 90% in both sale areas) due to the poor distribution of clothes in lower parts of the body. Finally, women felt less draughts than men but found them more annoying.

Aiming at solving all issues as above, doored cabinets should be installed. They are effective in improving local discomfort especially in summer and allow significant energy savings by also reducing cold aisle phenomenon. In particular, microclimatic conditions recorded near doored cabinets (e.g. B6 and B7) confirm the reduction of local discomfort due to the air stratification despite low PMV values (<-0.7) related to the reduction of the mean radiant temperature (cold glasses) and the air temperature (frequent doors opening). As alternative or in combination with doored cabinets, it should be necessary to review the design of HVAC systems by means of the zoning of areas hosting open cabinets or the using of specific set point values of the supply air. In the future the analysis will be extended to other supermarkets by focusing the study on the typology of cabinets (especially doored cabinets) and related disposition in sale areas, subjective issues (e.g. seasonal effects, a larger sample of interviewed, effect on children) and, finally possible effects of the thermo-hygrometric conditions upon energy issues and the residence times spent in the sale areas. This is especially because there is no clear evidence that doored cabinets do not affect sales volume.

**ACKNOWLEDGMENTS**

A significant part of this research was developed within the the "Renovation of existing buildings in NZEB vision (nearly Zero Energy Buildings)" Project of National Interest (Progetto di Ricerca di Interesse Nazionale - PRIN) funded by the Italian Ministry of Education, Universities and Research (MIUR).

**Symbols**

| | |
|---|---|
| CVC | Closed Vertical Cabinet |
| DLE | Duration Limited Exposure, min |
| $DLE_{min}$ | Minimal Duration Limited Exposure, min |
| $DLE_{neu}$ | Neutral Duration Limited Exposure, min |
| DR | Draught rate, % |
| $h_c$ | convective heat transfer coefficient, W $m^{-2}$ |
| $h_r$ | radiative heat transfer coefficient, W $m^{-2}$ |
| $I_{cl}$ | Mean basic clothing thermal insulation of interviewed, $m^2$ K $W^{-1}$ or clo |
| $I_{cl,dyn}$ | Mean clothing thermal insulation of interviewed corrected by body movements $m^2$ K $W^{-1}$ or clo |
| $I_{cl,j}$ | Intrinsic clothing insulation of a generic j-th customer in the sale area, clo |
| $I_{cl,r}$ | Mean clothing thermal insulation of interviewed corrected by body movements $m^2$ K $W^{-1}$ or clo |
| $I_{clu,i}$ | Effective thermal insulation of the individual i-th garments making up the ensemble, clo |
| IREQ | Required Clothing Insulation, $m^2$ K $W^{-1}$ or clo |
| $IREQ_{min}$ | Minimal Required Clothing Insulation, $m^2$ K $W^{-1}$ or clo |
| $IREQ_{neu}$ | Neutral Required Clothing Insulation, $m^2$ K $W^{-1}$ or clo |
| m | Number of customers in the sale area, 1 |
| OHC | Open Horizontal Cabinet |
| OVC | Open Vertical Cabinet |
| PD | Percentage of Dissatisfied, % |
| $PD_F$ | Percentage of Dissatisfied by questionnaires according to Fanger's approach, % |
| PIV | Particle Image Velocimetry |
| PMV | Predicted Mean Vote according to Fanger's theory, 1 |
| PPD | Predicted Percentage of Dissatisfied, % |
| RH | Relative humidity, % |
| SD | Standard Deviation |
| TSV | Thermal Sensation Vote on the ASHRAE Scale, 1. |
| $t_a$ | Air temperature, °C |
| $t_{a,1.1}$-$t_{a,0.1}$ | Air temperature difference measured at head and ankle level for a seated person, °C |
| $t_d$ | Dew point temperature, °C |
| $t_f$ | Floor temperature, °C |
| $t_g$ | Globe temperature, °C |
| $t_h$-$t_{an}$ | Air temperature difference measured between head (1.7 m above the floor) and ankle (0.1 m above the floor) for a standing person, °C |
| $t_o$ | Operative temperature, °C |
| $t_r$ | Mean radiant temperature, °C |
| Tu | Turbulence intensity, % |
| $v_a$ | Air velocity, $m \cdot s^{-1}$ |

**Greek Symbols**

| | |
|---|---|
| $\Delta t_{(pr,0.6)h}$ | Horizontal radiant asymmetry for a seated person, °C |

$\Delta t_{(pr,0.6)v}$ Vertical radiant asymmetry for a seated person, °C
$\Delta t_{pr,h}$ Horizontal radiant asymmetry measured 1.1 m above the ground, °C
$\Delta t_{pr,v}$ Vertical radiant asymmetry measured 1.1 m above the ground, °C

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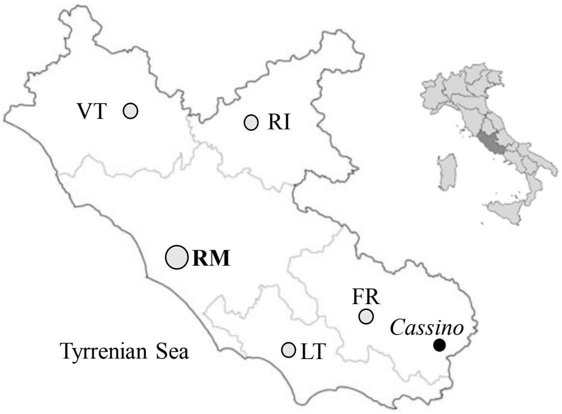
# Tables with captions

Table 1 – Main geographical and climatic data of Lazio (source: ISTAT - Italian National Institute of Statistics, 2017).




| | | |
|---|---|---|
| | Area | 17232 km$^2$ |
| | Population | 5652492 |
| | Density | 416/km$^2$ |
| | Capital | Rome |
| | Position | 41°53′35″N 12°28′58″E |
| | Degree day range (°C) of the main urban areas | |
| | Rome (RM) | 1240 – 3134 |
| | Viterbo (VT) | 1654 – 2343 |
| | Rieti (RI) | 1742 – 3187 |
| | Latina (LT) | 938 – 2426 |
| | Frosinone (FR) | 1099 – 3088 |
| | Cassino | 1164 |
| Month | Minimum and maximum outdoor air temperature values in the district of Cassino | |
| | Min (°C) | Max (°C) |
| June | 15.0 | 26.2 |
| July | 17.0 | 29.3 |
| August | 17.2 | 29.5 |
| September | 14.9 | 26.1 |
| October | 11.2 | 21.4 |
| November | 7.5 | 16.4 |
| December | 4.2 | 12.5 |

Table 2 – Description of the measurement points and cabinets in the four investigated supermarkets in figures 1 and 2. Vertical cabinets are 2.0 m in height. OVC=Open Vertical Cabinet; OHC=Open Horizontal cabinet; CVC=Closed Vertical Cabinet.

| Ref. | Season | Foodstuff | Type | Description |
|---|---|---|---|---|
| A1 | Summer | Dairy product | OVC | 6 m long with 2 lateral bodies 4 m long in front of an OHC |
| A2 | Summer | Delicatessen | - | Refrigerated counter in front of an OHC |
| A3 | Summer | Meat | OVC | 8 m long with 2 lateral bodies 4 m long in front of an OHC |
| A4 | Summer | Milk | OVC | 6 m long in front of an OHC |
| A5 | Summer | Yogurt | OHC | in front of an OVC 7 m long |
| A6 | Summer | Fruits & vegetables | OVC | 8 m long in front of a not refrigerated vertical cabinet. |
| A7 | Summer | Fish | OHC | 7 m long and 2 m deep |
| B1 | Autumn | Cured meats | OVC | 20 m long in front of an OVC 12 m long |
| B2 | Autumn | Cured meats | OVC | 20 m long in front of an OVC 12 m long |
| B3 | Autumn | Cured meats | OVC | 20 m long in front of an OVC 6 m long |
| B4 | Autumn | Milk - dairy product | OVC | 21 m long in front of a not refrigerated vertical cabinet 15 m long |
| B5 | Autumn | Milk - dairy product | OVC | 21 m long in front of an OHC 6.0 m long |
| B6 | Autumn | Dairy product | CVC | 20 m long in front of a CVC 17 m long |
| B7 | Autumn | Dairy product | CVC | 20 m long in front of a CVC 17 m long |
| C1 | Summer | Meat | OVC | 8.0 m long with two lateral bodies 4 m long in front of an OHC |
| D1 | Autumn | Meat - dairy product | OHC | 2 counterposed small OHC between an OHC and an OVC |

Table 3 – The classification proposed by ISO 7730 Standard [50].

| | **Category A** | | **Category B** | | **Category C** | |
|---|---|---|---|---|---|---|
| | **Condition** | **PD (%)** | **Condition** | **PD (%)** | **Condition** | **PD (%)** |
| **PMV** | -0.20 – 0.20 | ≤ 6 | -0.50 – 0.50 | ≤ 10 | -0.70 – 0.70 | ≤ 15 |
| $\mathbf{t_f}$ | 19 – 29 °C | ≤ 10 | 19 – 29 °C | ≤ 10 | 17 – 31 °C | ≤ 15 |
| $\mathbf{t_{a,1.1}\text{-}t_{a,0.1}}$ | < 2 °C | ≤ 3 | < 3 °C | ≤ 5 | < 4 °C | ≤ 10 |
| $\mathbf{\Delta t_{(pr,0.6)h}}$ | < 10 °C | ≤ 5 | < 10 °C | ≤ 5 | < 13 °C | ≤ 10 |
| $\mathbf{\Delta t_{(pr,0.6)v}}$ | < 5 °C | ≤ 5 | < 5 °C | ≤ 5 | < 7 °C | ≤ 10 |
| $\mathbf{v_a}$ | DR < 10 | ≤ 10 | DR < 10 | ≤ 10 | DR < 15 | ≤ 15 |

Table 4 – Basic clothing insulation values in clo (1 clo = 0.155 $m^2K/W$) calculated according to equations (1) and (2) and related standard deviations used in the present investigation. The gender difference is pointed out.

| **Supermarket** | **Subjects** | **Description** | **Women (clo)** | **Men (clo)** | **Mean (clo)** |
|---|---|---|---|---|---|
| A, C (summer) | Customers | 18 subjects: 56% of women | 0.39±0.08 | 0.44±0.08 | 0.41±0.08 |
| B, D (autumn) | Customers | 17 subjects: 53% of women | 0.63±0.12 | 0.69±0.14 | 0.66±0.13 |
| A, C (summer) | Staff | Underpants, overalls, socks, shoes | - | | 0.70 |
| B, D (autumn) | Staff | Underwear, long sleeves t-shirt, trousers, thermal jacket, socks, shoes | - | | 1.20 |

Table 5 – Average values of the main microclimatic variables measured at 1.1 m above the floor and PMV values referred to the customers (Cus) and the staff (St) in the two considered seasons. Mean and standard deviation (SD) of seasonal values and global comfort categories according to ISO 7730 are also reported [50]. DIS=Discomfort. Autumn (Summer) basic clothing insulation values for customers and staff were 0.66 and 1.20 clo (0.41 and 0.70 clo), respectively.

| Meas. Point | Type | $t_g$ (°C) | $t_r$ (°C) | $t_a$ (°C) | $t_o$ (°C) | $v_a$ (m/s) | Tu (%) | RH (%) | PMV | | Category | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Cus | St | Cus | St |
| **Autumn – HVAC set point: $t_a$= 20 ± 1 °C; RH = 50 ± 20 %** | | | | | | | | | | | | |
| A1 | OVC | 15.5 | 15.4 | 15.8 | 15.6 | 0.01 | 159 | 56.2 | -1.38 | -0.20 | DIS | B |
| A2 | - | 20.9 | 22.1 | 18.4 | 20.3 | 0.03 | 117 | 47.7 | -0.55 | 0.37 | C | B |
| A3 | OVC | 16.1 | 16.5 | 15.2 | 15.9 | 0.02 | 105 | 58.3 | -1.39 | -0.21 | DIS | B |
| A4 | OVC | 16.0 | 16.0 | 16.0 | 16.0 | 0.01 | 166 | 55.5 | -1.31 | -0.15 | DIS | A |
| A5 | OHC | 17.1 | 17.1 | 17.0 | 17.1 | 0.02 | 93 | 52.2 | -1.13 | -0.02 | DIS | A |
| A6 | OVC | 16.1 | 16.0 | 16.3 | 16.2 | 0.05 | 76 | 54.6 | -1.37 | -0.17 | DIS | A |
| A7 | OHC | 18.5 | 18.4 | 18.7 | 18.6 | 0.05 | 122 | 46.8 | -0.87 | 0.18 | DIS | A |
| B1 | OVC | 19.7 | 20.0 | 18.8 | 19.4 | 0.00 | 75 | 53.6 | -0.58 | 0.35 | C | B |
| B2 | OVC | 18.7 | 18.7 | 18.4 | 18.6 | 0.02 | 83 | 52.3 | -0.79 | 0.22 | DIS | B |
| B3 | OVC | 16.9 | 16.9 | 16.8 | 16.9 | 0.03 | 77 | 60.2 | -1.16 | -0.03 | DIS | A |
| B4 | OVC | 16.5 | 16.4 | 16.8 | 16.6 | 0.07 | 67 | 53.6 | -1.32 | -0.12 | DIS | A |
| B5 | OVC | 16.7 | 16.4 | 17.4 | 16.9 | 0.06 | 86 | 44.2 | -1.24 | -0.08 | DIS | A |
| B6 | CVC | 19.0 | 19.4 | 18.6 | 19.0 | 0.18 | 95 | 50.8 | -1.01 | 0.13 | DIS | A |
| B7 | CVC | 19.5 | 19.7 | 19.2 | 19.5 | 0.13 | 88 | 48.3 | -0.82 | 0.24 | DIS | B |
| D1 | OHC | 20.7 | 20.6 | 20.9 | 20.8 | 0.025 | 98 | 54.4 | -0.30 | 0.58 | B | C |
| Mean | | 17.9 | 18.0 | 17.6 | 17.8 | 0.047 | 100 | 52.6 | -1.01 | 0.07 | - | - |
| SD | | 1.8 | 2.0 | 1.5 | 1.7 | 0.049 | 29 | 4.4 | 0.35 | 0.24 | - | - |
| **Summer – HVAC set point: $t_a$= 23 ± 1 °C; RH = 50 ± 20 %** | | | | | | | | | | | | |
| A1 | OVC | 19.1 | 21.0 | 15.7 | 18.4 | 0.05 | 84 | 56.7 | -2.12 | -0.72 | DIS | DIS |
| A2 | - | 20.3 | 21.8 | 17.4 | 19.6 | 0.01 | 127 | 50.8 | -1.57 | -0.38 | DIS | B |
| A3 | OVC | 23.6 | 24.0 | 22.5 | 23.3 | 0.03 | 106 | 36.9 | -0.57 | 0.37 | C | B |
| A4 | OVC | 23.0 | 23.3 | 22.1 | 22.7 | 0.01 | 318 | 37.9 | -0.66 | 0.29 | C | B |
| A5 | OHC | 16.9 | 16.9 | 17.0 | 17.0 | 0.02 | 93 | 52.2 | -2.24 | -0.80 | DIS | DIS |
| A6 | OVC | 16.1 | 16.1 | 16.3 | 16.2 | 0.05 | 76 | 54.6 | -2.57 | -0.99 | DIS | DIS |
| A7 | OHC | 19.0 | 19.0 | 18.9 | 19.0 | 0.05 | 122 | 46.2 | -1.80 | -0.46 | DIS | B |
| C1 | OVC | 22.0 | 21.7 | 22.7 | 22.2 | 0.03 | 133 | 55.0 | -0.72 | 0.31 | DIS | B |
| Mean | | 20.0 | 20.5 | 19.1 | 19.8 | 0.031 | 132 | 48.8 | -1.53 | -0.30 | - | - |
| SD | | 2.7 | 2.9 | 2.9 | 2.7 | 0.017 | 78 | 7.7 | 0.79 | 0.55 | - | - |

Table 6 – Classes of risk reported in ISO 15265 standard [57]. DLEs have to be evaluated according to according to ISO 11079 (*) [65].

| **Class** | **Criteria** |
|---|---|
| Immediate constraint* | DLE < 30 min |
| Constraint in the short term* | $I_{clr}$< $IREQ_{min}$ and DLE < 120 min |
| Constraint in the long term | PMV < -2 and $IREQ_{min} \leq I_{clr} \leq IREQ_{neu}$ |
| Cold discomfort | -2 ≤ PMV < - 0.5 |
| Comfort | -0.5 ≤ PMV ≤ +0.5 |
| Warm discomfort | +0.5 < PMV ≤ +2 |
| Constraint in the long term* | DLE < 480 min |
| Constraint in the short term* | DLE < 120 min |
| Immediate constraint** | DLE < 30 min |

Table 7 – Cold discomfort assessment according to IREQ index in investigated measurement positions. In bold, microclimatic conditions such as $I_{cl,r}<IREQ_{min}$ have been highlighted. $I_{cl,r}$ values have been calculated on the basis of basic clothing insulation values in table 4. Mean and standard deviation (SD) of seasonal values are also reported.

| Ref. | Season | PMV | $I_{cl,r}$ (clo) | $IREQ_{min}$ (clo) | $IREQ_{neu}$ (clo) | $DLE_{min}$ (min) | $DLE_{neu}$ (min) |
|---|---|---|---|---|---|---|---|
| **Customers (Autumn)** | | | | | | | |
| A1 | OVC | **-1.38** | **0.6** | **0.75** | **1.1** | **66** | **220** |
| A2 | | -0.55 | 0.6 | 0.39 | 0.75 | 191 | >480 |
| A3 | OVC | **-1.39** | **0.6** | **0.75** | **1.1** | **66** | **219** |
| A4 | OVC | **-1.31** | **0.6** | **0.72** | **1.07** | **70** | **270** |
| A5 | OHC | **-1.13** | **0.6** | **0.63** | **0.99** | **83** | **>480** |
| A6 | OVC | **-1.37** | **0.6** | **0.71** | **1.06** | **71** | **293** |
| A7 | OHC | -0.87 | 0.6 | 0.5 | 0.85 | 123 | >480 |
| B1 | OVC | -0.58 | 0.6 | 0.49 | 0.87 | 156 | >480 |
| B2 | OVC | -0.79 | 0.6 | 0.56 | 0.93 | 122 | >480 |
| B3 | OVC | **-1.16** | **0.6** | **0.71** | **1.08** | **81** | **>480** |
| B4 | OVC | **-1.32** | **0.6** | **0.73** | **1.1** | **77** | **428** |
| B5 | OVC | **-1.24** | **0.6** | **0.69** | **1.07** | **83** | **>480** |
| B6 | CVC | -1.01 | 0.6 | 0.54 | 0.92 | 125 | >480 |
| B7 | CVC | -0.82 | 0.6 | 0.49 | 0.87 | 153 | >480 |
| Mean | | -1.07 | 0.60 | 0.62 | 0.98 | 105 | - |
| SD | | 0.30 | 0.00 | 0.12 | 0.12 | 40 | - |
| **Customers (Summer)** | | | | | | | |
| A1 | OVC | **-2.12** | **0.27** | **0.58** | **0.94** | **46** | **120** |
| A2 | - | **-1.57** | **0.27** | **0.46** | **0.81** | **59** | **263** |
| A3 | OVC | -0.57 | 0.27 | 0.1 | 0.47 | 210 | >480 |
| A4 | OVC | -0.66 | 0.27 | 0.14 | 0.51 | 159 | >480 |
| A5 | OHC | **-2.24** | **0.27** | **0.64** | **0.99** | **42** | **97** |
| A6 | OVC | **-2.57** | **0,27** | **0.71** | **1.06** | **38** | **79** |
| A7 | OHC | **-1.8** | **0.27** | **0.47** | **0.82** | **57** | **237** |
| C1 | OVC | -0.72 | 0.27 | 0.22 | 0.6 | 142 | >480 |
| Mean | | -1.53 | 0.27 | 0.42 | 0.78 | 94 | 159 |
| SD | | 0.79 | 0.00 | 0.23 | 0.22 | 66 | 85 |
| **Staff (Summer)** | | | | | | | |
| A1 | OVC | -0.51 | 0.61 | 0.58 | 0.95 | 236 | >480 |
| A5 | OHC | -0.59 | 0.61 | 0.49 | 0.86 | 177 | >480 |
| A6 | OVC | -0.77 | 0.61 | 0.55 | 0.91 | 132 | >480 |
| Mean | | -0.62 | 0.61 | 0.54 | 0.91 | 182 | |
| SD | | 0.13 | 0.00 | 0.05 | 0.05 | 52 | |

Table 8 – Measurement of the main parameters related to local discomfort. The percentages of dissatisfied have been calculated by means of equations reported in ISO 7730 [50]. (*) Draught rate model is applicable only for $v_a$>0.05 m/s [50]. Limit values of different PDs are listed in table 3. Mean and standard deviation (SD) of seasonal values are also reported.

| **Meas. point** | **Type** | **Vertical air temperature difference** | | **Warm or cold floor** | | **Cold wall** | | **Warm ceiling** | | **Draught rate** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $t_h$-$t_{an}$ | PD | $T_f$ | PD | $\Delta t_{pr,h}$ | PD | $\Delta t_{pr,v}$ | PD | DR |
| | | (°C) | (%) | (°C) | (%) | (°C) | (%) | (°C) | (%) | (%) |
| **Autumn** | | | | | | | | | | |
| A1 | OVC | 5.8 | 31 | 13.8 | 26 | 2.3 | 0.3 | 0.7 | 0.7 | * |
| A2 | - | 4.5 | 13 | 16.5 | 17 | 1.6 | 0.2 | 1.3 | 1.3 | * |
| A3 | OVC | 9.1 | 88 | 13.1 | 28 | 2.9 | 0.4 | 0.1 | 0.1 | * |
| A4 | OVC | 6.9 | 54 | 13.4 | 27 | 3.5 | 0.4 | 4 | 5 | * |
| A5 | OHC | 5.1 | 20 | 15 | 21 | 2 | 0.3 | 4.4 | 5.7 | * |
| A6 | OVC | 5.1 | 20 | 14.2 | 24 | 1.5 | 0.2 | 5 | 6.7 | * |
| A7 | OHC | 4.1 | 10 | 16.8 | 16 | 1.5 | 0.2 | 5 | 6.7 | * |
| B1 | OVC | 7.9 | 73 | 16.1 | 18 | 1.3 | 0.2 | 3.4 | 4 | * |
| B2 | OVC | 9 | 87 | 14.4 | 24 | 0.5 | 0.2 | 4.3 | 5.5 | * |
| B3 | OVC | 7.4 | 64 | 14.1 | 25 | 3.7 | 0.5 | 2.7 | 3 | * |
| B4 | OVC | 7.9 | 73 | 13.5 | 27 | 1.5 | 0.2 | 3.1 | 3.6 | 6 |
| B5 | OVC | 8.1 | 76 | 13.1 | 28 | 1.2 | 0.2 | 3.2 | 3.8 | 4 |
| B6 | CVC | 4.9 | 17 | 17.1 | 15 | 0.2 | 0.1 | 1.8 | 1.9 | 25 |
| B7 | CVC | 5.1 | 20 | 17.7 | 13 | 0.6 | 0.2 | 3.7 | 4.5 | 16 |
| D1 | OHC | 6.1 | 37 | 17.7 | 13 | 2.5 | 0.3 | 3.3 | 3.9 | * |
| mean | | **6.5** | **45.5** | **15.1** | **21.5** | **1.8** | **0.3** | **3.1** | **3.8** | **12.8** |
| SD | | **1.7** | **29.0** | **1.7** | **5.6** | **1.0** | **0.1** | **1.5** | **2.1** | **9.7** |
| **Summer** | | | | | | | | | | |
| A1 | OVC | 6.4 | 43 | 15.5 | 20 | 1.4 | 0.2 | 2.3 | 2.5 | * |
| A2 | - | 4.5 | 13 | 16.5 | 17 | 1.3 | 0.2 | 1.6 | 1.7 | * |
| A3 | OVC | 8.4 | 81 | 16 | 18 | 0.6 | 0.2 | 2.9 | 3.3 | * |
| A4 | OVC | 6.7 | 49 | 15.8 | 19 | 4 | 0.5 | 3.5 | 4.2 | * |
| A5 | OHC | 6 | 35 | 16.1 | 18 | 4.4 | 0.6 | 2 | 2.1 | * |
| A6 | OVC | 5.1 | 20 | 18.6 | 11 | 5 | 0.8 | 1.5 | 1.6 | * |
| A7 | OHC | 4.5 | 13 | 17.5 | 14 | 0.6 | 0.2 | 2 | 2.1 | * |
| C1 | OVC | 7.1 | 58 | 18.2 | 12 | 0.2 | 0.1 | 5.2 | 7.1 | * |
| mean | | **6.1** | **39.0** | **16.8** | **16.1** | **2.2** | **0.4** | **2.6** | **3.1** | |
| SD | | **1.4** | **23.8** | **1.2** | **3.4** | **1.9** | **0.3** | **1.2** | **1.8** | |

Table 9 – Post-processing of subjective data related to the question on the thermal sensation of the ASHRAE scale (How are you feeling now?) and comparison with the objective survey (PMV/PPD). (S) Summer; (A) Autumn.

| | **Season** | **Percentage of who voted on the ASHRAE scale (%)** | | | | | | | **TSV (-)** | **$PD_F$ (%)** | **PMV (-)** | **PPD (%)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **-3** | **-2** | **-1** | **0** | **+1** | **+2** | **+3** | | | | |
| C1 Men | S | 0 | 0 | 63 | 37 | 0 | 0 | 0 | -0.63 | 0 | -0.61 | 13 |
| C1 Women | | 0 | 10 | 50 | 30 | 10 | 0 | 0 | -0.60 | 10 | -0.79 | 18 |
| C1 All | | 0 | 6 | 56 | 33 | 5 | 0 | 0 | -0.61 | 6 | -0.72 | 16 |
| D1 Men | A | 12 | 0 | 38 | 50 | 0 | 0 | 0 | -0.77 | 13 | -0.25 | 6 |
| D1 Women | | 0 | 23 | 33 | 44 | 0 | 0 | 0 | -0.77 | 22 | -0.35 | 8 |
| D1 All | | 5 | 13 | 35 | 47 | 0 | 0 | 0 | -0.77 | 18 | -0.30 | 7 |

Table 10 – Summary of main objectives and findings of the present investigation.

| Objectives | Findings |
|---|---|
| <u>*Experimental site (i.e. Mediterranean climate) and seasons (i.e. summer and autumn)*</u><br><br>The choice of the experimental site (i.e. Mediterranean climate) and seasons (i.e. summer and autumn) was aimed at assessing the influence of doored and open refrigerated cabinets both on male and female customer's perception of thermal comfort when light clothes are worn (with related consequences in terms of cold stress). | Experimental results show the criticality represented by local and global thermal comfort perceived by customers in refrigerated areas of supermarkets especially in summer (average PMV of -1.53). In autumn (average PMV of -1.01) such situation is confirmed, although to a lesser extent. |
| <u>*Global and local thermal comfort*</u><br><br>There are no systematic studies focused on local discomfort near refrigerated cabinets (lack of protocols inspired to international standards in the field) in Mediterranean climates. | Local discomfort conditions are also critical in both seasons: i) average values of vertical air temperature difference (measured between ankles and head) of above 6 °C with related PDs above 39% have been measured; ii) average values of floor temperature below 16.8°C with PDs related to cold floor above 16% have been measured. |
| <u>*Objective assessment of thermo-hygrometric conditions*</u><br><br>No research paper exists focused on the assessment of cold stress (IREQ) in such a kind of environments (customers and staff) based upon worn clothing. In this paper robust protocols of objective assessment of thermo-hygrometric conditions compliant to ISO 15265 [57] and ISO 15743 [58] have been adopted. | As regards thermal stress conditions, results clearly show cold stress (PMV<-2) for customers in most of investigated positions. Notwithstanding this, DLEs calculated consistently with IREQ model [65] largely exceed mean residence times spent in sales area. In case of staff, worn clothes are enough to avoid cold stress with no risks for workers. |
| <u>*Male and female customer's perception of thermal comfort*</u><br><br>Gender related differences in thermal experience (global and local) have been investigated | No significant differences between thermal sensation votes (TSV) expressed by females and males have been found. Nevertheless, females resulted more unsatisfied than males. In summer (autumn) 10% (22%) of females are unsatisfied instead of 13% (0%), probably due to open shoes and lighter clothing worn. |
| <u>*Influence of different layout, HVAC, buildings and cabinet typology*</u><br><br>This investigation, carried out in four different supermarkets, was aimed at providing a wider picture on thermal comfort conditions in refrigerated areas induced by: i) the interactions with different HVAC systems, building envelopes and cabinet layout, ii) the different typology and arrangement of cabinets, and iii) the effect of seasonal set point of HVAC systems. | The influence of the listed factors on thermal discomfort can be evaluated by means of standard deviation or systematic difference of results in investigated cases:<br>i) concerning the interactions between different HVAC systems, buildings envelope and cabinets type/layout, a standard deviation of PMV values of 0.79 in summer and 0.35 in autumn was found. Furthermore, concerning the different characteristics of building envelopes, only warm ceiling seems to slightly affect comfort perception (3.8% and 3.1% dissatisfied during autumn and summer respectively), especially for supermarket A;<br>ii) the typology and arrangement of cabinets seem to affect mainly local discomfort due to vertical air temperature gradient and cold floor. In fact: i) OVCs determine a PD respectively about 62.9% and 25.2% in autumn and 50.2% and 16% in summer, ii) OHCs determine a PD% respectively about 22.3% and 16.7% in autumn and 24% and 16% in summer, iii) CVC resulted in PDs of about 18.5% and 14%, probably due to frequent doors opening.<br>iii) concerning HVAC setpoint, a mean air temperature reduction of about 3.9 °C (2.4 °C) in summer (autumn) was found in refrigerated areas. |

# Figures with captions

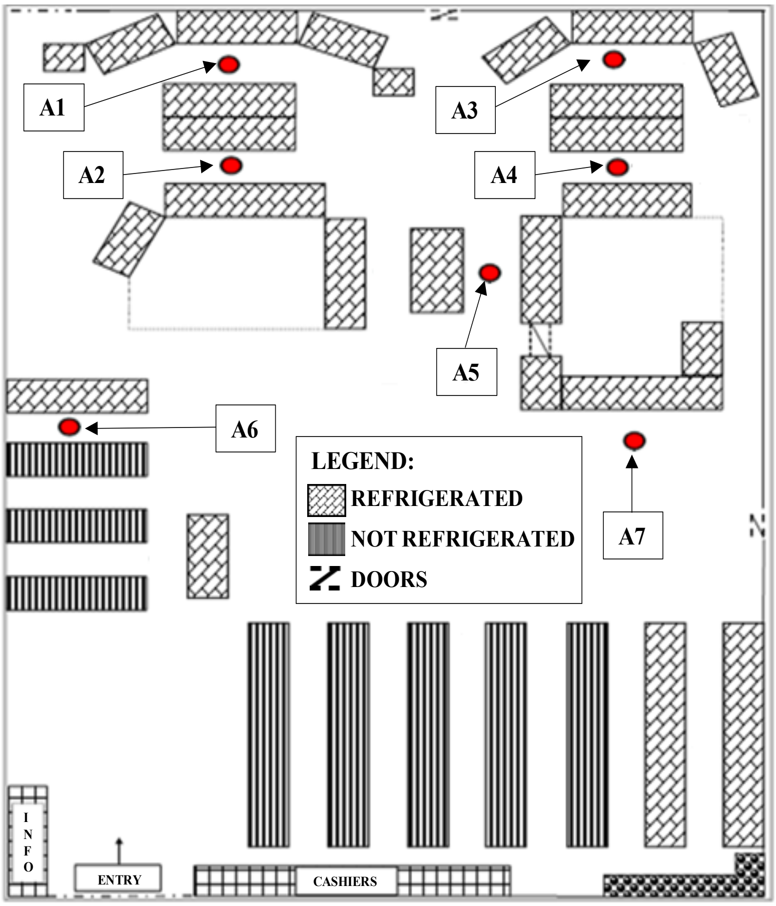



Figure 1 – Drawing of the investigated area of supermarket A with measurement points (not in real scale).

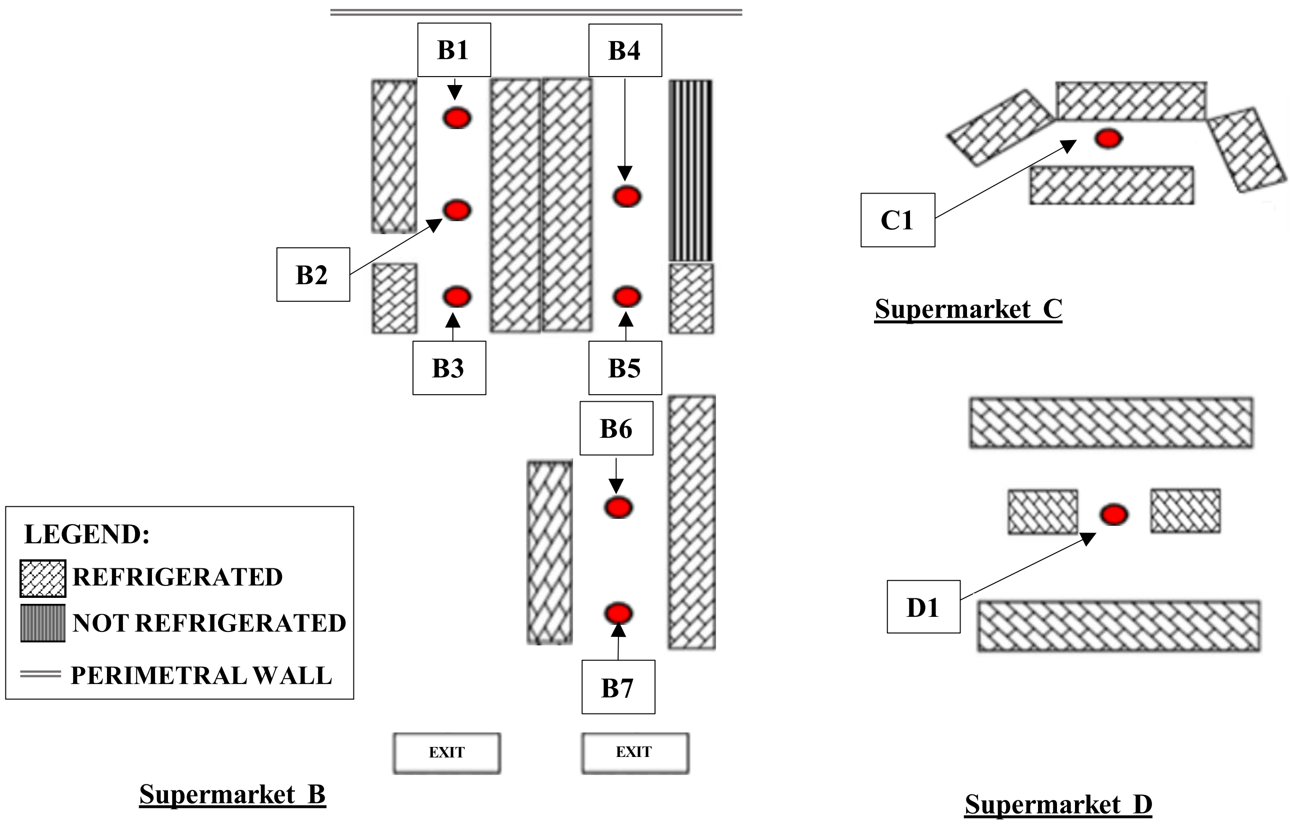



Figure 2 – Drawing of investigated areas of supermarkets B, C and D with measurement points (not in real scale).

Figure 3 – Experimental apparatus during measurement period and survey administration.

**1. How are you feeling now?**

Hot ☐
Warm ☐
Slightly warm☐
Neutral ☐
Slightly cool ☐
Cool ☐
Cold ☐

**2. Do you find this?**

Comfortable ☐
Slightly uncomfortable ☐
Uncomfortable ☐
Very uncomfortable ☐

**3. How would you prefer to be now?**

Much warmer ☐
Warmer ☐
Slightly warmer ☐
Neither warmer nor cooler ☐
Slightly cooler ☐
Cooler ☐
Much cooler☐

4. **How do you find this position (thermal state)?**

Perfectly bearable ☐
Bearable ☐
Fairly difficult to bear ☐

**5. Do you feel draughts?**

YES ☐
NO ☐

**6. How do you feel draughts?**

Pleasant ☐
Neither pleasant nor annoying ☐
Annoying ☐

**7. How do you feel (head)?**

Warm ☐
Neutral ☐
Cool☐

**8. How do you feel (hands)?**

Warm ☐
Neutral ☐
Cool☐

**9. How do you feel (feet)?**

Warm ☐
Neutral ☐
Cool☐

**10. How do you feel air (humidity)?**

Dry ☐
Neither dry nor humid ☐
Humid ☐

**11. How do you find this position (overall state)?**

Perfectly bearable ☐
Bearable ☐
Fairly difficult to bear ☐

Figure 4 – The section of the administrated questionnaire devoted to the global and local discomfort.

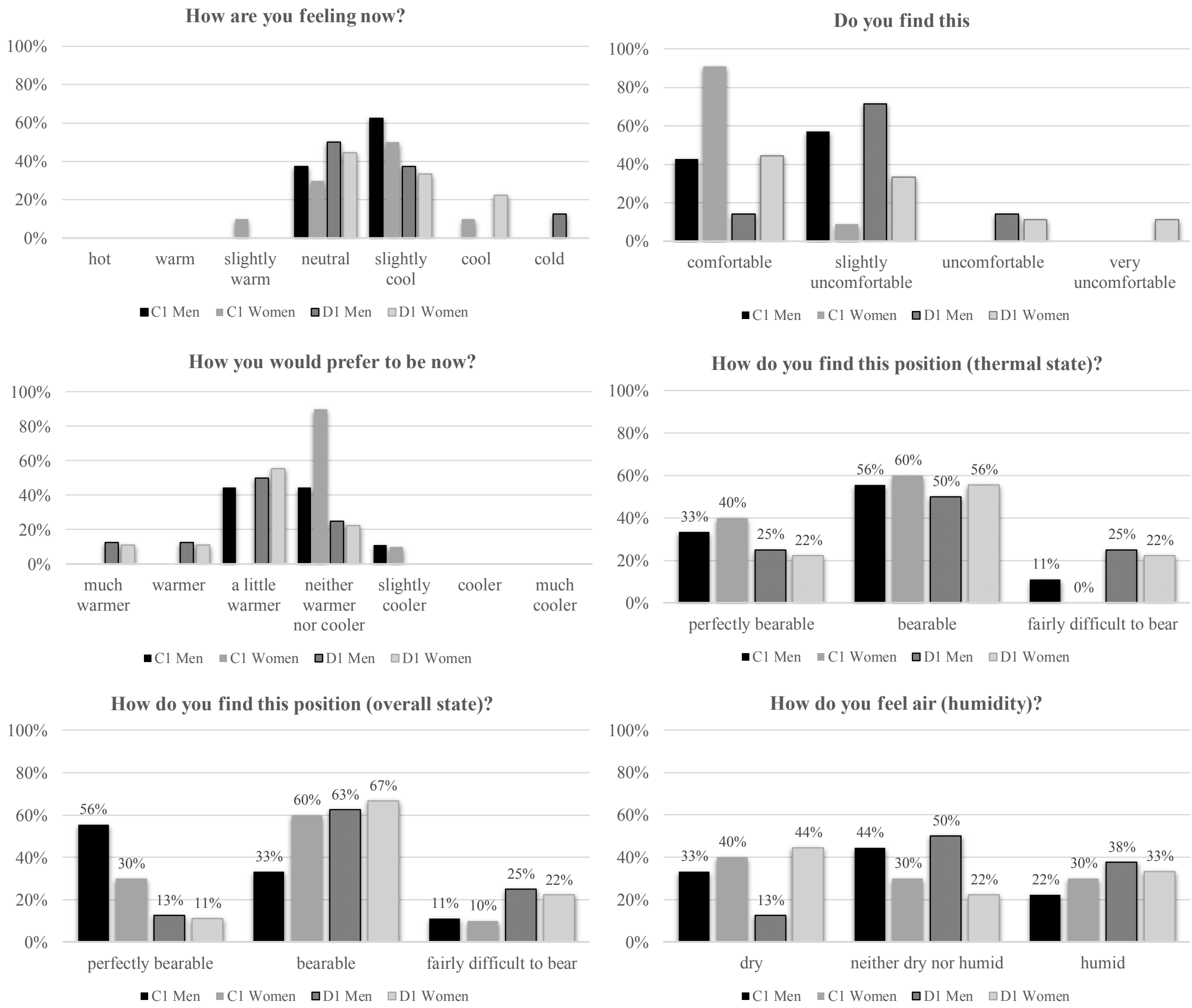



Figure 5 – Results of subjective investigations in supermarkets C and D (global comfort).

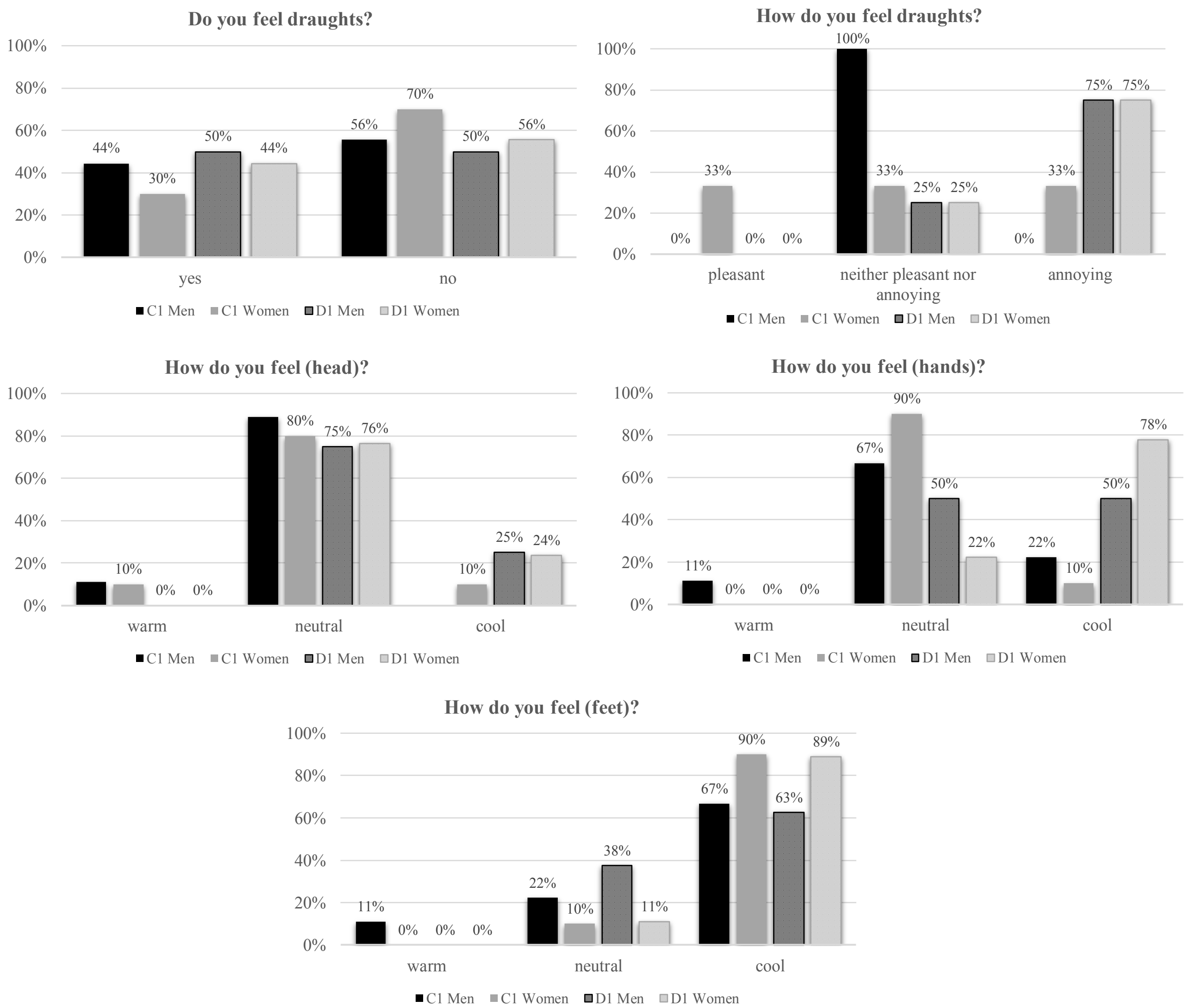



Figure 6 – Results of subjective investigations in supermarkets C and D (local discomfort).