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Optimization of indoor environment quality for hypermarket workers: from subjective response to objective design criteria

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Abstract

Thermal, acoustical, visual, and air quality conditions were investigated through both subjective and objective measures carried out in a hypermarket in Southern Italy. Different statistical techniques were used to point out the relations existing between subjective factors and global perception of IEQ. To derive practical guidelines to optimize IEQ conditions, the correlations between subjective ratings pertaining to different IEQ factors and the corresponding objective descriptors were found. Finally, combining above results with weights obtained from multiple regression showed that controlling IEQ by acting on single parameters would require unrealistic set-points. Conversely, the highest IEQ ratings can only be obtained by simultaneously optimizing the different attributes.

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Keywords: Indoor environment quality; hypermarkets; optimization

1. Introduction

A significant number of research efforts has been devoted to the understanding, measurement, and optimization of indoor environment quality (IEQ) in different types of spaces, a summary of which can be found in two recent reviews [1,2]. However, with reference to hypermarkets and large retail buildings, the literature offers a number of contributions focused on individual aspects of the problem, such as thermal comfort [3], air quality [4,5], acoustic

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comfort [6], and on subjective perception by occupants and on the influence of IEQ on health [7]. In addition to these valuable contributions, the authors carried out a systematic study aimed at understanding in a more comprehensive way how the specific features of such spaces, characterized by indoor characteristics that are far from being homogeneous, consisting of several sub-spaces with different combinations of environmental parameters, and occupants that rarely stay in a fixed position, influence IEQ. Taking advantage of a long and detailed survey carried out in a large hypermarket, in which data were collected about workers' comfort conditions involving all the IEQ factors together, the following aspects were investigated. First, the measurement method was validated for the specific type of environment and job typology [8]. Then, the main findings from the thermal [9], acoustical [10], and air quality [11] point of view were presented. Finally, a number of "best practices" were outlined to address the most common problems [12], and, at the same time, a study of the way different attributes contribute to the definition of the global perception of the IEQ was carried out, also using non-linear models to interpret the results [13]. Even though collecting data in a single hypermarket may apparently limit the extent of the analysis, it should be noted that the specificity of this group of buildings relies in the way the interior is arranged and how different sub-spaces are connected. From this point of view many similarities may be found between the surveyed building and others having the same function. Taking advantage of the results already collected, the present paper aims at investigating the practical consequences of such correlations in terms of their influence on objective parameters and on their respective set-point values.

Nomenclature

TSat	Thermal Satisfaction
VSat	Visual Satisfaction
IAQSat	IAQ Satisfaction
ASat	Acoustic Satisfaction
GSat	Global Satisfaction
LocDis	Local thermal dissatisfaction rating (obtained as sum of body parts where subjects felt cold/warm)

2. Methods

2.1. Site description

The research was carried out in a hypermarket located in Bari, in Southern Italy. The city has climate conditions common in Mediterranean area, with warm humid summers and mild winters. The Adriatic Sea gives mild temperature ranges: in January, the coldest month, the mean temperature is 8.7 °C while in August, the warmest one, it is 24.3 °C. The conventional period in which heating is used starts on November 15 and ends on March 31.

The shopping centre was completed in 2005 and includes a shopping arcade and a hypermarket. The hypermarket covers a total floor area of about 17,000 m^2, 10,900 m^2 of which are occupied by the air-conditioned sales area, 4,200 m^2 by the naturally ventilated warehouses and 1,900 m^2 by the air-conditioned food processing divisions. The mean ceiling height is 6.5 m in the sales area and warehouses, and 3.5 m in the food processing divisions because of suspended ceilings. The hypermarket is mostly lit by artificial lighting. Only the checkouts and warehouses benefit from daylight. Artificial light consists of down-lights located at ceiling height. The average number of daily customers is about 3000. The arrangement of different goods on sale is outlined in Fig. 1. The air conditioning system provides heating in the conventional period, cooling in summer, and fresh air supply in the remaining periods.

2.2. Data acquisition and questionnaires

The survey investigated the comfort conditions of the hypermarket staff mainly in winter and summer, analysing environment quality with the most unfavourable climatic conditions. However, field measurements were also carried out during spring and fall to study the effect of transition from heating to cooling, and vice versa, on comfort sensations.

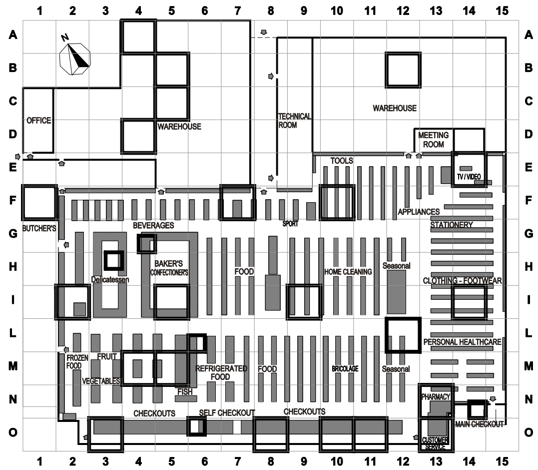

Fig. 1. Hypermarket plan, showing areas (in bold) where both subjective and objective measurements were carried out. The grid unit is 10 m

The measurement procedure has been thoroughly discussed and validated in [8]. Current standards were taken as a reference for instrument characteristics [14], questionnaire definition [15,16] and measurement methods [17-19]. In addition, luminance maps obtained using a calibrated digital camera with a fisheye lens were determined at selected positions. Indoor Air Quality (IAQ) parameters were measured only during the last part of the survey using two non-dispersive infrared sensors for CO_2 and, for a limited time, using a constant flow dust sampler for particulate matter (PM).

In all the cases, the most difficult aspect to take into account was related to most employees having jobs that require them to move between many different areas, so it was hard to define a fixed workplace. Because of the slow response time of some instruments, monitoring and evaluation points were kept fixed. The location of fixed point was decided taking into account the hypermarket layout (Fig. 1), the specific features of each job and the need to characterize every workplace, including, in particular, those showing interesting deviations from the average conditions. A total of 35 measurement positions were considered, often subdividing selected areas when non-homogenous conditions were observed. Continuous physical measurements were carried out during working days for time intervals from one to five hours at every measurement point, taking into consideration the HVAC system functioning time.

Employees working within the range of the measuring station were randomly invited to answer the questionnaire. In some cases they were asked to move closer to the measurement station, but when this happened they were asked to answer considering their subjective sensations when and where the questionnaire was filled in, even if it was not their customary workplace. The questionnaire was anonymous. In order to correlate objective parameters with subjective responses, the latter were paired with instrumental measurements averaged over the ten-minute interval before subjects returned their questionnaire.

A total of 610 questionnaires, filled-in by about 120 workers, were collected from February 2010 to July 2011, more or less equally distributed between summer (35%), winter (39%), and intermediate seasons (26%). As during the first part of the survey (until July 2010) a high degree of correlation was found between some groups of questions [8], in the second part of the survey the groups of questions were presented in random order to completely remove any risk of "automated response". A total of 291 questionnaires were collected using the new methodology. Then, a further refinement was carried out by removing subjects that provided markedly strange and incoherent responses. A total of 595 questionnaires made the final sample of data, 278 of which were in the subset with questions presented in random order. For the purpose of the subsequent analysis, the whole set was considered only to find correlations between subjective responses and objective parameters, while the "randomized" subset was used to retrieve the weights pertaining to individual comfort categories [13].

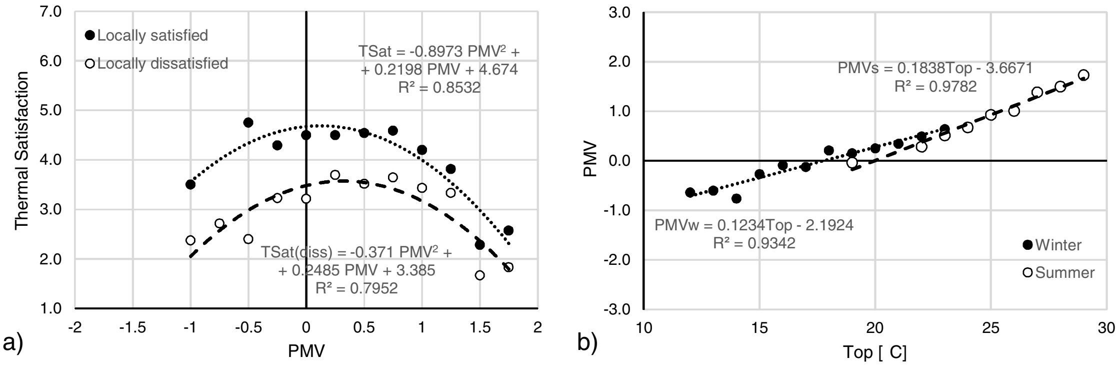

Fig. 2. (a) Plot of thermal satisfaction rating (TSat) vs. predicted mean vote (PMV) as a function of presence or lack of thermal local discomfort. (b) Plot of predicted mean vote (PMV) vs. operative temperature (Top) as a function season.

2.3. Analysis method

Statistical regression analyses were used to derive the degree of correlation between subjective sensations and objective parameters. In order to correctly interpret the results, all subjective responses were binned in intervals depending on the objective parameter under investigation (normally 1°C for temperatures, 1 dB for sound levels, and 50 lux for illuminance). The resulting average, provided it was based on at least five responses, was then correlated with the corresponding center value of the bin. Correlation coefficients (R^2) and residual probabilities (p) were used to judge statistical significance of the relations found. Correlations between different subjective ratings were analyzed in [13] using different methods. However, for the purpose of the present discussion, only results from stepwise multiple regression analysis were used. In this way the magnitude of the regression coefficients and their statistical significance defined the role played by each comfort category on IEQ.

3. Results

3.1. Individual attributes contributing to IEQ

In this section the correlations between individual attributes contributing to IEQ and objective descriptors were preliminarily investigated. Data were analyzed with reference to the whole sample of 595 responses. For IAQ no correlation was found because CO_2 concentration varied very little throughout the hypermarket. The minimum concentration of about 400 ppm was observed in the warehouse where, conversely, VOC concentration was the highest according to Amodio et al. [11]. In the shopping area, under normal conditions of customer presence, the maximum CO_2 concentration was observed, but it never exceeded 750 ppm thanks to mechanical ventilation. As this value is below the limit beyond which sick building syndrome may appear [20] this may explain why no significant correlation appeared in subjective responses. For thermal satisfaction (TSat) the correlation with predicted mean vote (PMV) was investigated. The latter is the reference parameter for thermal comfort in several IEQ assessment methods [2], and it has been shown to be very well related to actual thermal vote in the environment under investigation [8]. In addition, it has the advantage of representing thermal comfort conditions in a comprehensive way, also taking into account seasonal effects. Considering the significant influence that local thermal dissatisfaction had on subjective sensations [9], data were subdivided into "locally satisfied" (i.e. reporting no local thermal dissatisfaction complaint) and "locally dissatisfied" subsets. Results showed (Fig 2a) that for the "locally satisfied" subset the regression curve was statistically significant (R^2 = 0.853, p=0.001) and nearly symmetric on the vertical axis (the maximum appeared at a PMV equal to 0.122), and the average ratings remained in the satisfied zone within the interval from (–0.75 to +1.0), suggesting a moderate preference for "slightly warm" thermal sensation. This shift towards warmer sensation was even more evident when the "locally dissatisfied" subset was considered as in this case the correlation was equally significant (R^2 = 0.795, p=0.001) and the maximum appeared at PMV = 0.335. However, the most striking difference was represented by the systematic drop in the average responses that, in the second case, never exceeded 3.7, suggesting that lack of local thermal comfort implied a decrease by about one unit in TSat and, on average, impossibility to reach thermal satisfaction. This strong correlation between local discomfort and global comfort is not new, as analytical relations have been found by Zhang et al. [21], showing that in presence of at least two body parts feeling cold the overall sensation is substantially influenced by those parts. In order to relate PMV to a parameter representing the environmental conditions in both extreme seasons, operative temperature (T_{op}) was chosen. As shown in Fig. 2b, the correlation was high and statistically significant. A slight difference appeared in "neutral" temperature, being 17.8 °C in winter and 20.0 °C in summer, and in slopes. In fact, in winter a variation of 8.1 °C was required to achieve a unit variation in PMV, while in summer the value fell to 5.4 °C.

In order to find an objective parameter to be related to thermal local dissatisfaction rating, the typical set of descriptors proposed by ISO 7730 [17] was investigated, including air velocity, temperature gradients, and floor temperature, together with the corresponding percentages of dissatisfied (PD). Even though a good correlation (R^2 = 0.67, p=0.004) was found between average number of complaints for local dissatisfaction and the sum of the PD due to draught, ankle-head temperature gradient, and floor temperature (Fig. 3a), the best statistically significant correlation (R^2 = 0.85, p<0.001) appeared with floor temperature (Fig. 3b).

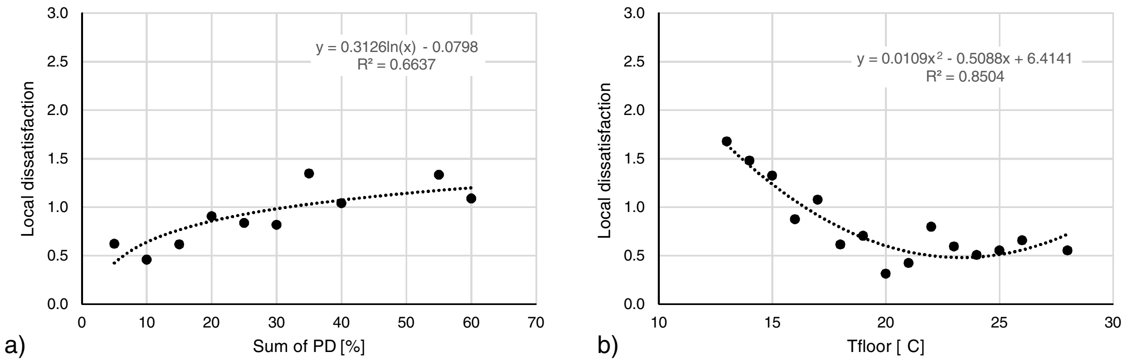

Fig. 3. (a) Plot of local thermal dissatisfaction rating (LocDis) vs. sum of the percentage of dissatisfied due to draughts, ankle-head temperature gradient, and floor temperature. (b) Plot of local thermal dissatisfaction rating (LocDis) vs floor temperature (Tfloor).

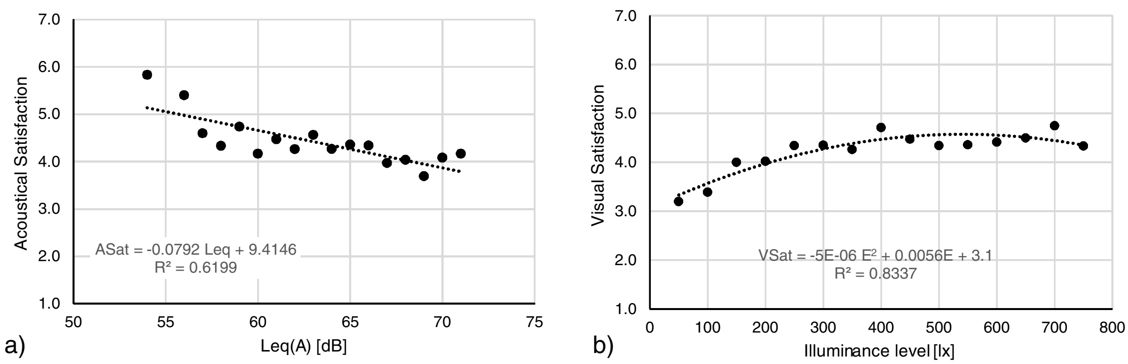

Fig. 4. (a) Plot of acoustical satisfaction rating (ASat) vs. A-weighted equivalent sound pressure level (Leq(A)). (b) Plot of visual satisfaction rating (VSat) vs illuminance level

In terms of acoustic satisfaction, considering the relatively small differences found by Della Crociata et al. [10] when different sub-sets were considered, the correlation between ASat and $L_{eq(A)}$ for the whole sample explored (Fig. 4a). Data were binned with reference to 1 dB intervals, and results showed that a statistically significant linear correlation ($R^2 = 0.62$, $p<0.001$) appeared and the threshold between satisfaction and dissatisfaction was at 68.3 dB. Finally, for visual satisfaction (VSat) a quadratic correlation ($R^2 = 0.834$, $p<0.001$) was found (Fig. 4b) with illuminance level (E). As already observed in the preliminary study, a slight dissatisfaction emerged only towards the lower end of the scale, while higher illuminance levels did not seem to provide a significant increase in VSat, possibly because of some sort of adaptation mechanism.

The above results may be briefly commented by comparison with studies referred to different buildings. Even though the main difference in hypermarkets is represented by the need for workers to move along different departments (about one third of the surveyed sample stated that he/she was in the area by less than half an hour), no statistically significant difference was found in the thermal response compared to subjects working steadily in the same place [8]. Clearly this does not imply a reaction comparable to occupants of other types of buildings, in particular considering the great variations observed in previous researches [1]. However, the correlations between subjective and objective parameters discussed in Sec. 3.1 recalled pretty well the trends observed by Cao et al. [22] in Chinese public buildings. Absolute values were obviously dissimilar, given the different nature of the buildings and of subjects' job under investigation, but the agreement in the type of relation (linear, quadratic) was good. For example, in the Chinese study, visual satisfaction showed a decreasing trend at very high illuminance levels, thus confirming that a quadratic regression may be more appropriate. For CO_2 concentration, very large variations were required to change subjective ratings, thus helping to explaining the lack of correlation observed in the present study.

3.2. Results from multiple linear regression analysis

As anticipated, stepwise multiple linear regression was used to quantify the weights that different categories had when contributing to GSat, even though results discussed in [13] clearly showed, by means of non linear methods, that different IEQ attributes may influence GSat in different ways. In any case, in multiple regressions each regression coefficient represents the variation induced on GSat following a unit variation in the given attribute rating, thus measuring its influence on the overall rating. With reference to the whole sample (Table 1), the analysis returned a major role of thermal and visual satisfaction followed by local thermal discomforts. Air quality and acoustic comfort had the lowest influence on IEQ with a rating that was nearly halved compared to other parameters. It was interesting to observe that if LocDis was not included in the regression analysis, the weights were redistributed, with an increase for TSat (that clearly became the most influential attribute), while VSat, ASat, and IAQSat remained substantially unchanged, confirming the orthogonality between the latter and LocDis. The explained variance, in this case, was only slightly reduced, with an increased RMS error.

Subdivision of the sample into more homogenous subsets was explored as a means to better understand the relative importance of the different attributes. Among all the possible subsets, one of the most interesting was that obtained by subdividing the sample between those experiencing no local thermal discomfort and the others. For the first group, the dominant attribute was VSat, followed by TSat, with ASat and IAQSat having a more than halved weight. Conversely, for the locally dissatisfied group TSat was largely dominant, followed by IAQ and VSat and finally, with a much lower weight, ASat. As the range of variation of PMV was the same for both groups (Fig. 2), this suggested that complaints for the second group arose from an increased sensitivity to temperature and thermal comfort, rather than worse environmental conditions.

Table 1. Summary of coefficients and their confidence intervals resulting from stepwise multiple regression analysis for whole sample and different subsets. Statistical significance: * = $p<0.005$; ‡ = $p\leqslant0.05$; † = $p>0.05$.

	Constant	TSat	LocDis	ASat	VSat	IAQSat	R^2	RMS
Whole 5p	0.34±0.44†	0.31±0.08*	-0.24±0.10*	0.15±0.06*	0.32±0.07*	0.18±0.08*	0.691	0.71

Whole 4p	-0.21±0.19	0.39±0.08*	Not incl.	0.16±0.07*	0.31±0.08*	0.20±0.08*	0.662	0.74
Locally sat	0.20±0.52	0.27±0.11*	Not incl.	0.19±0.09*	0.38±0.10*	0.15±0.10‡	0.669	0.69
Locally dis.	-0.21±0.64	0.40±0.11*	Not incl.	0.11±0.11†	0.25±0.12*	0.27±0.14*	0.582	0.75

Now, according to the above linear models, all the categories contributed to GSat, although with different weights. This implied that a lack in a certain category could be compensated by improving another one. However, as shown in [13], application of non-linear models suggests that local thermal dissatisfaction is a basic factor (acting negatively when at least two body parts are affected, but doing nothing if not), while acoustic satisfaction behaved as bonus factor (improving GSat in presence of a positive sensation, but having no detrimental effect if missing). Thus, trade-offs between different attributes need to be taken carefully.

4. Practical implications and conclusions

Combining the previous results it is possible to derive some strategies in order to optimize working environment in hypermarkets and shopping facilities with features comparable to the case under investigation. Even though this investigation is based on a survey that involved only a single building, it is important to underline that during visual inspection of other hypermarkets very similar layouts were found.

First of all the optimal parameter range was derived for the different IEQ attributes (Table 2), showing, in particular, that in winter the comfort zone for T_{op} was large enough to include most of the conditions observed. Conversely, in summer the values were on the low side, even lower than the values actually measured. Optimal floor temperatures also spanned over a large interval, with ideal conditions between 21 and 25 °C. For the sound levels the critical value proved to be rather high (and higher than optimal values found for offices), suggesting good adaptation capacity despite some complaints [10]. In order to maximize workers' satisfaction for the environment, the parameter variations required to change by one unit the attribute subjective rating were determined. Variations were somewhat large, but when starting from critical conditions they are not impossible to achieve. Combining such variations with the relative weights resulting from multiple linear regression analysis outlined a rough picture of the influence of environmental variables on overall sensation. The most striking result was the huge (and unrealistic) amount of variation that was required for each individual environmental parameter to affect GSat by one unit, clearly suggesting that only a combined action may be truly effective in IEQ optimization. Anyway, normalizing such variations by dividing by the smallest quantity (in this case T_{op} variation) offers the opportunity to investigate the equivalence (and potential trade-offs) between different environmental aspects. Results suggested that a 1°C variation in T_{op} corresponded to a 1.65 °C variation in floor temperature, to a 6 dB variation in L_{eqA}, to about 50 lux variation in illuminance level, and (taking advantage of Cao et al. data[22]) to a 700 ppm variation in CO_2 concentration. Compared to results from other researchers the 6 dB variation equivalent to 1 °C change in T_{op} was higher than the values observed by Clausen at al. [23] and by Pellerin and Candas [24], but smaller than those observed by Gunnarsen and Santos [25], likely as a consequence of the lower relative importance of acoustic satisfaction compared to thermal factors.

Now, considering the variations required for single parameters to affect GSat, and the difficulty to prove trade-off effects (at least according to [13]), it clearly appeared that global satisfaction could only be obtained by a combined action affecting all the attributes together. In addition, considering that most actions have energy consumption implications, it should be preferable to promote strategies with the lowest impact. For example, in the surveyed hypermarket, a pilot study was started to allow cashiers to use a less stringent dress code that could considerably limit

Table 2. Sensitivity analysis based on regression coefficients resulting from multiple linear regression. For quadratic regressions the parameter variations were calculated using linear interpolation, where this could be safely applied (far from maximum or minimum points).

	T_{op}	T_{floor}	$L_{eq(A)}$	E	CO_2
	°C	°C	dB	Lux	ppm
Optimal range according to regressions	13.7-21.8 (w) 17.2-22.8 (s)	16.4-30.3	<68 dB	200-800	n.a.

Parameter variation required to change relevant satisfaction by one unit	4	5	12	200	n.a.
Same as before, but based on Cao et al.[22]	5.3	n.a.	14	333	1667
Parameter variation required to change GSat by one unit	12.9	21.4	79.5	617	(9471)
Normalized variation to change GSat by one unit	1	1.65	6.2	48	(734)

complaints due to cold limbs. In this way, thermal local dissatisfaction was reduced without affecting environmental variables. In addition, the most "energy saving" solution to improve overall satisfaction is that of limiting noise level as ASat proved to be a bonus factor with a sufficiently high impact in most cases. Furthermore, sound pressure level reduction should also improve customers' satisfaction with minimum consequences on their purchasing attitude.

Acknowledgements

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