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Investigation of the impact of subjective and physical parameters on the indoor comfort of occupants: a case study in central Italy

Veronica Lucia Castaldo[a]*, Ilaria Pigliautile[a], Federica Rosso[b], Anna Laura Pisello[a,c], Franco Cotana[a,c]

[a]*CIRIAF – Interuniversity research center on pollution and environment Mauro Felli – Department of engeneering – University of Perugia, 06125, Italy*
[b]*DICEA – Sapienza Università di Roma, via Eudossiana, 18, 00184, Roma, Italy*
[c]*Department of Engineering, University of Perugia, Perugia, 06125, Italy*

Abstract

Indoor comfort perception of buildings occupants depends on several parameters related to physical boundary conditions but also to the adaptation capability of occupants themselves. According to standards, just physical ambient parameters are considered to evaluate comfort so non-measurable factors, such as psychological ones, are not taken into account. The present work aims to identify possible benefits in terms of occupants' comfort perception due to the maintenance of good quality work environment. To this purpose, the environmental multi-physics performance of a mixed industry-office building is investigated through both field microclimate monitoring and questionnaires campaigns. Results obtained are therefore compared and discussed.

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Keywords: indoor comfort, occupants, adaptive model.

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* Corresponding author. Tel.: +39 075 58533796/+39 340 5509277.
E-mail address: castaldo@crbnet.it

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1. Introduction

Occupants' perception of the indoor environmental quality is the object of many studies and can be analyzed by means of different approaches. International standards use to link indoor comfort conditions to specific ranges of physical parameters due to the objectivity of measurable data. ASHRAE 55 [1] and ISO 7730 [2] determine thermal comfort conditions in buildings through the heat balance model for human body by considering the comfort perception as dependent on the following six factors: (1) metabolic rate, (2) clothing insulation, (3) air temperature, (4) mean radiant temperature, (5) air velocity and (6) relative humidity. Furthermore, UNI EN 15251 [3] specifies how to design criteria for dimensioning the building and its systems. Specifically, these criteria are aimed at guaranteeing specific comfort conditions. From the thermal point of view, the standard distinguishes between mechanically conditioned buildings, where the comfort is evaluated by means of PMV and PPD from ISO 7730, and naturally ventilated buildings, where the application of the adaptive method is recommended. Moreover, EN 13779 [4] deals with performance requirements for ventilation to guarantee a good indoor air quality (IAQ). The estimation of IAQ is therefore associated to a maximum concentration limit of CO_2. Finally, the EN 12464-1 establishes lighting standards for indoor work places. Nevertheless, comfort perceptions of buildings occupants are not just related to physical parameters, but are also affected by physiological and psychological aspects. Many studies analyze it by coupling (i) the monitoring of environmental parameters and (ii) the questionnaires submission, and by generally focusing the attention on one environmental parameter at a time. As for the air quality, different works [5-6] detected poor air quality perception among occupants and a positive correlation between job satisfaction and ratings of work area environment quality. A similar method, i.e. parallel monitoring campaign of the ambient parameters and questionnaires submission, was followed by Collins et al. [7] to evaluate the office occupants' satisfaction with the lighting system. In this case, workers' perception resulted to be more related to the patterns of luminance in the space than to the illuminance level of their specific view task. Moreover, many studies dealt with indoor thermal comfort, which is the most important parameter influencing the indoor environment quality perception and therefore the building energy demand according to Frontczak and Wargocki [6]. In a research of Nakano et al. [8], the same workspace was founded differently perceived by groups of different nationality and gender whereas Yamtraipat et al. [9] associated indoor thermal comfort to (i) occupants' education level and on (ii) how much they were accustomed to use of air-conditioner. Many studies aimed at improving the adaptive approach for thermal comfort evaluation. This method considers occupants as agents interacting with their environment with multiple feedback loops and presenting a thermal perception influenced by the complexities of past thermal history, culture and technical practices [10]. To quantify the effects of different adaptation process some studies tried to include some of them within the predicted mean vote (PMV) which, at the moment, is the most common index used and suggested by standards, resting on the steady state heat transfer theory [11-15]. Fanger and Toftum [16] suggested an extension the PMV index to non-air-conditioned buildings in warm climate by introducing an expectancy factor *e* varying between 1 and 0.5 depending on the expectation level (high, moderate or low) and the local climate, i.e. duration of the warm period. Even if these approaches had produced an improvement of thermal comfort numerical evaluation, many others parameters could affect the real perception of buildings occupants, also related to collective influences and social norms [17-18].

Based on the outlined background, this work aims at highlighting how an aesthetically pleasant and comfortable workplace can positively influence occupants' perception of the indoor environment. To this aim, both a microclimate monitoring and surveys campaigns were carried out within a company located in Perugia (Italy) during the autumn and winter seasons. The experimental campaign was carried out by considering thermal, visual comfort, and air quality. The indoor comfort is evaluated according to existing standards and the results are than compared to surveys responses.

2. Methodology

The methodology consists in the comfort assessment carried out by combining (i) the monitoring of the environment physical data and (ii) the submission of questionnaires to the occupants. The monitoring campaign was carried out by an indoor microclimate station collecting physical data of (i) indoor air quality, (ii) illuminance level, (iii) global and (iv) local thermal comfort. The sensors included in the station are: thermal-hygrometer (air temperature (°C) and relative humidity (%)), surface and air temperature sensor (floor and air temperature at ankle level (°C)), black globe radiant temperature sensor (mean radiant temperature (°C)), hot wire anemometer (air speed - m/s, and turbulence - %), luxmeter (illuminance - lux), net radiometer (radiant asymmetry - °C), CO_2/CO/VOC sensors (CO_2/CO/VOC concentration - ppm). While the thermal-hygrometer and temperature sensors present a resolution of 0.01°C and an uncertainty of 0.1°C, the anemometer shows an uncertainty level of about 0.5÷1.5 m/s. Finally, the air quality sensors (CO_2, CO, VOC) are characterized by a resolution of 1-0.5 ppm and an uncertainty of ±50 ppm (+2%)-1%-3%, respectively. More in details, all the sensors are compliant with ISO 7726 [19] and were positioned almost in the middle of each working area close to the employees' workstations at the height of 1.10 m. At the beginning of each seasonal monitoring campaign, questionnaires were submitted via web to 250 occupants randomly selected among the company workers' list. The questionnaire deals with: (1) working schedule and possibility to control the environment; (2) thermal and lighting perception in terms of (i) sensation perceived, (ii) comfort, (iii) preferences, (iv) acceptability, and (v) tolerability; (3) general comfort condition and adaptability with respect to non-physical influences as (i) work environment quality perception, (ii) environmental quality of the home environment compared to the work place, (iii) health condition, and (iv) personal mood; (4) personal information (gender, age, clothing). More in details, the analysis of the subjective thermal perception is consistent with ISO 10551 [20]. The same procedure was extended to visual comfort evaluation due to the lack of available specific regulations.

3. Case study

The case study is a luxury clothing factory located in Perugia (Italy) composed by (i) four buildings, where the production takes place, and (ii) a restaurant. It is a local factory located in an 80000 m^2 complex composed by different buildings which differ from each other for the orientation and the main activity performed inside them:

- Building A, east-west oriented, is the "machinery area", where the core of the production takes place;
- Building B, north-south oriented, is the "control area", used for control of products and expeditions;
- Building C, east-west oriented, is the "administration area", where administrative computer stations are located;
- Building D, north-south oriented, is the "store area", where all the products are stored before shipping.

The case study factory complex represents a positive example due to company' policies to enhance the work environment quality, the well-maintained outdoor green environment which is visible from the inside and the restaurant service within the company's area (Fig. 1).

Fig. 1. Overview of the case study: a) view of the outside from the inner working area; b) view of the outdoor green area, c) building A, "machinery area"; d) building C, "administration area"; e) building B, "control area"; f) building D, "store area":

As regarding the sample interviewed, even if the number of questionnaires submitted is always the same (250), different numbers of responses are obtained during autumn (137) and winter (75), highlighting a decline in workers' interest in the study. Moreover, in winter a larger amount of people with higher education level is detected probably due to the higher number of interviewed between the ages of 31 and 40 (Figure 2). In general, females are always more than males (74% and 57% in autumn and winter, respectively) and have been company's employees from more than three years (75% and 63% in autumn and winter, respectively) with previous work experiences (87% and 85% of the total population) which means that they are in a stable work position and have the possibility to compare their actual situation with previous working contexts.

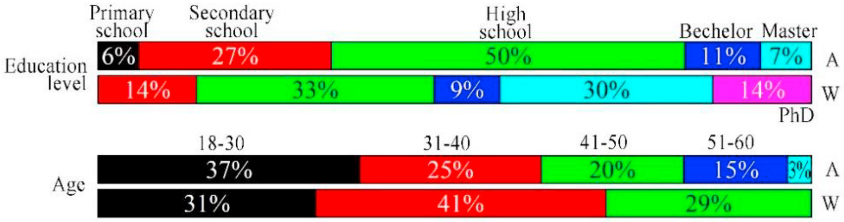

Fig. 2. Sample composition during autumn (A) and winter (W) questionnaires' campaigns.

4. Results

4.1. Monitored data analysis

The physical parameters monitored are compared to comfort ranges and threshold values proposed by standards. As concerning the indoor air quality, the concentrations of the monitored gases (CO_2, CO and VOC) are analyzed. The total absence of CO is verified. Moreover, CO_2 concentration varies during daytime due to the presence of people, while VOC concentration remains almost constant during a day since it is related to physical characteristics of the space such as paintings, furniture, etc. For these reasons, the indoor air quality level of each monitored workspace is presented in Table 1 by mean of (i) the absolute maximum peaks of CO_2 concentration and (ii) the mean value of VOC concentration detected during both autumn and winter campaigns.

Table 1. Indoor air quality, physical parameters monitored

Monitored Workspace	CO_2 concentration (ppm) absolute maximum peak		VOC concentration (ppm) mean	
	Autumn	Winter	Autumn	Winter
Building A, Machinery	720	853	4.32	5.19
Building B, Control	788	695	4.14	5.28
Building C, Administration	918	912	3.99	4.96
Building D, Store	614	805	3.84	4.95

CO_2 maximum concentration values are always below the upper limit suggested by EN 13779, i.e. 1000 ppm., and VOC never exceed values from literature (VOC maximum concentration limit from 10 to 1000 depending on the specific VOC considered). As regarding visual comfort, illuminance values detected are compared to lighting standard requirements of work spaces presented in EN 12464-1. According to that regulation, different illuminance values are considered for the monitored areas due to the different visual tasks that have to be satisfied. In details, a good illuminance level is detected in the machinery work area of building A (between 500 and 1000 lux) while slightly low values of that parameter are registered in the control area (building B) where a maximum of 413 lux is observed during winter with respect to a suggested minimum value of 500 lux.

4.2. Thermal comfort evaluation

Thermal comfort is detected by means of both the steady-state heat transfer theory (Fanger model) and the adaptive model, even if the case study building is mechanically conditioned and therefore its thermal evaluation criteria is based on PMV and PPD indexes according to the available standards. The application of both the methods is aimed at evaluating which approach better fits the real occupants' perception available from surveys among the occupants. The application of the adaptive methodology shouldn't be considered totally inappropriate since previous studies [12, 21] already dealt with thermal comfort evaluation of air-conditioned spaces by means of this approach and highlighted that the seasonal outdoor temperature can influence people's thermal perception. The comfort target ranges used for the analysis are the ones proposed by standards for our case study building category, i.e. II - normal level of expectation. Three synthetic indexes are presented for both the methods:

- Performance Index (PI), the percentage in time when the considered parameter falls inside the target range [22];
- Shift Index (SI), the percentage in time when the considered parameter falls outside the target range [23];
- Deviation Index (X_DI), a non-dimensional index which quantifies the distance from the target condition in terms of frequency and intensity of the gap [24](Equation 1):
  - $X_{M,s}$ and $X_{m,s}$ are maximum and minimum seasonal limits of the parameter of interest according to standards;
  - Ph and Pc are the periods of time when the parameter falls above or below the standards limits;
  - t_S is the duration of the whole monitoring campaign;
  - $t_{X,s}$ is the time period during which the comfort is respected;
  - $X\_DI_{BC,s}$ is the seasonal deviation index of the X parameter with respect to a base case of reference (BC). The BC is defined as the case characterized by a constant discrepancy of the X parameter from the standards' target. Different BCs are therefore selected for the different parameters evaluated as specified in the following sections of the work (sections 4.21.-4.2.2).

$$X\_DI = \frac{\int_{Ph}\left[X - X_{M,s}\right]dt + \int_{Pc}\left[X_{m,s} - X\right]dt}{X\_DI_{BC,s}} \cdot \frac{t_s - t_{X,s}}{t_s} \qquad (1)$$

4.2.1. Fanger model

In this sub-section, the thermal comfort is evaluated by means of PMV and PPD indexes according to ISO 7730. The parameters involved are (i) the physical ambient parameters collected during the monitoring campaign (T_a (°C), RH (%), MRT (°C), ws (m/s)) and (ii) two personal parameters: the metabolic rate and the clothing insulation of occupants. These two values are derived from the ISO 7730 standard lists [2]. The metabolic rate is chosen by taking into account the different typologies of activity performed in each monitored space, i.e. 1.3 met for the machinery area, 1.9 for both control and administration areas, 2.0 for the storage room. Moreover, the clothing insulation is derived by considering the typical dress code for each specific workspace and there are no differences between values selected for autumn and winter (0.90 for both machinery and control area, 0.80 for the administration area and 0.75 for the storage room). The obtained PMV and PPD (i) performance (PI), (ii) shift (SI) and (iii) deviation indexes (DI) are reported in Table 2.

Table 2. PI, SI and DI in terms of PMV and PPD of the four monitored areas in autumn (A) and winter (W)

Monitored Workspace	PMV						PPD					
	PI (%)		SI (%)		DI		PI (%)		SI (%)		DI	
	A	W	A	W	A	W	A	W	A	W	A	W
Building A, Machinery	46.0	40.8	54.0	59.2	0.17	0.21	42.0	34.7	58.0	65.3	0.24	0.31
Building B, Control	23.4	93.5	76.6	6.5	1.19	0.00	21.3	93.5	78.7	6.5	1.72	0.00
Building C, Administration	75.5	100.0	24.5	0.0	0.07	0.00	75.5	100.0	24.5	0.0	0.10	0.00
Building D, Store	59.2	61.2	40.8	38.8	0.17	0.13	57.1	57.1	42.9	42.9	0.24	0.19
	$PMV\_DI_{BC} = 0.1 \cdot t_s$ (h)						$PPD\_DI_{BC} = 2 \cdot t_s$ (% · h)					

4.2.2. Adaptive model

In this sub-section, thermal comfort is analyzed according to the adaptive theory even if the case study doesn't fit the standards requirements for this methodology, the aim is to investigate if such approach can allow to detect the real occupants' perception which is much affected by non-physical parameters. Therefore, the optimal operative temperature (OT_{opt}) is determined for all the monitored workplaces during the whole campaign as a function of the running mean external temperature obtained from data collected by the weather station located at the Engineering faculty of the Perugia's University. According to standards, the case study building belongs to the II category, i.e. normal level of expectation, therefore the comfort target range in terms of operative temperature goes from +3°C and -3°C with respect to the optimal temperature. High levels of comfort are detected in terms of performance index which reaches its minimum (93.9%) within the administration area in autumn while is always equal to 100% in winter. Even better results are obtained in terms of operative temperature deviation index calculated with respect to a reference base case presenting a constant deviation index equal to +1°C for the whole monitoring period. The obtained parameter values are always null.

4.3. Surveys analysis

In both the surveys, the majority of the population works in open-space areas with more than four workstations (82.9% in autumn, 81.1% in winter) and asserts that doesn't or cannot personally regulate temperature level of the conditioning system (92.0% in autumn, 89.3% in winter). Within these percentages, the greatest percentage would like to have this opportunity, i.e. 46.0% in autumn and 49.3% in winter. Also windows and doors opening/closing control is limited among the interviewed population. More in details, 54.7% and 66.2% of the population doesn't have the chance to open/close its workplace' doors in autumn and winter respectively. The access to windows' control is slightly higher, just 38.0% and 52.7% declare its impossibility to regulate windows opening with respect to autumn and winter respectively. The questionnaire structure allows to separately evaluate (i) visual and (ii) thermal comfort perceptions which are summarized in Tables 3 for both the questionnaire campaigns in terms of comfort, acceptability, and tolerability.

Table 3. Visual and thermal comfort according to both autumn and winter campaigns.

	Autumn					Winter				
Visual perception	-- (%)	- (%)	0 (%)	+ (%)	++ (%)	-- (%)	- (%)	0 (%)	+ (%)	++ (%)
Comfort	0.7	2.9	18.3	43.8	34.3	0.0	5.3	13.3	53.4	28.0
Acceptability	1.5	2.2	17.8	32.6	45.9	0.0	0.0	33.3	25.4	41.3
Tolerability	0.7	2.2	17.6	35.3	44.2	0.0	4.0	26.7	30.7	38.7
Thermal perception	--	-	0	+	++	--	-	0	+	++
Comfort	0.7	3.6	21.4	41.5	32.8	0.0	4.0	14.7	53.3	28.0
Acceptability	0.7	1.5	19.9	38.2	39.7	0.0	1.3	25.3	36.0	37.4
Tolerability	0.7	2.9	21.2	37.2	38.0	0.0	2.7	25.3	33.3	38.7

Each section of Table 3 has to be interpreted as follows:

- Visual/Thermal Comfort: (--) very uncomfortable, (-) uncomfortable, (0) neutral, (+) comfortable, (++) very comfortable;
- Visual/Thermal Acceptability: (--) absolutely unacceptable, (-) unacceptable, (0) rather acceptable, (+) acceptable, (++) absolutely acceptable;
- Visual/Thermal Tolerability: (--) absolutely intolerable, (-) intolerable, (0) rather tolerable, (+) tolerable, (++) absolutely tolerable.

Moreover, workers have been questioned on how much their comfort perception could be affected by non-physical parameters. In particular, they were asked to relate their visual and thermal perception to their (i) working area aesthetical quality, (ii) architectural quality of the environment at home compared to the one of the working area, (iii) health condition and (iv) personal mood. In general, the visual perception is considered more affected by the surrounding environment with respect to the thermal perception even if both are recognized as influenced by the aesthetical quality of the working area. In particular, 59.9% and 67.6% considers visual sensation affected by ambient quality in autumn and winter respectively, while 52.6% and 50.0% of the same population believes that also the thermal perception is influenced by a welcoming and cozy working area. More in general, over the 60% of employers interviewed relates its comfort sensation to its workspace architectural and aesthetical quality (66.4% in autumn and 79.7% in winter). Among them, the majority believes that the correlation is positive (80.2% in autumn and 86.4% in winter).

5. Discussion

The monitoring campaign showed a general good environment quality detected according to the standards. Good indoor air quality is registered within all the monitored workspaces and acceptable lighting levels are observed even if values below standard suggested limits are detected in winter within the control area of building B. Nevertheless, this winter lighting visual condition is not supported by surveys' responses. In fact, almost the same percentage indicates a neutral visual sensation in both seasons (around 40%) and during winter the highest percentage of bright and too bright visual sensation is registered (23.2% with respect to 12.5% of autumn). From the thermal point of view, according to the standards, the case study building has to be evaluated by application of the Fanger model since it is mechanically conditioned. Within the present work also the adaptive model is used to get out thermal performance indexes of the monitored areas. Therefore, values of these indexes calculated by means of both the models are compared. Fanger results are much more severe than the ones derived from the adaptive model application. Moreover, higher percentages of PI are detected in winter, made only exception for Fanger analysis of the machinery area in building A. In particular, discomfort highlighted by Fanger is related to slightly warm perception (PMV > 0.5) while discomfort estimated by the adaptive model is due to operative temperature detected below its lower comfort limit. These opposite results confirm that interpretation of thermal comfort perception by means of methods based on physical monitored parameters has to be carefully examined when no strong discomfort trends are detected as in this case (low values of OT_DI and PMV_DI). Furthermore, surveys submission allows to obtain (i) the percentage of interviewed dissatisfied in terms of thermal sensation (PD, percentage of interviewed who judged its thermal environment very uncomfortable or uncomfortable) and (ii) the mean thermal sensation vote for each season (TSV, average of thermal sensation vote considering the five points sensation scale elaborated accordingly to ISO 10551 [20]). The just presented parameters are then compared to PPD and PMV calculated by means of the Fanger model and averaged over all the monitored spaces. The gap observed supports the strictness of the Fanger method already highlighted by its comparison to the adaptive model. In particular, Fanger leads always to higher levels of thermal discomfort and the hugest gap is observed in autumn when +5.9% and +0.34 are detected in terms of percentage of dissatisfied and mean thermal vote with respect to questionnaires' results. Moreover, with respect to questionnaires results, higher percentages of dissatisfied detected in autumn do not correspond to higher sensation votes. It means that slightly warmer perception in winter, which is the most severe season, is preferred and related to higher levels of comfort.

6. Conclusion

In the present work, the occupants comfort perception is investigated. Indoor air quality, lighting level, global and local thermal comfort are detected by specific sensors in four areas of the case study factory in autumn and winter. At the same time, surveys on visual and thermal occupants' perception are randomly submitted to company's worker via web. The analysis of data highlighted general good environmental quality, but also higher levels of acceptance among occupants with respect to standards both from visual and thermal point of view. In particular, also in presence of lighting levels below regulations' limit, i.e. maximum of 413 lux, the great majority of occupants declared to have neutral visual sensation (74%) and even to perceive the work space bright or too bright (17.8% and 5.4% respectively). From the thermal point of view, an average PMV, calculated considering all the spaces monitored, of 0.44 and 0.40 is detected in autumn and winter respectively whit respect to thermal sensation votes obtained by questionnaires of 0.10 and 0.11. Same discrepancy is detected comparing calculated PPD (10.3% and 8.6% in autumn and winter) with interviewed dissatisfied (4.4% and 4.0% respectively). Previous researches [5-9] suggest that such gap between people opinions and physical analysis is due to non-measurable factors such as psychological ones. Concerning the specific case study, these factors influence positively occupants' general comfort perception even if the majority of workers don’t have the opportunity to control their working environment from the thermal point of view and don’t have the possibility to manage the opening/closing of windows/doors which are generally considered conditions negatively influencing the perception. Therefore, the discrepancy detected between the comfort level obtained from the monitoring campaign and from the surveys could be attributable to the pleasant aesthetic of the workplace, as it was recognized by more than the 80% of the interviewed. This demonstrates that a pleasant and likable architectural working environment can contribute to the increase the workers’ satisfactions.

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