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Original
Indoor environmental quality and global comfort: An in-field study in workspaces / Puglisi, GIUSEPPINA EMMA; Spigliantini, Giorgia; Oggiani, Niccolò; Shtrepi, Louena; Masoero, Marco Carlo; Corgnati, STEFANO PAOLO; Astolfi, Arianna. - In: JOURNAL OF PHYSICS. CONFERENCE SERIES. - ISSN 1742-6588. - ELETTRONICO. - 2069:(2021), pp. 1-8. (Intervento presentato al convegno 8th International Building Physics Conference (IBPC 2021) tenutosi a Copenhagen nel 25-27 August 2021) [10.1088/1742-6596/2069/1/012169].

Availability:
This version is available at: 11583/2971738 since: 2022-09-26T12:41:51Z

Publisher:
IOP Publishing Ltd

Published
DOI:10.1088/1742-6596/2069/1/012169

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23 April 2024

Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: G E Puglisi *et al* 2021 *J. Phys.: Conf. Ser.* **2069** 012169

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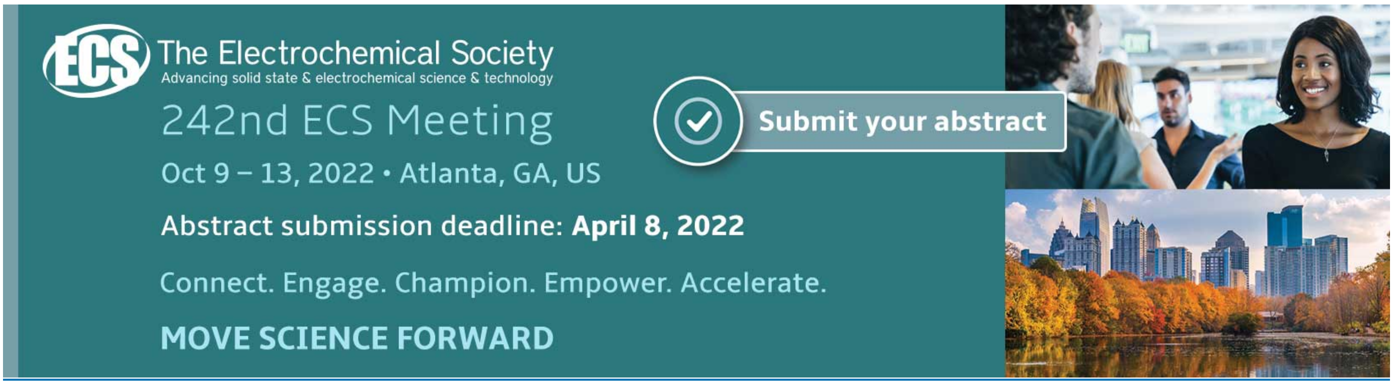

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Indoor environmental quality and global comfort: an in-field study in workspaces

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Abstract. The EN 16798-1 specifies the requirements to assess indoor environmental quality (IEQ) considering thermal, air quality, lighting and acoustics domains. A drawback of the standard is that it is based on an objective evaluation approach and does not account for the subjective perception. Also, the standard does not assess global IEQ nor comfort as a single index for the interaction of all the domains. This work tests the metrics proposed in the standard relating them to the occupants' evaluations. An in-field monitoring campaign was performed in the ARPA headquarter in Aosta (Italy), acquiring quantities to be correlated with the subjective perception of IEQ gained through surveys. An insight on the possible approach to communicate IEQ and comfort feedbacks to the occupants was investigated to promote their awareness. Preliminary results show that the occupants' perception can be predicted by adopting the approach proposed in EN 16798-1 in the case of thermal comfort, but limitations emerge about air quality, lighting and acoustics. Such result allows investigating how the environmental variables considered by the standard (e.g., the maximum sound pressure level or the maximum CO_2 concentration) can be adopted as predictors of comfort, thus how new parameters and assessment methods should be introduced.

1. Introduction

In the last decades, researchers have focused on studying the influence of Indoor Environmental Quality (IEQ) of workspaces on the occupants' perception, on their behaviour and on their productivity. When perceiving an increase in comfort and wellbeing, occupants report a higher degree of satisfaction in relation to the indoor space. However, the complexity of studying IEQ with a multi-domain approach considering the thermal, air quality, lighting and acoustics domains at the same time is still an open challenge. The European standard EN 16798-1 [1] specifies the requirements to design and assess IEQ with a multi-domain approach based on objective metrics: nevertheless, in the judgement of actual IEQ, occupant's perception is crucial and this aspect is not considered in the standard. So far, there is an evidence that each IEQ aspect influences the occupant's perception in workspaces. Very low or very high temperatures have several negative consequences on occupants affecting not only productivity but also mental comfort and health [2]. High concentrations of pollutants, as well as low ventilation rates, degrade air quality in workspaces and may reduce productivity by up to 15% on average [3]. A poor lighting working environment negatively affects occupants, in terms of productivity and efficiency [4], as well as for psychological and physiological negative consequences [5]. Noise from colleagues talking

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and moving is detrimental as it increases annoyances and mental health symptoms and reduces work productivity at the same time [6].

A recent review highlighted the need to investigate on the effects of multi-domain approaches on IEQ, occupants' perception and behaviour [7]. This study is a contribution in this field, based on a monitoring campaign in real workspaces aiming to acquire physical multi-domain quantities and to correlate them with the subjective perception in order to promote occupants' awareness and engagement. The preliminary outcomes give more insight on how the traditional objective metrics are effective in explaining and/or predicting the subjective perception of the indoor working environment. An insight on a possible way to communicate IEQ and comfort feedbacks to the occupants was also investigated.

2. Method

2.1. Case study

In field measurements were carried out in the offices of the ARPA (Agenzia Regionale per la Protezione dell'Ambiente – Regional Agency for Environmental Protection) headquarter of Valle d'Aosta region, Italy, located in Saint-Christophe (AO). The building is placed in an area belonging to the "E" climatic zone, being characterized by 2850 degree days (base 20°C). It is a two-storey self-standing building with an irregular plan layout, glass curtain walls, and a flat roof. Offices are either located at the ground floor or at the first floor, while the flat roof is dedicated to long-term monitorings as it is equipped with a weather station and an air quality monitoring system.

Three office types were selected in the building, with differences in working activity (but similar in terms of metabolic rate), room size and sun exposure. The typologies that were considered were: the LAB (a laboratory dedicated to water analyses), the NIR (an office dedicated to investigations on radiations), the Noise-office (an office dedicated to research and analysis related to noise exposure). Table 1 reports the main characteristics of the three spaces where measurements were taken.

Table 1. Main characteristics of the three spaces considered in the study (where LAB stands for laboratory, and NIR for radiation office).

	LAB	NIR	Noise-office
Floor of the building	Ground	First	First
Volume (m^3)	392.6	129.9	149.4
Room surface (m^2)	122.7	48.9	55.3
Exposure	South	South	North
Number of lighting fixtures	17	6	9
Type of lighting sources	Fluorescent	Fluorescent	Fluorescent
Number of occupants	3	3	3
Number of cooling/heating terminals	3	2	2
Type of cooling/heating terminals	Fancoil	Fancoil	Fancoil
Internal shadings	Venetian blinds	Venetian blinds	Venetian blinds
External shadings	Curtains	Shutters	Not present
Number of openable windows	6	5	6
Glass type	Double glass	Double glass	Double glass
Frame type	PVC	PVC	PVC
Acoustic ceiling	No	Yes	Yes

2.2. Environmental quantities measurement

Indoor environmental measurements were based on a multi-domain approach. The EN 16798-1 [1] standard was considered as the main reference for the organization of the monitoring activity and physical quantities were acquired to obtain, as a second step, indexes for the IEQ assessment. Table 2 provides a report of the measured physical quantities.

Table 2. Summary of the measured physical quantities divided per environmental aspect investigated. The reference standard to which each measurement agreed on is reported, as well as the used equipment and the measurement typology (i.e., spot or long-term).

	Measured parameter		Reference	Measurement equipment	Spot measurement	Long-term measurement
Thermal comfort	Indoor temperature	T_i (°C)	EN 16798-1 [1] UNI EN ISO 7730 [8] UNI EN ISO 7726 [9]	Testo 480 Testo 174H	X	X
	Outdoor temperature	T_o (°C)		Hobo		X
	Indoor relative humidity	RU_i (%)		Testo 480 Testo 174H	X	X
	Outdoor relative humidity	RU_o (%)		Hobo		X
	Mean radiant temperature	T_{mr} (°C)		Testo 480	X	
	Air velocity	v_{air} (m/s)		Testo 480	X	
Air quality	CO_2 concentration	CO_2 (ppm)	EN 16798-1 [1]	Testo 480	X	
	Particulate matter PM1, PM2.5, PM10	PM (μg/m^3)		Air Beam	X	
Acoustic comfort	Sound pressure level	L_{eq} (dBA)	ISO 1996-1 [10]	Sound level meter	X	
				"SEM" [11]		X
Visual comfort	Illuminance	E_m (lux)	EN 12464-1 [12]	Testo 480	X	

2.2.1. Thermal comfort measurements. Indoor air temperature and relative humidity, mean radiant temperature, and air velocity were acquired as spot measurements using the multisensor Testo model 480. It was positioned either at a height of 0.6 m or 1.1 m from the floor level to characterize the perceived comfort of a seated or standing occupant, respectively. The Testo model 174H instrument was used, instead, to measure the indoor temperature and relative humidity during the long-term monitoring. The Onset data logger model HOBO was used for outdoor measurements of temperature and relative humidity. It was placed at a height of 1.5 m from the ground and inside of an appropriate box in order to preserve it, and was left in a fixed position for the entire duration of the monitoring campaign. From the Testo model 480 acquisitions, the evaluation of the predicted mean vote (PMV) and of the predicted percentage of dissatisfied (PPD) could be obtained as they are function of the measured temperature, relative humidity, mean radiant temperature and air velocity [13].

2.2.2. Air quality measurements. Air quality, expressed in terms of CO_2 concentration, was measured using the multisensor Testo model 480, which was set for spot measurements as for the thermal comfort quantities described in the paragraph above. The particulate matter presence was monitored using the HabitatMap model AirBeam tool. It is accurate in measuring the presence of particulate matter PM1, PM2.5 and PM10 thanks to the optical scattering technology. Data collected with the AirBeam were transferred via Bluetooth to an Android device and then to an Air Casting platform.

2.2.3. Acoustic comfort measurements. Spot measurements to acquire the punctual noisiness of the considered spaces were done using a SINUS SoundBook, based on the Samurai software, connected to a class-1 microphone PCB model 377B02. Sound pressure levels (SPLs) in frequency and in time were thus obtained. Long-term measurements were instead performed using the Speech and Sound SEMaphore (SEM, [11]), an innovative tool for sound pressure level monitoring which is able to give a visual feedback to the occupant by means of a light signal that turns into green, orange or red depending on the measured SPL. In such a way, an active control of noisiness can be done. To the aim of the present study, however, the visual lighting feedback was disabled, and the SEM devices were only used for the SPLs acquisition. A future development of the study will include the enabling of such function in order to increase the occupant's engagement.

2.2.4. Visual comfort measurements. Illuminance measurements were performed, again, with the multisensor Testo model 480. The device set-up and usage are the same described in subsection 2.2.1.

2.3. Subjective perception

The involved occupants of the considered office spaces were invited to answer a survey that was designed to be filled in specific moments (point-in-time) to be directly correlated with objective spot measurements. It was based on a multi-domain approach to account for the perception of all the environmental domains that characterize the overall comfort at the same time. Nine occupants were involved in the subjective perception evaluation, consisting in three occupants per each space. The survey was administrated online via Google Form day by day to ease the data acquisition and to reduce any possible risk of spreading of the infection due to the COVID-19 situation.

The survey was aimed at providing data to be correlated with the physical quantities measured during the monitoring campaign. Only the perception of the summer period was evaluated with it, as measurements were repeated in time but always in this season. It contained 55 questions, which cannot be reported in detail in the present work, divided into seven sections, namely:

- Section 1: personal data of the occupant (i.e., gender, age, being a smoker or not);
- Section 2: questions on the condition in which the survey is filled in (i.e., artificial lights on/off, windows opened/closed, cooling system on/off). Furthermore, the typology of clothes worn by the respondent was investigated in order to determine, afterwards, the thermal insulation degree (in CLO) based on ISO 7730 [8];
- Section 3: questions on the thermal comfort, based on EN ISO 10551 [14] and ASHRAE 55 [15], to be answered on the basis of a 7-point Likert scale (from "too cold" to "too warm");
- Section 4: questions on the air quality, based on a 5-point Likert scale to evaluate either the perception of the odours in the environment and the degree of annoyance related to it;
- Section 5: questions on the visual comfort related to the amount of light perceived on the working area, to be answered on the basis of a 5-point Likert scale;
- Section 6: questions on the acoustic comfort related to the perception of noise and the related annoyance in the working area, to be answered on the basis of a 5-point Likert scale;
- Section 7: questions on the overall indoor environmental comfort, with answers based on a 5-point Likert scale.

2.4. Feedback to the occupant

By correlating the objective and subjective data, obtained from the in-field monitoring and from the survey, it has been possible to plan a strategy for the communication of the outcome of the observations to the occupants. As it is not easy to find a unique way to give such information, which is comprehensive of several quantities not always considered at the same time, a simple way was designed to the aim of the study. A first level of feedback was determined by providing the occupant with the outcomes of the objective measurements. In particular, for each environmental aspect measured, one representative quantity was selected and then reported to the occupant, namely: indoor air temperature (T_i, °C) for the thermal comfort, carbon dioxide concentration (CO_2, ppm) for air quality, sound pressure level in the environment (L_{eq}, dBA) for the acoustic comfort, illuminance (E_m, lux) for the visual comfort. A second level of feedback was determined by correlating the objective measurements outcomes with the subjective responses. Each parameter (i.e., T_i, CO_2, L_{eq}, E_m) was correlated with the related responses given in the surveys, and then a single index of satisfaction was deduced per each environmental aspect.

As an average among the four indexes, a further overall index was obtained in order to provide the occupant with a single information determining the degree of satisfaction related to the global indoor environmental quality. From a graphic point of view, together with the numerical indexes the occupant was given a IEQ degree with colored label: “excellent” in dark green, “good” in light green, “average” in yellow, “poor” in orange, “very poor” in red. Last, a brief but clear sentence that summarized the combination of numeral index and colored symbol was also added, e.g., “the environment is too warm”. As such, the occupant is stimulated to have an active behavior to reach a good degree of thermal comfort.

2.5. Design of experiment

The IEQ monitoring activity involved in field measurements and surveys administration to occupants. It was organized in two phases. Phase 1 lasted from Aug. 10th to Aug. 14th and was dedicated to the acquisition of the responses to a preliminary overview survey on the perceived global comfort, whose results are not reported hereby. During this phase, a researcher collected all the geometrical and usage characteristics of the three spaces. Phase 2 lasted from Aug. 17th to Sept. 2nd and was dedicated to spot and long-term measurements in the spaces, as well as to the administration of the survey. Spot measurements lasted for one day a week and for the entire working period (8 hours), resulting in IEQ quantities measured across three days per each space. Long-term measurements lasted for three days a week and for the entire working period. The survey administration was done in the morning and in the afternoon to acquire the occupants’ impression via surveys in the same days of spot measurements.

3. Results and discussions

3.1. Environmental quantities measurement

Two approaches were adopted for thermal comfort, i.e., the one based on the PMV and PPD [13], and the one based on the adaptive comfort [16]. The former typically evaluates the perceived thermal comfort when a heating/cooling system is switched on, and it is calibrated to provide more restrictive ratings. As in the present work only the LAB environment respected such condition, the adoption of such approach can be misleading. The adaptive comfort approach correlates subjective and objective measurements, and is adequate for evaluations in spaces not equipped by fully mechanical climatization systems and where occupants can interact with the environment, e.g., by opening/closing windows. Table 3 shows the results from the application of both approaches. They appear to be contradictory, especially as far as the judgment is concerned: all environments in all the monitored days present 90% of satisfied occupants with a rating of “1” for adaptive comfort, but such behaviour corresponds to PMV and PPD categories that are worse, e.g., in the NIR environment. A possible explanation can be that the PMV and PPD approach was adopted with the cooling system switched off.

3.2. Relationship between objective quantities and subjective perception

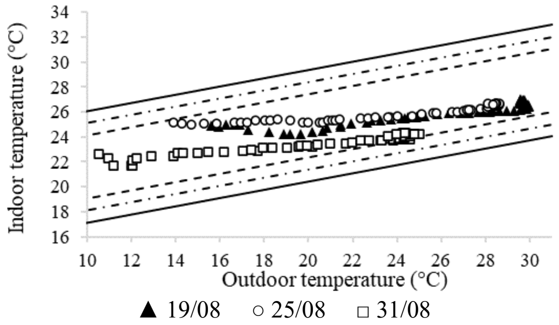
From a methodological point of view, it is interesting to analyse the objective data together with the subjective ones. As the NIR and Noise-office environment had similar characteristics and features, results were averaged and compared – and referred to as “Offices” – to those obtained for the LAB.

As far as the thermal comfort is concerned, Figure 1 represents the relationship between objective measurements and subjective answers. As two evaluation approaches were adopted, both were analysed to this aim. For indoor temperatures in Offices higher than 25°C, the PMV was in the range of -0.5 and +0.5 on average. Under the same temperature condition, however, the subjective perception assessed through the survey (question 3, question “how do you perceive the environment”, answers from -3 – too cold – to +3 – too warm –) ranged between 0 and +1.5, on average. For lower temperatures the two approaches yielded nearly similar values (i.e., -0.5 and 0, on average for PMV and adaptive comfort, respectively). With regards to the LAB, the two approaches gave similar outcomes, as the cooling system was switched on and thus an assumption for the application of the PMV approach was respected.

Table 3. Main results on thermal comfort in terms of predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) calculated for morning (am) and afternoon (pm) observations. The adaptive comfort approach results are also reported as overall satisfaction percentages and related graphs between the measured indoor and outdoor temperatures.

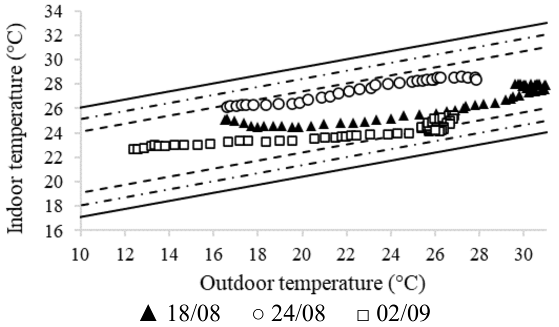
LAB

Monitoring date	19/08	25/08	31/08
Satisfaction	90%	90%	90%
Category	1	1	1
PMV (am)	0.06	-0.1	-0.6
PPD (am)	5.1 %	5.2 %	12.5 %
Category (am)	1	1	3
PMV (pm)	0.52	0.2	-0.4
PPD (pm)	10.7 %	5.8 %	8.3 %
Category (pm)	3	1	2



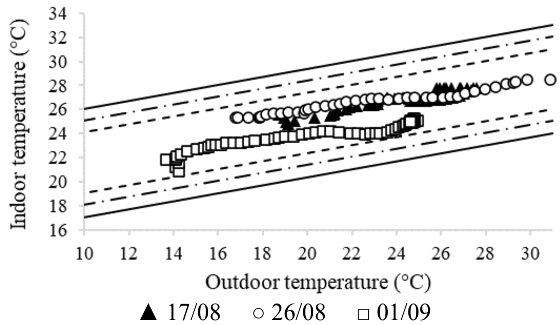
NIR

Monitoring date	18/08	24/08	02/09
Satisfaction	90%	90%	90%
Category	1	1	1
PMV (am)	-0.50	-0.44	-0.65
PPD (am)	10.2 %	9.0 %	13.9 %
Category (am)	3	2	3
PMV (pm)	0.54	0.47	-0.14
PPD (pm)	11.1 %	9.6 %	5.4 %
Category (pm)	3	2	1



Noise-office

Monitoring date	17/08	26/08	01/09
Satisfaction	90%	90%	90%
Category	1	1	1
PMV (am)	0.04	0.09	-1.18
PPD (am)	5.0%	5.2 %	34.3 %
Category (am)	1	1	4
PMV (pm)	0.34	0.57	-0.57
PPD (pm)	7.4 %	11.8 %	11.8 %
Category (pm)	2	3	3



Air quality was assessed measuring the concentration of CO_2 in the air. A relationship with the perception of air odour in the environment was also studied based on a 5-points Likert scale (from 1 – strongly unpleasant – to 5 – strongly pleasant). Correlations were weak and not significant (Pearson's correlation coefficients of -0.2 and p-value = 0.167). This outcome may be related to the fact that the measured values for CO_2 concentration are lower than the admitted ones reported in EN 16798-1 [1] (i.e., fixed at 1000 ppm), so a significant variation in the subjective perception could not be assessed.

The visual comfort was investigated asking the occupants to rate the quantity of light on the desk with a 5-points Likert scale (from 1 – not sufficient – to 5 – excessive). As the visual conditions were similar among all the considered environments, results from Offices and LAB were averaged together to build a more robust database. Subjective ratings were correlated with the measured illuminance values and resulted in weak and not significant dependence (Pearson's correlation coefficients of 0.4 and p-

value = 0.06). UNI EN 12464-1 [12] would require an illuminance > 500 lux on the desk, but the measured values were below this such threshold and thus visual comfort is not predicted effectively.

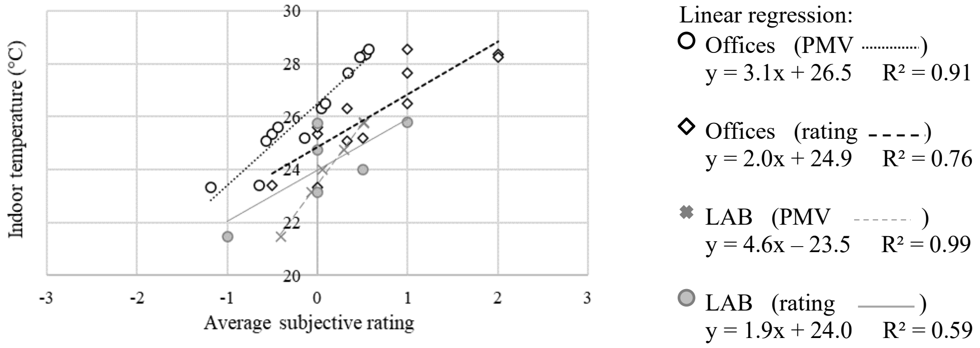


Figure 1. Predicted mean vote (PMV) and average subjective mean ratings (question 3 of the survey, 7-point Likert scale) as a function of the indoor temperature.

As far as the acoustic comfort is concerned, occupants were asked to rate the degree of annoyance associated to the noise based on a 5-point Likert scale (from 1 – irrelevant – to 5 – strongly relevant). Ratings were correlated to the A-weighted equivalent SPLs measured in the environments and resulted in very high and statistically significant relationships (Pearson's correlation coefficients of 0.52 and 0.43 for Offices and LAB, respectively, with a p-value < 0.05). However, the robustness of such relationship established with a linear regression analysis was very low (R^2 equal to 0.19 and 0.27 for LAB and Offices, respectively). This can be due to the fact that each occupant provided a subjective rating on the acoustic comfort, but the objective measure associated was a sound pressure level equal for each subject and not related to a particular position in the room or to a particular characteristic of the noise itself.

The identification of cross-modal correlations, i.e., the investigation on the mutual relations between different domains of IEQ, was not performed as it did not fall in the scope of the study. The main aim hereby pursued was identifying robust metrics through which IEQ could be measured and characterized. As some metrics did not predict adequately the subjective perception of a physical domain, further assessments are needed to establish a baseline to build cross-modal correlations.

4. Conclusions and future perspectives

The preliminary outcomes of the presented work can be summarized as follows:

- The adaptive comfort approach seems to better represent the real and overall occupants' feeling, however a prolonged monitoring campaign should be designed to cover more than one weather season. This would help extending the outcomes to a more general working condition;
- As far as thermal comfort is concerned, the PMV approach is not representative of the subjective perception of Offices occupants for indoor temperatures higher than 25°C. Below such threshold, both the PMV and the adaptive comfort approaches are suitable to evaluate thermal comfort and the physical quantity of temperature is a good predictor of it;
- Considering air quality, more proper metrics than CO_2 concentration should be evaluated, as in this study was not representative of occupants' perception;
- With respect to the visual comfort, illuminance does not account for perceptual implications. Therefore, a possibility is to go beyond the traditional metrics considering other parameters such as the colour temperature, type of light source and fixture, psychophysical effects on occupants;
- With regards to the acoustic comfort, the sound pressure level is a weak predictor of the perceived comfort, and a possible investigation in future studies can be related to particular components of the monitored sounds, maybe applying the psychoacoustics approach [17].

The proposed experimental campaign can be replicated to build a robust database of multi-domain quantities. With respect to the feedback to the occupants, the approach adopted was based on a simple and schematic format: it can be considered as a good starting point and should be tested in an intense way to understand how it can be enhanced for an effective application and engagement in everyday life.

Acknowledgment
The authors are grateful to Paola Lerario as this work was supported by the Prevention and Protection office of Politecnico di Torino. Also, they are thankful to Sonja Di Blasio for her help in the first stages of the monitoring campaign.

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