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Assessing Overall Indoor Environmental Comfort and Satisfaction: Evaluation of a Questionnaire Proposal by Means of Statistical Analysis of Responses

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ABSTRACT

Considering all aspects of indoor environmental comfort (thermal, visual, acoustical and air quality) and their interactions, questionnaires aiming at detecting assess people's perception of indoor environmental quality (IEQ), well-being and satisfaction should be designed in a more homogeneous way. In particular, the choice of the questions, response options and scales adopted must satisfy consistency criteria between different IEQ areas, but also allow a direct correlation to specific measurable quantities. In this work, the design of a comprehensive questionnaire is presented for assessment of overall IEQ in educational buildings. Its ability to effectively describe users' sensation, preference, comfort and satisfaction for all four IEQ domains (thermal, visual, acoustic and air quality) is evaluated in terms of effectiveness, efficiency and resolution, using experiments and statistical analysis. The analysis shows the agreement of mean votes with environmental parameters, correlations between sensation, comfort, satisfaction in each IEQ domain, and the relationship between scales and distributions of votes in each domain.

INTRODUCTION

The quality of the indoor environment can be evaluated (i) objectively by means of the measurements of the physical quantities related to one or more environmental aspects, namely thermal, air quality, visual, and acoustic, or (ii) subjectively, by means of occupants' feedback typically assessed through surveys. The objective evaluation compares the environmental characteristics with reference ranges of physical parameters considered as comfortable, not directly capturing the actual occupants' perception, but relying on baseline relations between environmental conditions and users' satisfaction. Unfortunately, only relatively recently these studies have focused on capturing the interactions between physical quantities and different comfort domains, leaving the prediction of the occupant's response under multi-stimuli conditions, typical in real

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environment, still an open question.

In addition, it is well-known that when people feel discomfortable, they take actions (such as opening windows, adjusting shades, managing lights, adjusting the thermostat, etc.) in order to restore their comfort, thus affecting the building performance and energy demand. Moreover, when people act to restore comfort in one domain, comfort in another domain could be compromised. For example, in naturally ventilated buildings, occupants might close the windows to feel warmer or to reduce external noise, thus worsening air quality and defeating the purpose of the entire concept.

For the above reasons, there is a need to study and understand the occupants' comprehensive perception of the indoor environment, which can be investigated by means of subjective surveys through questionnaires. There are different international standards providing guidelines for inspecting occupants' comfort using subjective evaluations, namely ASHRAE Standard 55 (ASHRAE 2017), EN ISO 10551 (CEN 2019) and EN ISO 28802 (CEN 2012), all referring to adult workers. EN ISO 28802 (CEN 2012) and EN ISO 10551 (CEN 2019) consider all the environmental aspects, but they do not suggest homogeneous questions for the different IEQ aspects, which would allow to study the interactions between different domains. In particular, questions use different wording and evaluation scales. Despite recent efforts in this direction (Tang *et al*. 2020; Buratti *et al*. 2018), there is no systematic common approach for collecting comprehensive occupant responses in multiple comfort domains. The lack of consistency is detrimental to any attempt of assessing the contribution of each domain to global comfort, as well as understanding interactions between comfort domains.

This paper presents the design and experimental validation of a questionnaire, able to capture occupants' personal state and satisfaction for the individual aspects of the indoor environment and its global assessment. The questionnaire design has followed three main criteria, (i) adopting the same subjective lexicon (or psychological continua, as defined in EN ISO 28802) for the different comfort aspects, (ii) applying the same scale graduation for corresponding questions and (iii) investigating the subjective global evaluation besides the single-aspect evaluation. Although the questionnaire targets school environments, the approach can be easily extended to different contexts.

METHODOLOGY

Aims and psychological continua

The presented questionnaire has been designed to collect subjective responses in educational buildings with the aim of understanding how people perceive the environmental stimuli, and how much they are satisfied singularly (i.e., one stimulus at a time) and globally. To assess global comfort inside a building, it is necessary to investigate their sensation, preference, comfort and satisfaction considering the thermal, olfactory, visual and acoustic experiences or domains. To assess and compare the contribution of each domain, similar psychological continua are investigated using equivalent questions for each domain.

Before presenting the questionnaire in more detail, it is worth introducing the definitions of the considered continua. Sensation is what the subjects feel by means of their senses (touch, smell, sight and hearing) in relation to one or more stimuli received from the environment. For some of the aspects the human body has specific receptors that can be more directly implied in sensation (i.e., heat/cold) and, in general, presence or absence of comfort, while in other cases (e.g.: light, noise, odour) receptors are mainly playing a sensorial role while sensation is produced by complex interactions. Nevertheless, it seems that sensation is the first and immediate subjective response to the physical environment (Chinazzo *et al.* 2019) and that it has to be reported excluding any mediation by rational or irrational evaluations. For this reason, sensation votes allow a direct correlation between subjective evaluation and objective environmental measurements, providing an understanding of the environmental conditions affecting sensation. Nevertheless, sensation votes themselves are often insufficient to determine comfort and satisfaction. That is justified by the fact that sensation votes other than neutrality (or "0") might nevertheless indicate a condition of preference. For instance, in the evaluation of thermal comfort, one might feel (slightly) warm or (slightly) cool and still prefer "no change" (indicating a form of acceptability and satisfaction (CEN 2012)).

Preference and related votes express how people would like to be in relation to the conditions they are experiencing when asked. Preference also indicates the direction of change and to what extent an action is required, in correlation with the amount of perceived discomfort. Preference votes closely correlate to comfort and/or satisfaction (d'Ambrosio *et al*. 2013, von Grabe *et al*. 2008). Nevertheless, in this work, we consider preference questions to assess single specific needs, much related to the sensation question -leaving comfort questions to account for different contributions including specific annoyance factors such as localized discomfort. Moreover, preference for non-neutral sensation is common and often not symmetrical around neutrality (Corgnati *et al*. 2005, Van Hoof 2008).

The third psychological continuum to collect a comprehensive subjective response is comfort. While for thermal and visual comfort formalized definitions are provided (thermal comfort being the "condition of mind that expresses satisfaction with the thermal environment" (ASHRAE 2017, CEN 2006); visual comfort is defined as "a subjective condition of visual well-being induced by the visual environment" (CEN 2018)), acoustic comfort and the IAQ are of much less standardized (Frontczak *et al*. 2011). Herein, the definitions provided above can be transferred to the other domains of comfort. As stated above, the comfort question is here intended to include the impact of a range specific discomfort factors. In the case of thermal comfort, for instance, comfort questions are intended to capture the overall impact of local discomfort aspects, while preference refers to "global comfort" (related to the global thermal balance).

Finally, although comfort expresses a form of satisfaction with the environment, occupants are also asked to explicitly evaluate their satisfaction with the indoor environment. As explained in the ASHRAE 55 standard, satisfaction surveys are used "to evaluate thermal comfort response of the building occupants in a certain span of time". Thus, occupants' satisfaction refers to a longer span of time than comfort and it could be affected by several factors such as the task, the individual expectations, and the relevance ascribed for the environmental aspects. Instead of redundantly replicate preference or comfort, which are point-in-time related, the satisfaction scale allows a longer evaluation of the environment, in each specific domain.

Questionnaire design

The proposed questionnaire includes 7 different parts (Table 1). The first one contains general questions, personal and anthropometric data (age, weight, height, gender identity, nationality, native tongue, etc.), along with some questions about school life. In the second part, respondents are asked to provide information related to the specific moment when they fill the questionnaire: clothes worn, activity carried out during the previous hour, position in the classroom, and self-evaluation of health and the alertness states. The following four central sections focus on the subjective experience regarding thermal, visual, acoustic and IAQ environments respectively. In these sections, the order of the questions is maintained the same: sensation, preference, sources of discomfort and related annoyance level, comfort, effects on productivity and satisfaction. To avoid biases or fatigue effects, the order of the four environmental sections is randomized. The last part of the questionnaire includes questions addressing the global comfort, as well as the individual relevance of each domain of comfort in the evaluation of global comfort and satisfaction.

The questions' wording and the scales for the answers were chosen in accordance with EN ISO 10551 (CEN 2019) and EN 28802 (CEN 2012). For thermal, visual, and some acoustic aspects, symmetrical 7-degree two-pole scales were used, the point of indifference corresponding to the vote "0" and the degrees of intensity ranging from -3 to 3. For acoustics and IAQ, 4-degree one-pole scales were chosen to characterize sensation; the vote "0" represents the absence of the effect and the degrees of intensity range between 1 and 3. In more detail (Table 2), more than one sensation question was formulated for the visual, IAQ and acoustic domains. Indeed, while the question related to the thermal sensation has a standardized formulation, widely used in literature and in relevant standards (CEN 2006, CEN 2019, ASHRAE 2017, CEN 2012), that is not the case for the other domains. Sensation about air quality was evaluated in terms of air freshness (Candido *et al*. 2015) and smelliness (CEN 2012). Visual sensation was inspected by asking to rate the brightness of the environment (CEN 2012, Andersen *et al*. 2009), and the illuminance on the desk and on the blackboard/whiteboard. For acoustics, the attributes are the noisiness of the environment (CEN 2012, Candido *et al*. 2015), the loudness, and the clarity of the teacher's voice, and room reverberation (Astolfi *et al*. 2008, Ricciardi *et al*. 2018, Yang *et al*. 2019).

Table 1. Questionnaire Sections

#	Section	Composition of questions
1	General Information	Age, height, weight, gender, nationality, mothertongue, smoker, use of glasses/lenses, use of hearing devices, satisfaction related to classroom, school, relation with teacher, relation with classmates.
2	Information related to the moment	Activity carried out in the past 30 min, clothing items worn, how students take notes, alertness, health.
3-6	Thermal/acoustic/IAQ/visual domain	Sensation, preference, sources of discomfort and related annoyance rating, comfort, performance, satisfaction.
7	Global comfort	Global comfort, relevance score attributed to each domain, global satisfaction.

Table 2. Sensation Scales Used to Evaluate the Four Comfort Domains

Environment	Code	Attribute Characterized	Scale
Thermal	S1	Thermal environment	-3 (cold) to 3 (hot)
IAQ	S1	Air freshness	0 (fresh) to 3 (stuffy)
	S2	Air smelliness	0 (odourless) to 3 (very odorous)
Visual	S1	Visual environment	-3 (very dark) to 3 (very bright)
	S2	Desk	-3 (very dark) to 3 (very bright)
	S3	Whiteboard/blackboard	-3 (very dark) to 3 (very bright)
Acoustic	S1	Acoustic environment	0 (quiet) to 3 (loud)
	S2	Loudness of the teacher's voice	-3 (very loud) to 3 (very soft)
	S3	Clarity of the teacher's voice	0 (clear) to 3 (very unclear)
	S4	Reverberation of the room (sounds)	-3 (very dry) to 3 (very reverberated)

Preference scales were defined in agreement with the corresponding sensation scales even if they relate only to the sensation questions labelled as S1 in table 2. For the evaluation scales (comfort, satisfaction), 4-degree one-pole scales were chosen, the vote "0" intended as "absence of discomfort/dissatisfaction".

Questionnaire evaluation and validation

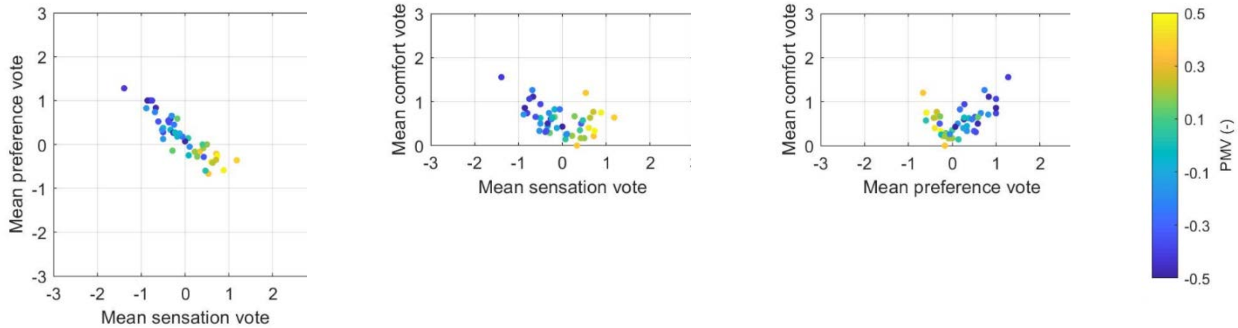
Establishing the goodness of a questionnaire means evaluating (i) its capability of discriminating different subjective responses under different environmental conditions (effectiveness), (ii) the ability to identify all environmental and contextual factors affecting comfort and the way occupants express it (efficiency) and (iii) the ability of capturing the different level of judgement on each question (resolution). The questionnaire effectiveness can be evaluated by analysing the mean sensation, preference, and comfort votes expressed by different panels of subjects, in relation to the physical parameter deemed to be representative of the environmental conditions in each domain. The questionnaire efficiency can be tested by performing a multilinear regression analysis in which individual sensation votes are predictors and comfort votes are the response variables, thus checking the significance level of the sensation variables. The questionnaire resolution can be investigated by means of a qualitative analysis of the distribution of the votes expressed in the sensation and preference scales, in the four domains. To this aim, the questionnaire was administered in a pseudonimized form to students and teachers during several experimental campaigns carried out in two school buildings located in Bolzano and Rome during the heating season. During the questionnaire administration, ongoing and point-in-time measurements were carried out to investigate the possible correlation between students' responses and the measured physical parameters related to the four environmental aspects, i.e., thermal, visual, acoustic and indoor air quality. Students and teachers were asked to fill the questionnaire during the last 10-15 minutes of a regular class, while sitting at their desk. After data collection, responses by people with cognitive or acoustic impairment were removed. The present work discusses the analyses conducted on the responses provided by students only, i.e., a total of 694 responses divided into 45 panels, corresponding to the group of students in a given classroom at a certain time.

RESULTS

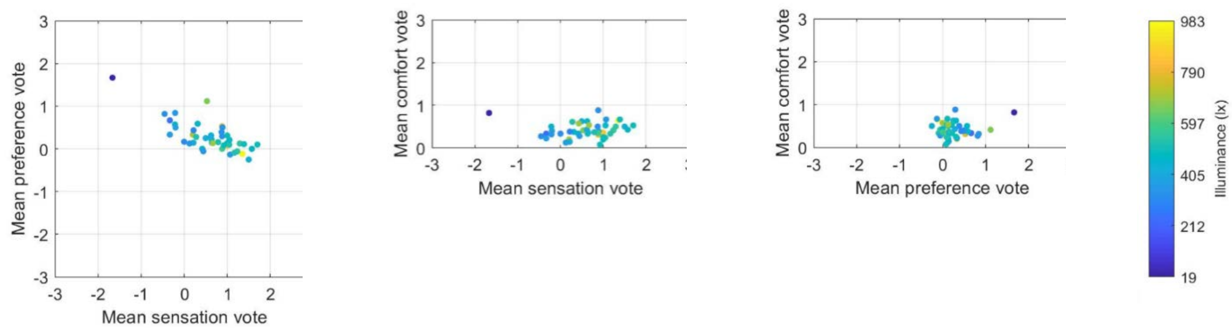
Questionnaire Effectiveness

Figure 1 reports scatter plots of the mean votes of sensation, preference and comfort for each of the four investigated domains for the 45 panels, i.e. group of students interviewed in the same classroom at the same time. In each domain, the three charts represent 2-D slices of a 3-D plot representing each panel's triplet of votes in the sensation/preference/comfort space. The colors of the points relate to the magnitude of each variable (shown in graph legends) measured during the class. For the thermal environment, the environmental conditions were summarized through an equivalent Predicted Mean Vote (PMV) calculated from the mean air temperature, relative humidty, air velocity and mean radiant temperature monitored during the lesson, and considering a standard clothing level of 0.9 and a metabolic rate of 1.2 met. For the IAQ, visual and acoustic domain, CO_2 concentration, desk illuminance and A-weighted equivalent sound pressure level were used to describe the environmental conditions.

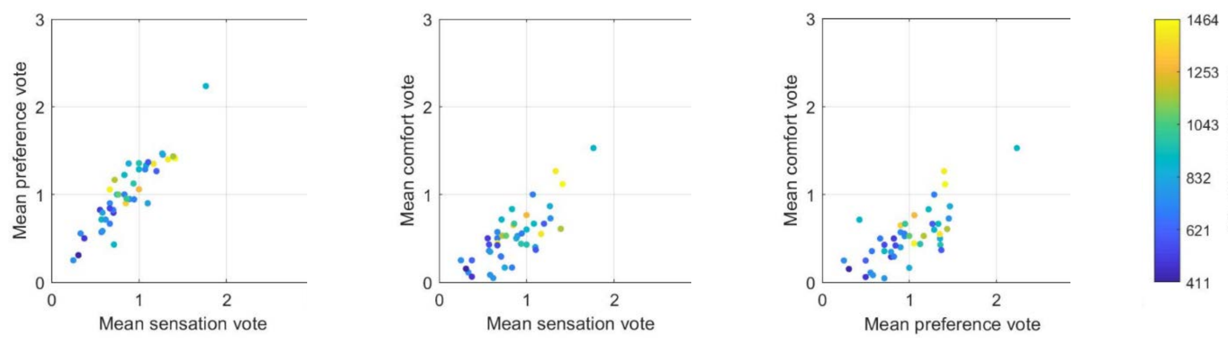
Thermal environment. Figure 1a shows a clear correlation between mean sensation and preference votes, slightly flattened in the 4^{th} quadrant (suggesting a neutral preference for slightly warm conditions). Since mean sensation and mean preference votes gather in the [-1; 1] interval, considerations on values beyond these limits might be affected by limited representativeness. The preference-comfort diagram shows an almost symmetrical distribution of votes around neutrality.



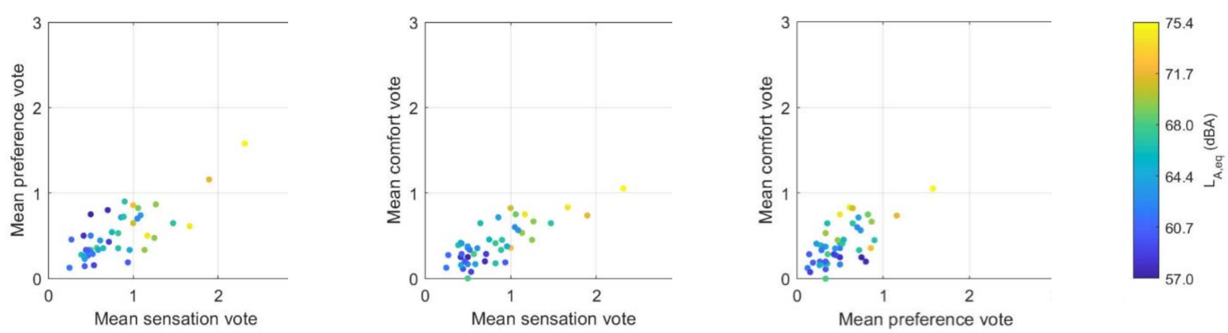
a) Thermal environment



b) Visual environment



c) Indoor air quality



d) Acoustic environment

Figure 1 Scatter plots of mean sensation, preference, and comfort votes of each panel in the four comfort domains: a) thermal, b) visual, c) indoor air quality and d) acoustic environment. The color of the dots matches the magnitude experimental conditions collected during the questionnaire administered to the the 45 panels.

Similar considerations hold for the sensation-comfort scatter plot, thanks to the fairly good linear relation between sensation and preference votes. The PMV computed for each panel, visualized through the color scale, matches well with respective positive and negative sensation votes.

Visual environment. In the visual domain, the sensation/preference relation is not diagonal: for positive sensation votes (bright environment), a flattening of the scattered data is observed. This is confirmed in the sensation-comfort plot: all mean sensation votes, ranging [-2; +2] are associated to a comfort vote between "0" (comfortable) and "1" (slightly uncomfortable). The agreement between mean votes and desk illuminance suggests the existence of a threshold beyond which sensation votes are almost invariant to the environmental stimuli.

Indoor air quality. The sensation-preference scatter plot displays a clear correlation. Mean votes extend significantly towards the extremes of the scales compared to other domains, indicating a greater occurrence of high values. The preference-comfort relation has slope lower than one, meaning that preference does not have so much hold on the evaluation of comfort: expressing a preference of "1" (slightly fresher preference) does not necessarily have a negative meaning in terms of comfort. The same holds for sensation votes. The agreement with experimental data of CO_2 concentration show that, in general, lower CO_2 concentration identifies better comfort conditions, while higher CO_2 concentrations relates to higher discomfort.

Acoustic environment. Though the acoustic domain is characterized by the same scales used in the IAQ analysis, the dispersion of sensation-preference mean votes is much larger. The sensation-preference diagram highlights the presence of many points with sensation greater than zero and preference "0" (slightly noisy/noisy environment, yet not preferring it quieter). This reflects on the sensation-comfort relation; comfort votes tend to vary less than the variation in the sensation votes. Votes agree well with the sound pressure level measured in the classrooms; the degree of acceptability of quite noisy environment is a feature that deserves further investigation.

Questionnaire Efficiency

As previously discussed, multiple questions regarding sensation were proposed in this work (Table 2). It is therefore necessary to understand whether all the proposed sensation questions reported are necessary and useful for the evaluation of comfort. The results of a multilinear regression analysis are presented in Table 3.

Sensation questions were formulated using either unipolar or bipolar scales. As a preliminary analysis, the input data for the linear regression were the actual values for unipolar scales and the absolute values of bipolar scales, in the attempt to correlate them to the comfort unipolar scales. Further investigation on the dependencies and relations between the scales will be carried out in future works. For the thermal environment, the sensation question is significant at a 5 % significance level. In the visual environment, the question labelled S1 is not significant at the 5 % significance level, given the other terms considered in the model. The only significant questions are S2 and S3 (brightness/darkness of the desk and of the whiteboard/blackboard). The estimated coefficient related to the S2 variable is anyway quite low, showing a weak dependence. Both questions regarding IAQ (air freshness and air smelliness) are significant at the 5 % significance level. For the acoustic environment, the only question that is not significant at the 5 % significance level is S4 (room reverberation). Moreover, the regression coefficients attributed to S2 (loudness of teacher's voice) are low. For those domains in which sensation questions alone are not sufficient to determine comfort conditions, a deeper insight concerning the modelling of comfort votes is required in future studies, based on other ordinal and categorical variables.

Table 3. Regression Analysis of Sensation Votes using Comfort as Response Variable

Environment	Code	Estimate	Standard Error	p-value
Thermal	|S1|	0.505	0.032	2.43e-49
IAQ	S1	0.486	0.028	6.39e-56
	S2	0.174	0.028	5.65e-10
Visual	|S1|	-0.012	0.030	0.695
	|S2|	-0.026	0.021	0.391
	|S3|	0.128	0.030	1.71e-05
Acoustic	S1	0.270	0.036	2.28e-13
	|S2|	0.078	0.038	0.038
	S3	0.298	0.053	3.56e-08
	|S4|	0.061	0.032	0.058

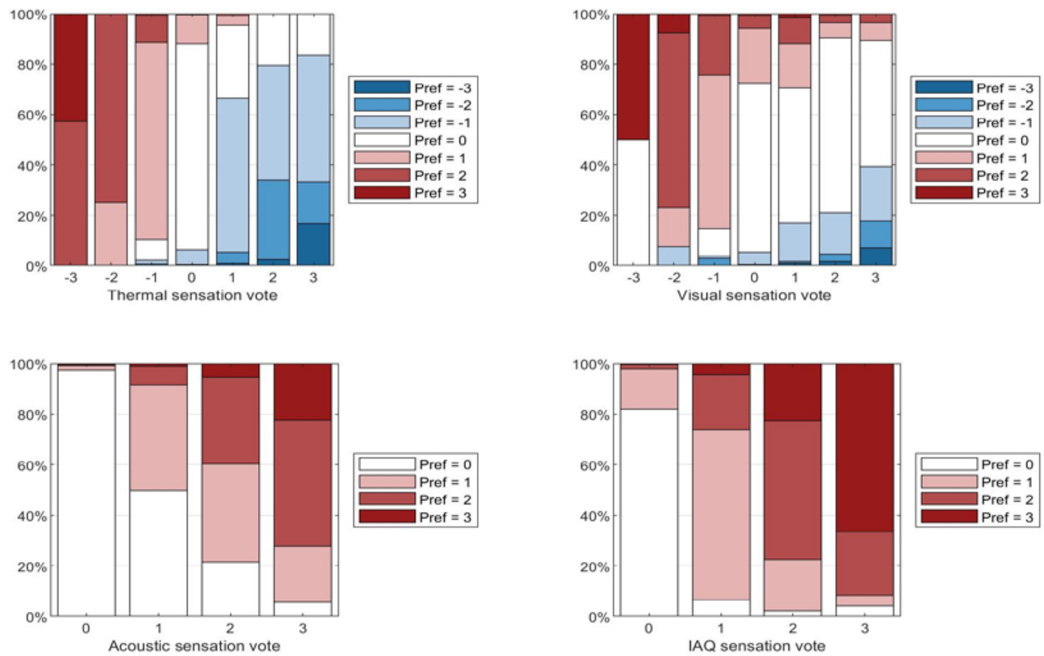


Figure 2 Distribution of preference votes based on the sensation votes in the four comfort domains.

Questionnaire Resolution

The study of the resolution of the scales allows understanding the relation between the scales, and evaluating possible conversion rules. Figure 2 shows the distribution of preference votes that individuals expressed for each of the sensation votes. The thermal environment shows a share of neutral preference (no change) votes for higher (+1, +2, +3) sensation votes, while this does not occur for lower (-1, -2, -3) sensation votes. This asymmetrical behaviour was also highlighted in previous analysis on mean sensation and preference votes. In the visual environment, neutral preference (no change) is expressed as the most common vote in all positive sensation categories, indicating that bright sensation of the visual environment is preferred even if with some increase of the preference for darker conditions. Sensation -3 is probably associated with some special tasks requiring the room to be darkened and therefore it does not necessarily correspond to preferred changes. The distribution of votes in the unipolar scales in the acoustics and IAQ, is similar. In both, there is a clear predominance of "0" preference votes (no change) associated to "0" sensation votes. For the IAQ, votes equal to "1" (slightly stuffy) trigger a larger share of preference votes "1" (slightly fresher) than the respective case for noise. Similarly, sensation "2" corresponds, in the vast majority of the cases, to a preference of "2". In the acoustic domain, transition between comfort and discomfort is delayed to sensation equals "2" (noisy), that splits preference votes between "1" and "2". In any case, the limited availability of votes at the extremes of the scales, suggests a caution in drawing conclusive rules.

CONCLUSION

This paper presents the design of a questionnaire developed to investigate subjectively the occupant's comfort in each domain (thermal, visual, acoustical, air quality) as well as global comfort. An experimental campaign gathered subjective evaluations and objective data in Italian classrooms, used to validate the questionnaire's effectiveness, efficiency and resolution. Effectiveness was qualitatively assessed through the agreement of mean sensation/preference/comfort votes with environmental parameters and found perceivable. In some domains, such as for visual comfort and IAQ this correlation is weaker than in others. Further work is needed to evaluate if this mismatch is due to the formulation of the questions, or due to a difficulty of the occupants to discriminate or evaluate different environmental conditions, as it seems the case with CO_2 concentration and IAQ. To evaluate questionnaire efficiency, a regression analysis was conducted, showing that not all the sensation questions used in this research are significantly correlated to the comfort votes. It will be necessary to assess whether, these variables gain significance using alternative analysis techniques or additional inputs, otherwise sensation questions will then be reformulated or discharged accordingly. Concerning the questionnaire resolution, the analysis of the distribution of preference votes based on sensation votes is regarded as a preliminary step towards the investigation of the resolution of the scales and their mutual relations. In particular, the analysis has demonstrated that the 7-point scale for thermal and visual sensation and the 4-point scal for IAQ and acoustic sensation are suitable to discriminate conditions related to different preference distributions. A clear correspondence was found between thermal and IAQ sensation and preference scales, while in the acoustic and visual domains, the distribution of neutral preference votes encompassed sensation votes related to noisier and darker conditions respectively. This aspect will be further investigated by collecting more subjective responses in environments with more "extreme" comfort conditions.

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