Occupant feedback on indoor humidity assessment

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Abstract

Heating, ventilation, and air conditioning systems can adjust indoor temperature, air quality, and humidity levels, regulating occupants' comfort. In this study, we focus on humidity, a parameter whose regulation is energy-intensive, and research is limited compared to thermal regulation. Research focuses on new technologies and materials to improve energy efficiency in humidity control; here, we study how it affects building occupants and the conditions in which they are affected. Using statistical tools on a sample of post-occupancy evaluation questionnaires, we investigate whether building occupants can assess indoor humidity effectively through three lenses: judgment, perception, and subjective preference. We show that while occupants can determine their preference in temperature, interpretation error is detected when it comes to humidity. Through exploratory and confirmatory analysis, it appears that humidity preference might be subject to greater variability in occupants' responses, calling for further investigation to verify the consistency of these observations across different populations. By confirming ineffective subjective assessment of indoor humidity, the existing comfort levels could be extended, and significant energy savings could be achieved.

Keywords: Humidity, building occupants, feedback, confirmatory factor analysis

1. Introduction

People spend a lot of time indoors, and to create suitable conditions, buildings consume energy that takes a considerable share of the world's demand - approximately one-third of global final energy use is directed towards buildings, which emit a slightly smaller share of global energy-related greenhouse gas emissions (UN Environment and International Energy Agency 2017). These proportions are even greater when it comes to densely populated cities, where modern comfort standards set higher energy demands. Heating, ventilation, and air conditioning (HVAC) systems ensure that building occupants are comfortable by regulating indoor conditions related to temperature, humidity, and indoor air quality. However, they require energy; for instance, while in general, there have been reports of HVAC systems consuming roughly 40% of the primary energy consumed by buildings when considering the residential building stock, air conditioning can climb over 50% in tropical climates (Chua et al. 2013). In the European Union, where most of the building stock is ageing and inefficient, space heating can reach 80% of the average specific consumption (Martinopoulos, Papakostas, and Papadopoulos 2018). HVAC systems, therefore, present an area with great potential for energy savings, contributing to decreased carbon footprints as well.

Addressing humidity through HVAC systems is key to achieving thermal comfort in buildings, but regulating this parameter requires considerable amounts of energy. In particular, the process of removing humidity is energy intensive; a study has shown that raising humidity setpoints by 30% can decrease energy consumption almost by half (Xu et al. 2023). Beyond decreasing the setpoints for humidity, dehumidification (removing humidity) is a field of ongoing research; from the commonly used cooling coils to the more advanced liquid desiccant dehumidification technologies (Gao and Lu 2024). Through these advancements, studies have shown a considerable potential for energy savings through improvement in the efficiency of processes or equipment. For instance, Che et al. explored how a retrofitted HVAC system can create comfortable indoor conditions while reducing energy consumption and used dehumidification as a key feature; the overall reduction of energy

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use reached 50% while maintaining adequate levels of indoor thermal comfort (Che et al. 2019). Mumtaz et al. adopted new combinations of novel technologies (membrane dehumidification and dewpoint evaporative cooling), achieving up to 50–90% energy savings and up to 50% reduced GHG emissions (Mumtaz et al. 2023). It, therefore, seems possible to maintain thermal comfort in buildings and achieve energy savings through retrofits, but the investment and running costs of the required systems constitute a great expense and possibly extra control strategies (Vakiloroaya et al. 2014).

Research on the topic of humidity and how it can be managed through HVAC systems is evolving, introducing new materials, technologies, and approaches. What is disputed in the literature is whether indoor humidity specifically affects building occupants and in which conditions. Up to now, research has regarded humidity within thermal comfort assessments but not as an individual component (Alaidroos and Mosly 2023; Cho et al. 2023).

With this study, we aim to fill this gap and determine whether building occupants are able to assess indoor humidity effectively. To do this, a dataset of post-occupancy evaluations accompanied by field measurements is used. The employment of consolidated statistical methods and Confirmatory Factor Analysis (CFA) is used for its exploration.

2. Methods

2.1. Data sample and sites

The dataset used for the analysis consisted of answers to post-occupancy evaluations (POEs) questionnaires distributed in different living spaces. In particular, the case study involves fourteen buildings that are either public, commercial, or private and located in four countries (Norway, France, Cyprus, and Italy), covering a variety of climatic regions across Europe and different building types and typologies. Table 1 presents the demographics of the case study buildings, including name, type, total area of the building, and number of zones participating in this study.

Table 1. Demographics of case study buildings

Country	Building name	Building type	Area (m^2)	Number of zones in which indoor environmental conditions are monitored
Norway	Eidet Omsorgsenter	Health care centre	7039	5
	Ellingsøy Idrettshall	Sports center	2610	2
	Flisnes Barneskole	Elementary school	4477	2
	Hatlane Omsorgsenter	Health care centre	5980	5
	Moa Helsehus	Medical center	2700	6
	Spjelkavik Ungdomsskole	High school	9700	5
	Tennfjord Barneskole	Elementary school	2490	7
France	Green’ER building (G2Elab)	Campus building	700	8
Cyprus	Guy Ourisson Building (GOB)	Campus building	2020	9
	Graduate School (GS)	Campus building	580	6
	Novel Technologies Laboratory (NTL)	Campus building	2440	4

Italy	C2 Tower	Residential Apartments	1250	4
	C3 Tower	Residential Apartments	1250	4
	C4 Tower	Residential Apartments	1250	4

From the dataset, non-numerical values (NAN) were filtered out and then randomly divided into two subsets. The first subset was used for exploratory factor analysis. The second subset was used for confirmatory factor analysis. The responses were treated as ordinal variables. This approach allows levels of agreement or intensity to be recognised without assuming a uniform distance between different levels of agreement or intensity.
In the present study, factor analysis was applied to the data collected to obtain a preliminary understanding of the underlying factor structure. This methodological choice was primarily aimed at assessing the effectiveness of the items used in the questionnaire in measuring the theoretical construct of interest, which is subjective thermal comfort. Through this approach, it was possible to identify the main underlying factors and ascertain the relevance of the questionnaire scales in the specific study.

2.2. Factor analysis configuration

Factor analysis is divided into two main techniques: exploratory and confirmatory. Exploratory factor analysis (EFA) is mainly used to uncover the underlying factor structure by associating one or more latent factors with a group of observed items (Woods and Edwards 2007). CFA is utilised to confirm whether the hypothesised factor structure is present in the survey data and to validate the hypothesised relationships between the observed variables and their underlying latent constructs from a background theory (DeVellis and Thorpe 2021; Mueller and Hancock 2015). The purpose of CFA is to test the factor structure suggested by the previous exploratory factor analysis (EFA) by establishing an explicit and direct connection between the theoretical constructs and the measured variables. Based on the results of EFA analysis, in CFA, these three latent factors are being configured:

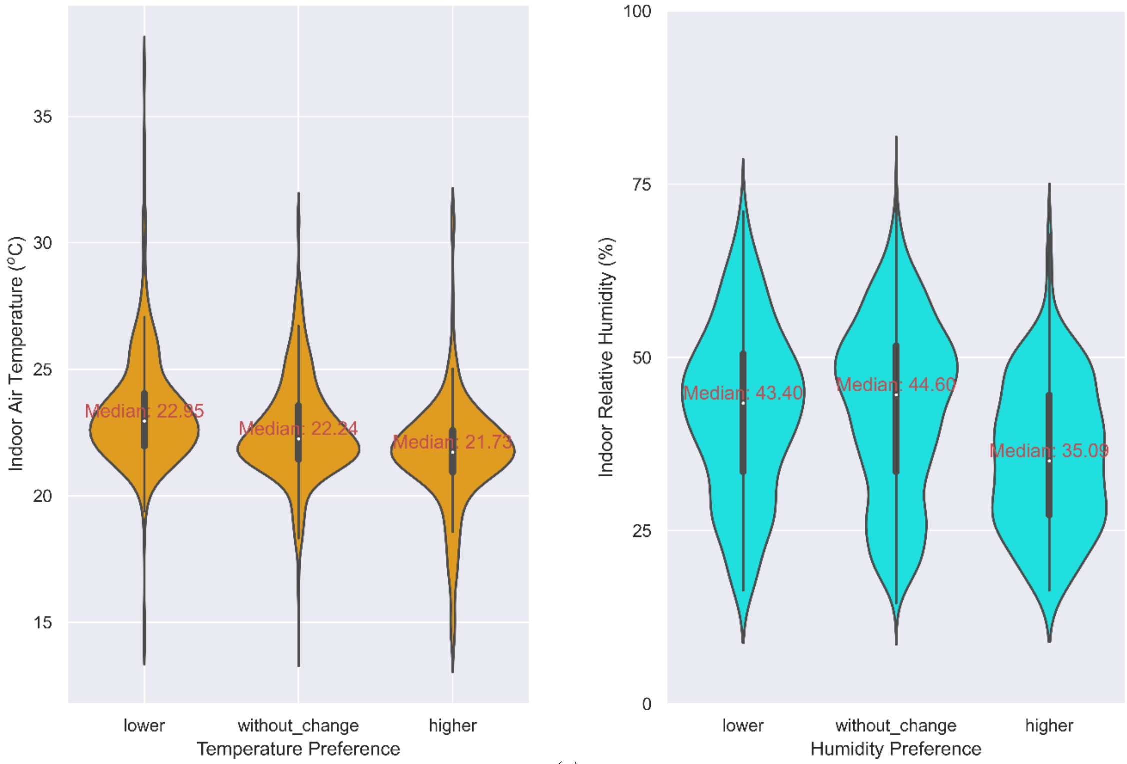
I. **Temperature judge factor**: This factor can hence be interpreted as a construct relating to how individuals find and judge the air temperature.
II. **Temperature Preference Factor**: This factor represents a combination of preference and subjective perception relating to air temperature and/or humidity.
III. **Humidity Assessment Factor**: This factor can be interpreted as a construct derived from the evaluative, judgmental and preference responses of individuals in relation to humidity.

3. Results

3.1. Observations of responses over field measurements

This section presents a statistical analysis of occupants' responses on preference for both temperature and humidity in comparison with their respective field measurements. By associating occupants' responses about their preference (i.e., "lower", "without change", or "higher") on humidity and temperature with their corresponding field measurements, i.e., indoor relative humidity (%) and indoor air temperature (°C), at the time of the completion of the questionnaire, we can identify if there is a pattern that relates occupants' responses and indoor environmental measurements. In particular, this exercise can provide some insights into how indoor conditions such as relative humidity and air temperature affect human preferences.

The graphs in Figure 1 show the probability distribution of each preference response collected during the field campaign. Note that violin plots can depict distributions of numeric data for one or more categories using density curves (width is approximately equal to the frequency). Statistical information such as median, 1st and 3rd quartile, min, and max values are presented as well. For temperature preference, as presented in Fig. 1(a), occupants prefer "lower" temperature with a median indoor air temperature of 22.95 °C, "without change" at 22.24 °C and "higher" temperature at 21.7°C. Hence, the temperature preference question could characterise the indoor air temperature on average. On the other hand, for the humidity preference question, as presented in Figure 1(b), occupants prefer "lower" humidity with median indoor relative humidity at 43.4%, "without change” at 44.6% and “higher” humidity at 35%. This indicates that building users expressed different preferences on humidity, i.e. lower and without change, even if humidity values were similarly distributed. Differently, they expressed the willingness to have higher relative humidity when it was lower. From these results, it appears that people are more sensitive to lower values of relative humidity (Q1 equal to 15%) and properly require an increase in it. In comparison, higher values of relative humidity (Q3 equal to 73%) do not trigger a clear preference.



(a)
(b)

Figure 1: Violin plots of occupants' responses on preference for (a) temperature and (b) humidity for their corresponding indoor measurements

3.2. CFA

In this section, exploratory and confirmatory factor analysis (EFA/CFA) techniques are used to investigate, test and validate latent factors related to occupants' preferences for temperature and humidity. EFA helps to identify potential underlying factor structures in the data, while CFA is used to confirm and validate these structures, ensuring that the relationships between observed variables and latent factors are valid and reliable. To conduct EFA/CFA analyses, a total of 2188 answers (including NaN values) were collected and analysed. The data consists of the answers to the Post Occupancy Evaluation (POE) questionnaire related to thermal comfort with regard to temperature and humidity items. The data came from different living spaces, such as classrooms, single or shared offices, private flats and laboratories. The participants were children (584), young (536), adults (987) and elderly (62). Data was further divided into country-specific subsets for Norway (1202) and Cyprus (762).

Pre-processing involved removing missing values and dividing the dataset into two parts, one for exploratory factor analysis (EFA) and the other for confirmatory factor analysis (CFA) for independent validation of the factor structure. Furthermore, all variables were ensured to be coded in the same direction. Finally, the responses were treated as ordinal variables. The choice to treat the data as ordinal allows for the identification of levels of agreement or intensity without assuming a uniform distance between different levels of agreement or intensity. This type of approach is crucial because it influences the choice of estimation methods and the interpretation of results in the CFA.

The factorial structure that emerged without applying any level of aggregation confirms the presence of several components of the latent thermal comfort construct represented by judgement, perception and subjective preference for humidity and temperature (Figure 1). The latent factors specified in the CFA fit the observed data well, as demonstrated by the Comparative Fit Index (CFI) and Tucker-Lewis Index (TLI) values, which are above the commonly accepted threshold of 0.95 (Xia and Yang 2019). While the Root Mean Square Error of Approximation (RMSEA) and the Standardized Root Mean Square Residual (SRMR) are below the acceptable thresholds of 0.05 for RMSEA and 0.08 for SRMR, respectively (Shi, Maydeu-Olivares, and Rosseel 2020). Considering the factorial loadings, most items converge well with their factor, indicating a clear association with the respective constructs, *except for the humidity preference item*, which shows a factorial loading below the threshold of 0.7 (Cheung et al. 2023). On the other hand, correlations between the factors are weak to moderate; none of the correlations exceed the critical value of 0.85 (Henseler, Ringle, and Sarstedt 2015), confirming adequate discrimination between the factors examined.

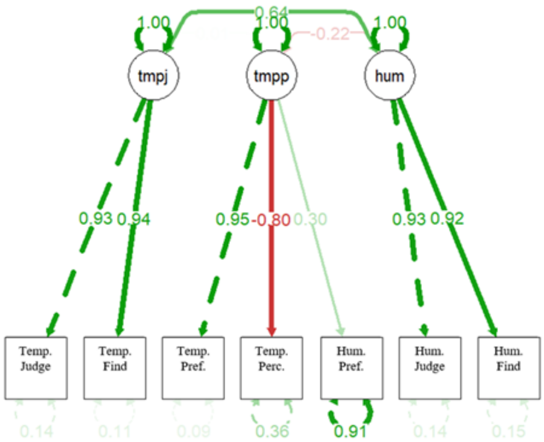
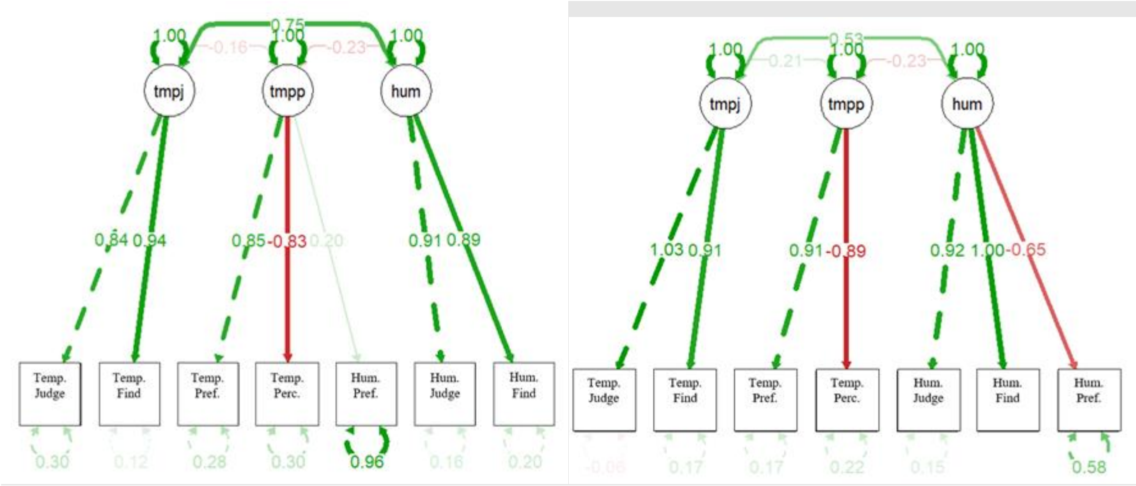


Figure 2: CFA factor loadings

The CFA was conducted separately on two countries (Norway and Cyprus) by frequency of responses, confirming the factorial structure, although with differences in the way the items are interpreted or evaluated by the participants, in particular, the humidity preference item seems to be subject to different interpretations by the participants.

In Norway (Figure 3(a)), where the answers come predominantly from primary school classes, the humidity preference item is grouped in the latent factor of temperature perception. Consequently, the humidity preference item is dissociated from how people judge and find humidity rather than finding its place in the context of temperature preferences and perceptions. Within this factor, humidity preference moves in the same direction as temperature preference, and both show an inverse relationship with temperature perception. In short, when the temperature is perceived as cold, the preference for temperature and humidity is that both are higher and vice versa. However, the humidity preference item has a low significance for the latent factor of which it is a part, an indication that it does not tie in well with the rest of the scale and that the answers given to this specific item could be subject to random error.

In Cyprus (Figure 3(b)), on the other hand, where the responses come predominantly from adults in single or shared offices and from tertiary school classes, the humidity preference item is not related to temperature preference but is associated with and moves in the opposite direction from items that measure how people actually judge and find humidity. In short, when humidity is found and judged as excessively high, the preference for humidity is lower, and vice versa. It should be noted, however, that although the humidity preference item has a discrete significance for the latent factor of which it is a part, with a factorial loading of -0.65, it is still just below the commonly accepted threshold of 0.7.



(a) (b)

Figure 3 CFA factor loadings for Norway (a) and Cyprus (b)

Compared to the other items of the same construct and the items of the other constructs whose factorial loadings exceed the reference threshold, the preference for humidity, however, seems to be subject to greater variability in the subjective assessment of the respondents.

Based on these results, EFA showed that factors appear to be related to several aspects of thermal comfort from the temperature and humidity items, such as judgement, preference and perception, indicating that the questionnaire items effectively capture multiple dimensions within these constructs. CFA validated the suggested latent factor structure, showing, however, that some areas of the questionnaire need attention to improve convergent and discriminant validity. The overall reliability of the thermal comfort questionnaire was adequate, with potential for improvement through in-depth evaluation of individual items (in this case, the humidity preference items) and implementation of necessary adjustments.

As a limitation, it is important to note that the analysis conducted did not include the temporal dimension despite the longitudinal nature of the data. The decision to treat the responses as independent, despite the possible overlap between participants on different days, is a pragmatic choice given the complex nature of the data. Consequently, although factor analysis provides useful initial insights, it is emphasised that an in-depth exploration of changes in the underlying factors, both in terms of qualitative significance and quantitative changes in factor levels over time and by levels of aggregation, would require analytical approaches specifically geared towards longitudinal data processing (Corballis and Traub 1970; Henseler, Ringle, and Sarstedt 2015).

4. Concluding remarks

The evaluation of subjective and objective data for both indoor air temperature and relative humidity on the dimension of occupants' preference shows that humans can assess more clearly variations in temperature rather than variations in humidity.

Although the results of the CFA analysis demonstrated a solid factorial structure for temperature-related preferences, the same was not found for humidity-related preferences. The CFA, conducted for the overall data sample and separately for the highest sample size pilots (Cyprus and Norway), showed that humidity preference presented high variability between those two groups compared to the remainder of the items. This suggested that the humidity-related preferences might be influenced by different interpretative frameworks or subjective biases of the participants, etc.

In summary, the subjective evaluation of occupants on humidity preference shows indications of unreliability that could create issues in the design of an occupant feedback-based control system. Therefore, in the development of thermal comfort evaluation or control algorithms, we suggest to avoid humidity-related occupant feedback that is subjective.

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Appendix: Post-Occupancy Evaluation Questionnaire

This section provides the Post-Occupancy Evaluation (POE) questionnaire used to collect occupants' feedback from the 14 pilot buildings.

The questionnaire is fully anonymized, and the experimental design is randomized, therefore NO data is related to the individual person. Therefore, every time you answer this questionnaire, we need to acquire few information to contextualize your feedback. Thank you for your understanding and precious support.

SECTION 1: Personal information

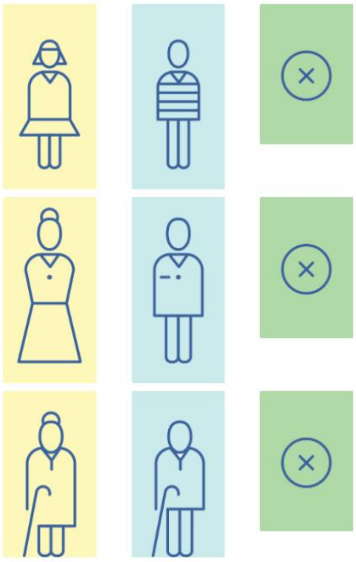
Purpose: understanding potential differences in thermal comfort perception and/or use of systems

1. Hello! Who are you?

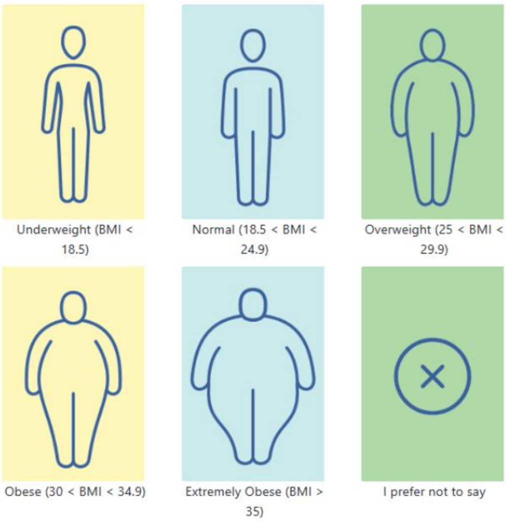
11 – 24 years

25 – 64 years

> 65 years



2. How would you describe your body dimension? Please, make your best guess



SECTION 2: Personal factors

Purpose: understanding if personal factors may affect the thermal response of a person.

3. Which ensemble best describe your clothing right now?

Shorts
(clo 0.36)

Casual
(clo 0.57 – 0.67)

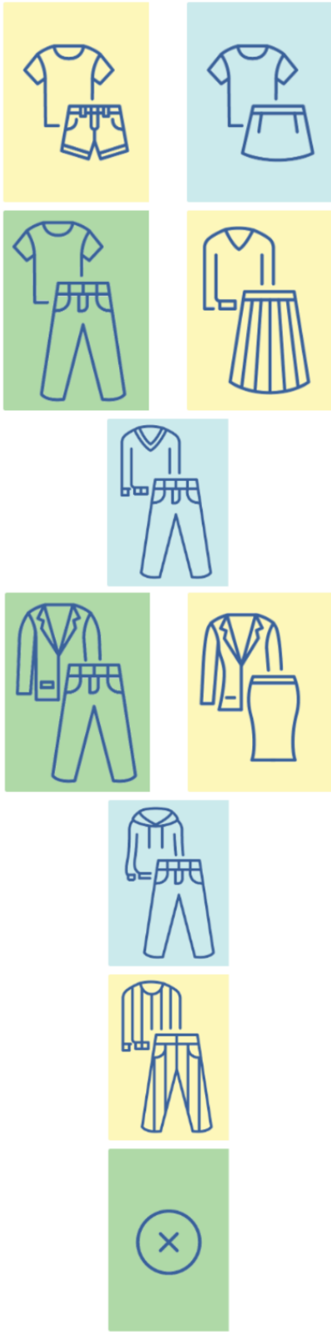
Business casual
(clo 0.61)

Formal
(clo 1.04-1.14)

Athletic
(clo 0.74)

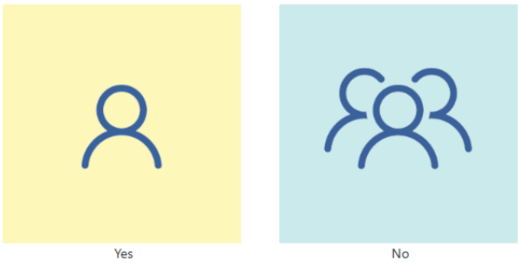
Sleepwear
(clo 0.96)

I prefer not to say



4. Which activity better describes what you are doing now?

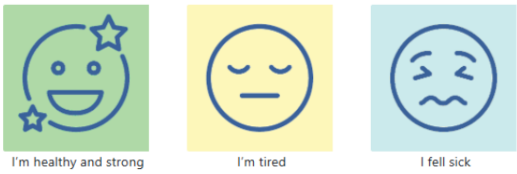
5. Are you alone in this moment?



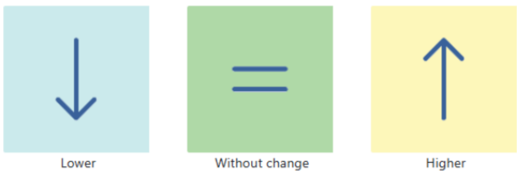
SECTION 3: Thermal comfort assessment

Purpose: assessment of the thermal environment.

6. How do you feel now?



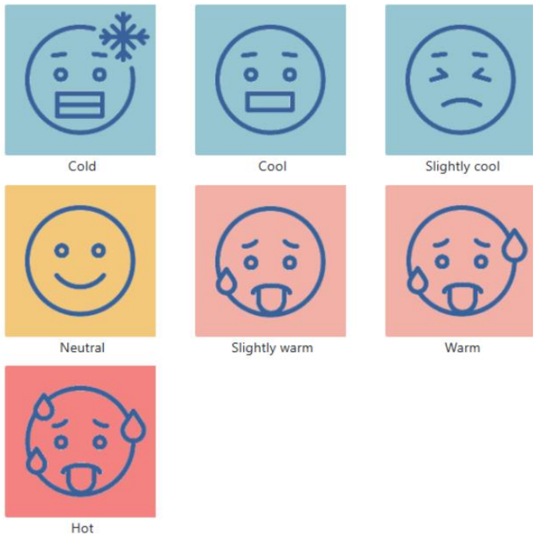
7. At this precise moment, would you prefer the room temperature to be ... ?



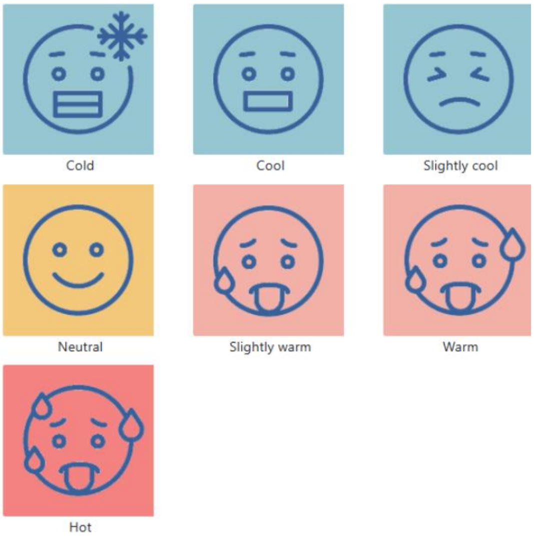
8. At this precise moment, how do you judge the room temperature on a personal level?

9. At this precise moment, how do you find the room temperature?

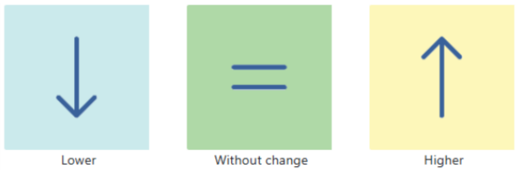
10. At this precise moment, how do you perceive the room temperature?



10. At this precise moment, how do you perceive the room temperature?



11. At this precise moment, would you prefer the humidity in the air of the room to be ...?



12. How do you judge, on a personal level, the humidity in the air of the room?

13. At this precise moment, how do you find the humidity in the air of the room?

14. Are all windows and doors closed at the moment?