# An international Round Robin Test in test rooms: moving forward together to understand human-building interactions




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**Abstract.** Test room experiments allow to study human-building interactions under controlled environmental boundaries. Differences in experimental design, methods, and contextual variables specific to the location and test room features, result in experimental outcomes that are difficult to generalize and compare. This paper presents an international Round Robin Test activity consisting in the replication of the same procedure in different test rooms worldwide to capture contextual variables effects on human-centric studies and to deepen multi-domain human comfort topics. The campaign focused on the hue-heat hypothesis and investigated the effect of coloured electric-light on human thermal responses (both perceptual and physiological) with the aim of (i) analysing the existence of cross-effects between visual and thermal comfort domains and (ii) correlating physiological signals variations to different testing conditions. Overall, 76 subjects were involved in four laboratories during a summer campaign. Each subject was exposed to a controlled and fixed thermal environment while varying three lighting conditions throughout a single test. No significant crossed effects were verified. The same procedure will be repeated in winter to account for seasonal variability and identify new research questions in the framework of this promising cooperation that will be extended to a broader network of facilities.

**Keywords.** Multi-domain comfort, hue-heat hypothesis, cross-modal effect, test room, round robin test

# 1. Introduction

People's perception of the environment affects how they interact with buildings and this in turn influences the building's energy consumption (Delzendeh, Wu, Lee, & Zhou, 2017). One way researchers study human-building interactions are in a controlled environment is by conducting test room experiments (Pisello & al., 2021). However, because of differences in experimental design and methods, and since each test room can be different in terms of its design features and location, it can be difficult to compare and generalize the results from these experiments. To address the inter-laboratory comparability problem, researchers often use a technique called a Round Robin Test (RRT). This is when the same experiment is done multiple times, but in different laboratories. A RRT could be conceived (i) to determine the "true" value of the research objective thus providing a benchmark for future research (De Santis, et al., 2017); (ii) to examine and self-calibrate individual laboratories or to certify their accuracy; (iii) to assess how repeatable and reproducible the results of a specific well-controlled analytical method or experiment procedure are by having different laboratories with different equipment and researchers following the same protocol (Asdrubali, et al., 2022; Baldinelli, et al., 2019).

Despite the growing attention on multi-domain human comfort, multi-domain approaches have been less explored than single approaches (Heydarian, et al., 2020) and the results of multi-domain experiments are often inconclusive or contradictory (Schweiker, et al., 2020), most likely due to inconsistent experimental approaches, study reporting, and lack of established procedures for assessing cross-modal and combined effects (Chinazzo G. , et al., 2022). According to a recent review paper specifically addressing human comfort experiments in test rooms (Pisello & al., 2021), 23% of the total number of experiments conducted in this field (396) were multi-domain experiments and just 17 dealt with thermal-visual interactions. Among others, Chinazzo and Andersen (2018) investigated the effect of daylight through three types of coloured glass on thermal response and overall comfort at three temperature levels and it was found that sunlight transmitted through stained glass primarily affects people's thermal responses through psychological effects rather than physiological. Chinazzo et al. (2018) investigated the hue-heat-hypothesis (HHH), which states that thermal responses can be affected by colours, in case of daylight filtered through stained glazing. Other researchers mainly focused on the influence of coloured electric light. Equivalent metabolic rate was introduced by (Omidvar & Brambilla, 2021) as a novel parameter to include the hue-heat effects in conventional thermal comfort models. They found that the maximum and minimum effects of lighting colour on physiological responses and thermal perception were observed at 4000 K and 6500 K Correlated Colour Temperature (CCT) respectively. The results also showed that thermal perception is more sensitive to colour temperature changes in warm environments. Additionally, Wu et al. (Wu, et al., 2022) focused on the impact of heat and light on human perception and work performance in underground working environments. The results showed that air temperature had a more significant impact than light, but the interaction between colour temperature and air temperature had a significant impact on several evaluation parameters. A previous study (Du, Zhang, & Zhao, 2022) also explored the impact of temperature, light, and sound pressure level on people's perception of environmental comfort in the waiting hall of high-speed railway stations. They found that in a warm indoor environment in winter, people's perception of thermal comfort increases as the level of illumination increases. Specifically, people's evaluation of thermal comfort in environments with 1500-3000 lx was higher than in environments with 150-500 lx. A similar result was found in office spaces with daylight by Chinazzo et al. (2019). In addition, the authors found that the only presence of daylight, compared to a lack of it, could result in a higher thermal comfort of occupants.

Given this framework, there is a lack of standardization in design and experimental validation procedures for multi-domain environmental perception studies, which can limit the ability to perform error and uncertainty analysis, ensure quality control, and replicate the results. Additionally, many test room experiments are limited to specific climate zones (Pisello & al., 2021). This can further introduce biases in the interpretation of the results and in the generated knowledge.

This paper presents an International Round Robin Test Rooms activity, established in the framework of IEA EBC Project Annex79, as an inter-laboratory experiment involving research institutes worldwide, covering both temperate and continental climates. The activity implies the replication of the same experimental procedure in different test rooms with a group of volunteers locally recruited and selected to be in a comparable age range and balanced in terms of gender. This international cooperation aims to capture the effect of contextual variables on human-centric studies and to gain better understanding of multi-domain human comfort topics that are still being debated in the scientific community by accelerating the process of disclosing human perception in the built environment. Here, the first experience carried out in this framework is reported. The main focus of this research is the HHH to examine whether the use of coloured electric light can influence people's thermal response. The research objective is twofold: to analyse the existence of cross-effects between the domains of visual and thermal comfort, and to test the potential correlations among environmental, personal, and contextual variables on human physiological responses (more specifically, Heart Rate - HR).

The structure of this paper is as follows: Section 2 reports the methods used for testing rooms, equipment, procedures, and data processing. Section 3 presents the results of the study on the cross-modal effects on both perceptual and physiological dimensions. Finally, in Sections 4 and 5 discuss the findings and draw conclusions.

# 2. Methods

### *2.1 Test rooms and equipment*

Four institutes participated in the experimental stage, namely: (1) University of Perugia (Perugia, Italy), (2) Construction Technologies Institute – ITC (Milan, Italy), (3) Budapest University of Technology and Economics (Budapest, Hungary), and (4) Concordia University (Montreal, Canada). As a consequence, experiments were run in three countries and two continents. According to the Köppen Classification

(Peel, Finlayson, & McMahon, 2007), the former two locations belong to a humid subtropical climate (Cfa) and the latter two to a warm summer continental climate (Dfb).The dimensions of the usable space of test rooms varied between 23.7 m² (2) and 10.64 m² (4). The internal finishes present a composition that reproduces similar visual and thermal effects indoors, described in Table 1.

**Table 1**

*Construction characteristics of the test rooms participating in the Round Robin Test*

| Lab. | Construction characteristics |
|---|---|
| 1 | Walls, floor and ceiling covered by a grey plasterboard layer; Strip of rigid extruded polystyrene in middle of the walls, showing the radiant system |
| 2 | Plaster white walls and dark grey steel tiles floor; Soundproof tiles with light reflectance value of 86% |
| 3 | Wall covered with white paint, except one black that shows airflow; cassette ceiling type and floor covered by tiles |
| 4 | Walls covered by polished chrome plasterboard layer, ceiling constituted of suspended ceiling panels and grey floor covering |

The cooling and heating systems are composed of radiant and HVAC systems for facilities 1,2 and 3 and of a perimeter heating system and HVAC system for facility 4. The preferred strategy adopted for the radiant system is the reversible air-to-water heat pump, in the three mentioned cases enabling also independently heating and cooling of the surfaces. The HVAC system variates between the facilities, respectively (1) a reversible air-to-air heat-pump with eight distribution channels and two air extractors; (2) a reversible direct expansion heat pump, equipped with 2 ceiling supply air vents and; (3) and (4) with a modular air handling unit.

The lighting fixtures allow the modification of the CCT in the room, through the change of the hue of the electric light and its intensity. Facilities 1, 3 and 4 presented LED panels, used in the neutral phase, and RGB reflectors, for the 1st and 2nd lighting conditions. The ITC adopted a LED panel, with adjustable CCT, and two bulb lamps, one halogen and another led, with fixed CCTs.

The HR was monitored using the Empatica E4 (McCarthy, Pradhan, Redpath, & Adler, 2016) device in the case of facilities 1 and 2, the Beurer chest band (Beurer, n.d.) for facility 3 and the Fitbit smart watch (Feehan, et al., 2018) in facility 4. The environmental parameters collected in each facility are described in Table 2.

**Table 2**

*Collected environmental parameters in each test room participating in the Round Robin Test*

| | | Laboratory | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 |
| Monitored parameter | Air temperature | ✓ | ✓ | ✓ | ✓ |
| | Globe temperature | ✓ | ✓ | ✓ | ✓ |
| | Superficial temperature | ✓ | ✓ | - | - |
| | Relative humidity | ✓ | ✓ | ✓ | ✓ |
| | Air velocity | ✓ | ✓ | - | ✓ |
| | Illuminance on the work plan | ✓ | ✓ | ✓ | ✓ |
| | Illuminance at the sight height | ✓ | ✓ | ✓ | ✓ |
| | CCT | ✓ | ✓ | ✓ | ✓ |

## *2.2 Experimental procedure*

The performed experimental campaign took place in summer (June-September 2022) and focused on the exposure of recruited subjects to a specific combination of thermal and visual stimuli. Each domain factor that was designed and controlled throughout the tests is summarized in Table 3. The thermal conditions were chosen to be slightly divergent from the thermal neutrality according to the EN ISO 7730:2005 and BS EN 16798-1:2019, for the summer. Indeed, the operative temperature range suggested for a thermally comfortable single office (level of activity 58 W/m² corresponding to "seated relaxed") belonging to the B category (i.e., acceptable PMV in between -0.5 and +0.5) is 24.5 ± 1.5 °C for the cooling season, referring to a specific clothing level of 0.5 clo. Under the same rationale, participants were asked to wear pre-defined clothes, e.g., short-sleeved shirt, light trousers, underwear, socks, and sport shoes, to have a similar clothing insulation value (0.5 clo). Desired lighting conditions were reached only through artificial lighting systems while daylight access was avoided to limit both uncontrolled variations of the lighting conditions according to the daytime, and radiant asymmetries affecting local thermal comfort. All the tests were performed during the mornings, to keep the same circadian rhythm level between all the recruited participants.

**Table 3.**

*Conditions adopted for thermal and visual domains*

| Domain | Designed factor | Levels |
|---|---|---|
| Thermal | Operative temperature | 24 °C (slightly cool), 28 °C (slightly hot) |
| | Relative humidity | 45±5% |
| Visual | CCT | 2700÷3000 K (red light), ~4000 K (neutral light), 6000÷6500 K (blue light) |
| | Illuminance on the desk plan | ~500 lx |
| | Illuminance at sight height | ~300 lx |

One subject at a time performed the test to avoid any inferences on the environmental perception due to facial masks that may be needed due to the pandemic contingency (Figure 1a-d). Each test lasted 110 minutes (Figure 1), with fixed thermal conditions and variable lighting conditions. Therefore, each participant repeated the test twice to be exposed to the two temperature conditions (repeated measures design), in two different not consecutive days to guarantee at least one wash-out day between the two sessions. This approach was chosen as lighting is quickly adjusted indoors and people can adapt to it in a quicker way compared to the thermal conditions. The experiment consisted of the following stages:

- Acclimatization under neutral light, 30+10 minutes (Cosma & Simha, 2018; Bellia, d'Ambrosio Alfano, Fragliasso, Palella, & Riccio, 2021): this period allowed participants to adapt to the indoor temperature being exposed to a neutral whitish light (around 4000 K). During this phase participants instructed about the experimental procedure, read the information sheet, signed the consent form, and filled in a general survey with personal data (gender, age, weight, height). During the last 10 minutes the subjects were assumed in thermal equilibrium with the environment and retrieved responses representative of the current environmental exposure.

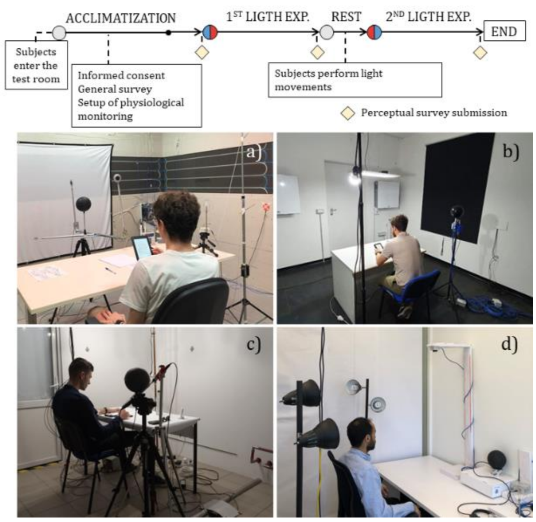
- 1st lighting stage, 30 minutes (Chinazzo & Andersen, 2018; Brambilla, Hu, Samangouei, Cadorin, & Davis, 2020; Toftum, Thorseth, Logadóttir, Markvart, & Stoffer, 2021): participants were exposed to the first light condition. Since the two lighting conditions were factored in time to reduce carry-over effects and to keep metabolic levels comparable between the two stages, half of the participants were exposed to blue light condition on the first stage while the others start with the red one.

- Resting period, 10 minutes: between the two light scenarios, the participants were exposed to the neutral lighting condition for reducing carry-over effects (i.e., CCT around 4000K as in the acclimatization phase). This approach was used in other experiments (Baniya, Tetri, Virtanen, & Halonen, 2016). During this phase, participants did very light movements (i.e., on-site walking for 5 minutes) to avoid decreasing the metabolic rate and keep it at a certain level.

- 2nd lighting stage, 30 minutes: participants were exposed to the second light condition

**Figure 1**

*Experiment procedure and pictures of the on-going test at laboratory (a) 1, (b) 2, (c) 3, and (d) 4.*



The perceptual thermal responses were collected through a standard right-here-right-now thermal and visual comfort questionnaire. The survey was submitted at the end of the acclimatization phase (corresponding to the neutral light condition) and at the end of both 1st and 2nd lighting exposure stages.

### 2.3 Data processing

The occurrence of a cross-modal effect between visual and thermal domains was verified by comparing the expected thermal vote, computed according to the Fanger model (PMV), and the observed thermal vote (OTV), as expressed by test participants through the submitted surveys. Indeed, PMV was computed through the comfort package, "comf", developed for the R environment (Schweiker M. , 2016) and accounts only for monitored thermal stimuli, while OTV is the perceptual response provided by participants at the end of the lighting stages. Discrepancies between predicted and observed votes could thus be imputable to the cross-modal effect. The statistical significance of the observed divergence between PMV and OTV was tested through a pairwise comparison between different light exposure conditions (within-subjects factor). The ANOVA test for repeated measures was performed (1) without including between factors or covariates, (2) including the laboratories where the test took place as a between-subjects factor, (3) further including personal and contextual variables, i.e., gender, lighting exposure order, as between-subjects factors, and (4) further introducing the Body Mass Index (BMI) as covariate (ANCOVA test). Before performing each test, related assumptions were analysed. Sample sphericity was verified for all the tests (p-values ranging between 0.779 and 0.871, related to test 2 and 3, respectively), while the homogeneity of variance (Levene's test) was not met for the sample gathered under neutral light condition in test (2) and (4) so that related results cannot be confidently reported in the following section.

The physiological dimension was accounted by applying a mixed effects regression model (Winter, 2013) to fit the observed instantaneous HR (dependent variable) based on monitored air temperature coupled to a variety of datasets including environmental, personal, and contextual variables. The adoption of the mixed effects regression model allowed to include observed environmental conditions rather than the designed ones so to capture possible fluctuations throughout a test. The adopted datasets were the following: (1) air temperature and gender, (2) air temperature and the laboratory location, (3) air temperature, gender, and laboratory location, (4) air temperature and CCT, (5) air temperature and illuminance on the work plan. The goodness of fit for the generated regression models was quantified through the log-likelihood value. The higher the value of the log-likelihood, the better a model fits a dataset. Therefore, the impact of variables added to the base model (the one describing HR variation by monitored air temperature values) was verified through the likelihood ratio test consisting of comparing the likelihood of two models with each other. Finally, the significance of the single variable effect on HR was verified through ANOVA test.

## 3. Results

### 3.1 Sample description

The whole campaign involved 76 subjects (38 females) in the age range 19-45 years old and with an average Body Mass Index (BMI, the ratio between a body's weight and the square of height) of 22.7±3.6 kg/m$^2$. Table 4 presents the sample characterization for each laboratory taking part to the RRT.

**Table 4**

*Sample description for each test room participating in the Round Robin Test*

| | Laboratory | | | |
|---|---|---|---|---|
| | **1** | **2** | **3** | **4** |
| | **Nr. of recruited subjects (female)** | | | |
| | 30 (15) | 28 (14) | 4 (1) | 14 (8) |
| | **BMI [kg/m$^2$] (mean±sd)** | | | |
| | 21.5±2.3 | 23.6±4.3 | 23.1±6.2 | 23.8±3.0 |
| | **Frequency distribution per age class** | | | |
| **<20** | 2 | 1 | 0 | 1 |
| **21-30** | 28 | 9 | 3 | 7 |
| **31-40** | 0 | 17 | 1 | 6 |
| **>40** | 0 | 1 | 0 | 0 |

### 3.2 Cross-modal effects on perceptual responses

The average differences and related standard deviations observed between collected from expected thermal votes (OTV-PMV) were equal to -0.12±1.03, 0.33±0.87, and 0.06±0.95 for the blue, neutral, and red light exposure conditions. The performed statistical tests reported a significant deviation of the observed thermal sensations from calculated PMV. Nevertheless, pairwise comparisons among different lighting conditions showed that significant differences occurred only between the neutral light exposure and the blue/red light conditions, while no significant differences were observed between blue- and red-light scenes (Table 5).

**Table 5**

*Results of the ANOVA tests*

| Performed test | Pairwise groups | p-value |
|---|---|---|
| (1) | Neutral/Blue | .000 |
| | Blue/Red | .066 |
| | Neutral/Red | .003 |
| (3) | Neutral/Blue | .000 |
| | Blue/Red | .180 |
| | Neutral/Red | .005 |

Concerning performed test 3, the effect of introduced between-subjects factors (laboratory, gender, and light exposure order) was further analysed reviling a statistically significant impact only for the laboratory variable (.001). The pairwise comparisons among laboratories resulted in significant differences in observed PMV-OTV retrieved at the Concordia University with those collected both (i) at the Budapest University of Technology and Economics (.017) and at the University of Perugia (.013).

### 3.3 Cross-modal effects on physiological responses

The base model, i.e., the one describing the instantaneous HR variations in accordance with the simultaneously observed air temperature values, presented a log-likelihood value equal to -1735.1. This value did not vary at all by introducing information about the laboratory where the test took place (model 2) and the illuminance on the work plan (model 5). The same log-likelihood value decreased down to -1735.0 including gender (model 1) and -1733.4 including CCT (model 5). In any case, observed changes in the goodness of model fit were not significant as verified thanks to the ANOVA test.

## 4. Discussion

In line with the HHH, expressed thermal votes were higher under red-light and lower under blue-light conditions if compared to the expected values according with Fanger model. Nevertheless, obtained results did not provide evidence for the existence of a crossed effect between visual and thermal domains due to different CCTs obtained via coloured electric lights. Indeed, significant effects were only observed comparing light-neutral environment to the blue- and red-light conditions while differences between red- and blue-light scenes were not statistically significant. Therefore, the significant variations could be most probably related to the thermal adaptation of subjects throughout the test since thermal votes under neutral (whitish) light conditions were collected always at the end of the acclimatization phase. Therefore, the outcomes of this study are in line with those studies that did not confirm the HHH in the literature. Among others, (Bannett & Rey, 1972) did not find a significant correlation between the colour of worn goggles (red, blue, and clear) and the expressed thermal comfort in a sample of 21 students exposed to controlled dynamic thermal conditions. The HHH was not verified also in the study conducted by (Baniya, Tetri, Virtanen, & Halonen, 2016) that followed a procedure much closer to the one proposed in this RRT: 16 subjects were exposed to two constant thermal environments (20 °C and 25 °C) with a lighting system with an adjustable CCT that was set on three levels (2700 K, 4000 K, and 6200 K).

As a further outcome of the RRT, the variable 'laboratory' (representative of contextual factors) was significant in some tested models. The context where the test takes place can thus affect the results. However, this significant difference seems to not be imputable to the climatic contexts since it was observed between the sample group tested in the Concordia University test room (Dfb climate) and the sample groups participating to the experimental campaign at both Perugia (Cfa) and Budapest Universities (Dfb). This aspect should be further investigated in future studies. Moreover, differences in tested sample size among laboratories may compromise the relevance of these outcomes. Nevertheless, the RRT activity is still ongoing so that the whole database at disposal for this investigation will increase in size to ensure more robust findings.

Concerning the analysed physiological response, it was found out that the goodness of model fit for the HR signal did not improve by progressively adding complexity to the model: adding new variables, doesn't matter which (gender, laboratory, CCT, or illuminance), did not improve the model fit in any case. This means that human physiological response, in terms of HR, does not vary significantly among individuals, at least under the slightly uncomfortable thermal conditions here tested. Moreover, previous studies already found out that changes in hue of light did not influence human physiological response (Chinazzo & Andersen, 2018). A similar data processing approach could be implemented considering different environmental boundaries.

## 5. Conclusion

Test room experiments are a common approach to investigate human-building interactions. Nevertheless, differences in experimental design and characteristics of the facilities result in outcomes that are difficult to compare and generalize. This work reports about a first-of-its-kind international collaboration that brings the RRT approach into human-based research. The designed experimental protocol focused on the HHH and was replicated in four laboratories involving 76 subjects. Recruited volunteers were exposed to constant thermal conditions (designed to be slightly cold and slightly warm, according to standards) and three coloured electric lights (whitish, bluish, and reddish) during a single test lasting 110 minutes. Both perceptual and physiological responses were collected during the test. Data processing did not find out significant cross-modal effects between visual and thermal domains, i.e., expressed thermal comfort not significantly related to the lighting exposure condition, or changes in HR signals imputable to personal or contextual variables.

The presented summer campaign is only a first part of the proposed RRT activity which already involves 9 research institutes from Italy, Germany, Hungary, the USA, Canada and Brazil. The activity is designed to have both a winter and a summer data collection campaign to further account for seasonal variability. Furthermore, In accordance with the multi-domain theory, relevant environmental features, such as CO2 and VOC concentrations, as well as background noise levels, were recorded in laboratories equipped with proper monitoring tools during the Round Robin Test. These additional data are included in the shared database and will be further investigated in future studies. The impact of contextual variables, including test rooms décor and appearance will also be explored in future campaigns.

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