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CONSTRUCTION AND BUILDING PERFORMANCE

BUILDING AND DESIGN TECHNOLOGIES

IMMERSIVE VIRTUAL VS. REAL ENVIRONMENT: A VALIDATION FIELD-STUDY TO ASSESS OCCUPANTS' WORK PRODUCTIVITY AND COMFORT

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Abstract

In order to maximise occupants' well-being and work efficiency, keep satisfying environmental conditions, and minimise costs and impact related to the operative and energy use, a "human-centric" approach is more and more pursued in buildings' design and performance assessment. In this context, the use of Virtual Reality (VR) is emerging due to its advantages (low cost, repeatability, and speed of execution) compared to physical study settings. However, in Immersive Virtual Environments (IVE), it is important to ensure that data represented and collected faithfully replicate the physical environments. In order to provide a further contribution in terms of IVE validation process in the building field, this research presents results from an experimental study, where subjects' performance tests and comfort assessments were compared in real and virtual office settings under three different walls colour layouts and two air temperature levels. "Internal", "ecological" and "construct" validity of the IVE have been demonstrated. Findings revealed no statistically significant differences in productivity and sensation votes and in the impact of colour and temperature variables. Results then highlight a strong agreement of the two tested environments, revealing that VR is a potentially reliable tool to measure its real counterparts in terms of occupants' productivity, perception, and behaviour under different test conditions.

Keywords

Human-centric design, Immersive virtual environment, Work efficiency, Thermal and visual comfort, Wall colour.

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1. INTRODUCTION

Nowadays, there is a strong need and a growing concern to save resources from buildings due to the large amount of energy consumed and emission produced, and, at the same time, to create efficient and comfortable living and working places because of the large portion of working hours spent indoor.

A two-way relationship between users and built environments is highlighted. On one side, occupants have significant impacts on buildings use and energy consumption. According to the International Ergonomics Association Annex 53 [1], among the factors affecting the building energy consumption, occupants' activities, behaviour, and indoor environmental quality play a crucial role. On the other, changes in the built environment impact human comfort, state of mind, and corresponding reactions. It is evident a strong causal relationship between design and occupants' health, well-being, and productivity, demonstrating "the impact of the workplace on

Nomenclature	
IEQ	Indoor Environmental Quality
IVE	Immersive Virtual Environment
VR	Virtual Reality
RE	Real Environment
VRSQ	Virtual Reality Sickness Questionnaire
met	Metabolic rate
clo	Clothing insulation
TSV	Thermal Sensation Vote
VSV	Visual Sensation Vote
R	Red
W	White
B	Blue

the workforce" [2]. Indeed, the office's physical environment is made up of several environmental factors affecting occupants: indoor air quality and ventilation, thermal comfort, lighting and daylighting, noise and acoustics, office layout, biophilia, and views, look and feel, location, and amenities [3].

Hence, the concept of the human-centred perspective or user-centred design has been introduced. It deals with the need of focusing buildings' design, use, and maintenance actions on "humans factors", such as end-users needs, requirements, and preferences [4]. The overall aim should be to maximise occupants' well-being and work efficiency, to keep satisfying environmental conditions related to different stimuli (thermal, visual, acoustic, air quality) while minimising costs and impact related to the operative use (energy, maintenance costs), and to employee productivity, which typically account for about the 90% of the business' operating costs and it is a major concern for every organization [5].

Although well-being, comfort, and productivity research has been studied for decades, there are several and significant obstacles toward the acceleration of knowledge in this field. The cause is related to the erratic, unpredictable, stochastic, complex, and interdisciplinary characteristics of occupant nature [6], which make it difficult to accurately model and predict occupant behaviour and well-being since the early design stage and to achieve the highest contextualization to avoid prediction errors. Another problem is related to the need to study all variables, such as the multiple environmental stimuli and their combinations (multi-domain and crossed effect), not only a single predictor at a time. Lastly, the difficulty of controlling the variation of design and environmental conditions to be reproduced by full-scale experimental studies (in-situ or laboratory environments) involves a considerable waste of time and resources and does not allow the creation of specific correlations for each design case.

In order to overcome these limitations of traditional studies, there is a growing trend towards the use of Virtual Reality (VR) as a valid mean to simulate alternative building design configurations, to guide choices, to assess alternatives and changes in real-time without the limitation of physical models. In the past few decades, the improvement in graphical renderings and audio setting enhanced the immersion levels within the virtual environment (VE), creating the Immersive Virtual Environment (IVE) defined by Jim Blascovich [7] as "VEs that organise sensory information in such a way as to create a psychological state in which the individual perceives himself or herself as existing within the VE". The main advantages, and the differences with the traditional technologies and systems used to physically evaluate the comfort-oriented design, are: low cost, repeatability, speed of execution. Due to these potentialities, IVEs has increasingly been used to study how changes in indoor conditions (lighting, walls colour, windows size) influence occupants' comfort, performance, and behaviour.

However, the actual challenge lies in obtaining valid, reproducible, and generalised research findings from the virtual to the real setting. As reported by Saedi et al. [8], there are five major validity types that should be considered for IVEs validation purposes. "Ecological validity" is evaluated through the IVEs capability to adequately represent the real environments and is strongly linked to the concept of sense of presence and immersivity, because the more a person achieves the "sense of being there", the more the responses would match those in the real environment (RE). Secondly, the "internal validity" occurs if the entire IVE can be easily controlled, eliminating the cause-effect relations by developing completely comparable scenes. "Construct validity" is achieved if real and virtual environments produce comparable applied measures and coefficients, while "external validity" is supported if the researchers are allowed to generalise the results of the study to a larger number of users, places, or times. Lastly, "criterion validity" is established by demonstrating comparable levels of prediction between the real and the virtual setting, for example, comparing responses to future performance or behaviour. In general, the absence of statistical difference in the results between RE and IVE sessions validates the VE and allows researchers to generalise the findings beyond the virtual setting.

To date, only a few studies examined the adequacy of IVEs for validation purposes through the comparison with the real counterpart while assessing users' comfort levels and satisfaction (e.g. [9–16]), productivity [17], occupant behaviour [8, 9, 18]. Hence, thermal behavioural and performance studies employing VR are still at the initial state. There is the need to further validate IVEs through a comprehensive methodology able to effectively perform comparisons with in-situ outcomes.

The main focus of this study is then to provide a contribution to the VR validation in the field of human-centric building performance by testing the potentialities of using a modelled IVE, in comparison with a RE, to analyse users' productivity, thermal and visual perception in a workplace. The colour of the office indoor walls was investigated as a specific design aspect due to the importance of these stimuli on human psychological responses.

2. METHODS

The experiment office room was located in a laboratory of the Department of Information Engineering (DII) at Università Politecnica delle Marche (Ancona, Italy). A group of 23 volunteer participants was recruited to perform a productivity test and to answer to a thermal and visual sensation questionnaire under two types of stimuli: three "walls colour" (white, red, blue) in combination with two levels of "temperature" set point (17°C and 22°C, during the heating season). The tests were conducted both in the RE and then in the corresponding IVE.

2.1. TEST ROOM SETUP

The test room was created by delimiting a portion of a larger office environment with curtains. Three sides of the test rooms were equipped with three coloured curtains (white, blue, red), which were replaced during the different tests. In addition, a black curtain was used to screen daylight from the windows to guarantee the same artificial lighting conditions during the test days. The size of the testing area was about 3.60 (L) x 2.40 (W) x 2.80 m (H) and was equipped with a desk and seats to host up to 3 volunteers for each test. The basic layout is shown in Figure 1.

The room was equipped with two LED lamps installed on the room ceiling and two work lamps placed on the desks; both set at a correlated colour temperature of 4000K (neutral white), considered functional for working activities. The task area consists of four workstations. The illuminance level (E_m) on each workstation was measured by using two broadband radiometers to ensure the minimum requirement of 500 lux (measured values 554lx ÷ 584lx) for each workstation [20].

The indoor air temperature, air velocity, humidity, and operative temperature, were recorded with a time step of one second by using the *Dantec Dynamics ComfortSense* climate station (Fig. 1b).

2.2. IVE SETUP

The virtual office was created starting from the 3D geometric model of the test room then improved by using *Unity* software [21] to apply the Capsule Camera (first-person player control tool), lights, and materials, and making the virtual immersive 3D representation more realistic.

In order to create a virtual environment that successfully replicates the real one and achieves a high level of immersivity to all subjects, it was necessary to properly address the colour setup in the model.

Lightings (point lights and spot lights) were set with an RGB value corresponding to 4000K to represent the realistic lighting conditions of the real office room.

While concerning the curtain walls, a spectrophotometer (*CM-2500d Konica Minolta*) was used to measure the luminance parameters (L*) and chromatic components (a*b*) of the related CIELab model. The device was at first calibrated for the white and the black colour. The SCE (Specular Component Excluded) method was selected to properly measure the colour of the irregular and

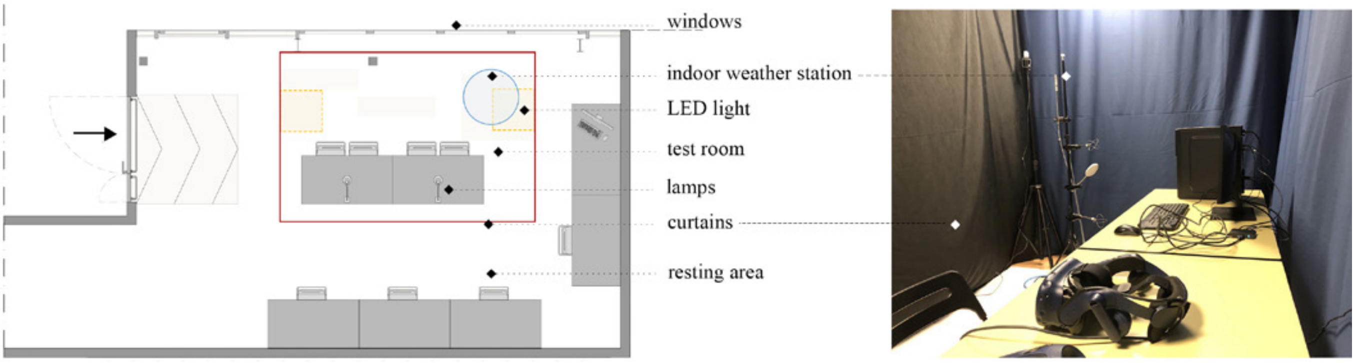

Fig. 1. *Test room layout (a) and the IVE setup (b).*

non-glossy diffusing surface of the fabrics. Five measures (measurement area ϕ 8 mm) were performed for each coloured curtain. Then the average values have been calculated and converted into RGB model coordinates to be applied in the Unity 3D model albedos (Fig. 2).

Six IVE scenarios were created according to the setting of the experimental activity with the three wall colours and two temperature set-point. Each scenario was characterised by a different productivity test with the same difficulty, consisting of a text written on a sheet of paper applied on cubic elements over the working desk.

Moreover, a “scene 0”, containing the correct text for the pre-experimental phase, was also modelled.

Participants viewed the virtual office environment through a Head-Mounted Device (HDM) by *HTC VIVE PRO Eye* (1440x1600 resolution image per eye). The experiments began with the device setup to correctly adjust the subjects’ distance between the lenses (reflecting interpupillary distance), thus making the headset more comfortable and improving the sharpness of the visualised images.

2.3. EXPERIMENTAL PROTOCOL

Each participant completed the experiment on four different test days with a few days in between, performing the productivity tests and answering the survey for each wall colour and two temperature set-points, for both the RE and IVE.

At the beginning of the experiment on each day, a pre-experimental phase was carried out for 15 minutes (black rectangles in Fig. 3). While sitting in the resting

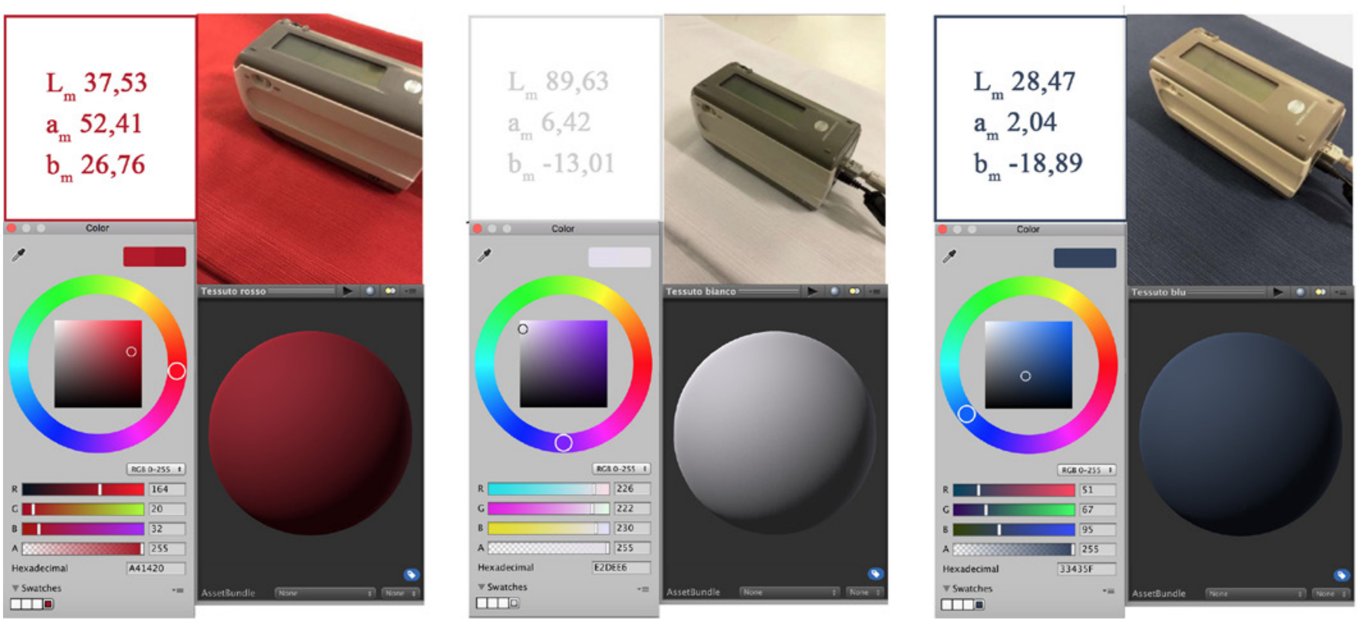

Fig. 2. *Curtain colour measurements with the spectrophotometer, CIELab, and RGB coordinates in Unity Albedo.*

area, volunteers were allowed to acclimatise to the environmental conditions, to get informed about the instruction on the experimental procedure, to complete the pre-experiment questionnaire, and to read the productivity text in the original version without errors.

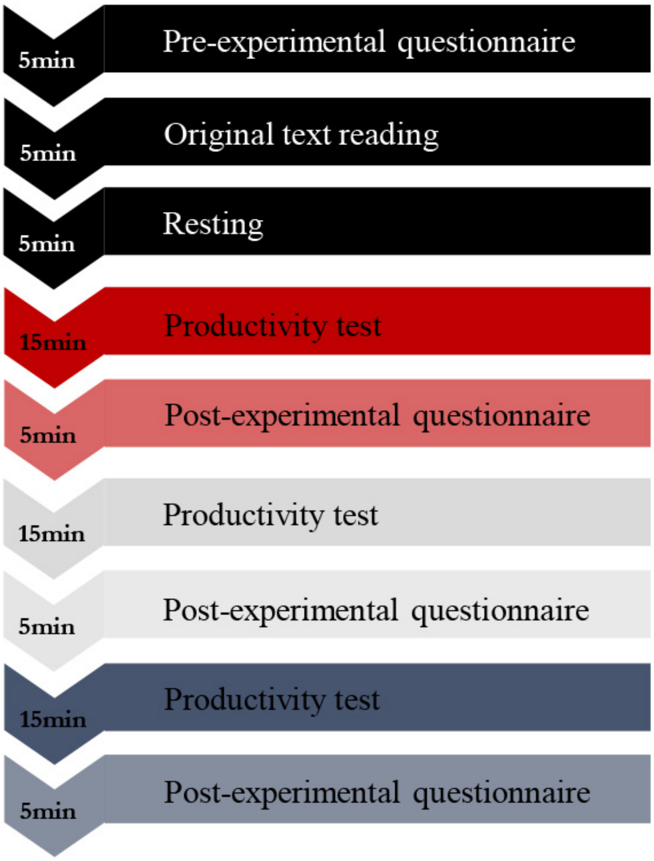

Fig. 3. *Experimental schedule.*

Then they entered the test room, and the experiment began with a short orientation section (3 min) by focusing on the colour walls to be unconsciously affected by colour stimulus, followed by the proofreading tasks. In order to avoid cybersickness during the IVE sessions, participants were exposed to each operative test for a maximum of 15 minutes for each walls colour.

After the experiment, participants were welcomed back in the resting area to complete the post-experimental survey, while the coloured curtains (RE) or the scenes on *Unity3D* (IVE) were changed by the staff.

The proofreading task and survey procedure were repeated once for each colour (Fig. 4). Of course, participants were unaware of the three walls colours order and the two operative temperatures, thus avoiding any expectation concerning the experimental conditions.

2.4. EXPERIMENTAL DATA COLLECTION

The authors collected the following data to answer the research question about the construct and the ecological validity purpose: productivity test, pre and post-experimental questionnaire with comfort and cybersickness assessment. Naturally, volunteers were not informed about

Fig. 4. *Volunteers during RE tests in the office room with the three colour layouts and the corresponding IVE scenarios.*

the aims of the study in order to get answers based on their authentic feelings.

Throughout the productivity test, participants completed a proofreading task which is a common obligation for an office environment, and it is also compatible with virtual environments due to its easy reproducibility. Indeed, concerning previous users' office performance evaluations in IVEs, the most common used methodologies are (in relevance order): proofreading task, stroop tests, visual tasks, executive functions, problem-solving.

Several versions of the same 48 lines text were created: an original version without errors (i.e., grammatical errors, typos, words replacements, etc.) to be read by participants during the pre-experimental phase and a modified one used during the operative phase to evaluate the work efficiency by counting all the errors contained (totally 12). While keeping the same number (12) and typology, the errors in the text were changed among each experimental session creating a similar level of difficulty.

Prior to the operative phase, participants completed a pre-experiment survey in the resting area regarding their demographics (gender, age, height, employment, health status) and personal information. The latter was composed of two checklists. The first was for the metabolic rate (met) evaluation [22], based on the physical activity done 30 minutes before the test; the second checklist aimed to estimate the clothing insulation value (clo) of participants' garments [23].

After both the physical and virtual environment productivity test sessions, participants were required to complete a post-experiment survey. It was designed with closed and open-ended questions to retrieve information concerning thermal sensation (Section II) and visual sensation (Section III).

Participants' thermal sensation was evaluated by measuring the Thermal Sensation Vote (TSV) [24] based on a 7-point scale from «-3=cold» to «+3=hot».

Moreover, to understand their perception about artificial lighting colour in both RE and IVE, the Visual Sensation Vote (VSV) on a 5-point scale (from «+0=warm» to «+4 =cool») was assessed together with the glare evaluation causing visual discomfort.

It is worth reminding that there was also a virtual office test experiment. Thus, in order to control IVE data quality, to limit the duration of an experiment to less than 20–30 min, Section IV was added to collect information about the cybersickness due to the VR exposure. The Virtual Reality Sickness Questionnaire (VRSQ) [25], based on a 5-degree scale (from «0=not at all» to «+4=a lot»), was adopted to rescue nine typical symptoms: general discomfort, fatigue, eyestrain, difficulty focusing, headache, the fullness of head, blurred vision, dizzy (eyes closed) and vertigo.

3. RESULTS

In the following sections, the analysis of the two collected datasets (in RE and IVE) is conducted for each parameter (productivity, thermal and visual sensation) concerning the three validation goals of this study. The internal validity was achieved by developing completely comparable scenes plus by providing repeated-measure design research. The ecological validity of the modelled office IVE has been evaluated through the results from cybersickness analysis. The construct validity was assessed by looking for any difference in the tested variables given by the two environments. Hence, the differences (Δ) on errors detected by the participants and on the thermal and visual sensation votes between RE and IVE under each experimental condition were analysed (between groups comparisons). Moreover, productivity and comfort were compared within the experimental condition to find out if the three walls colour and two temperature set-points lead to the same effect in both the real and virtual office.

3.1. PARTICIPANTS

For this study, 23 participants (52% male and 48% female) were recruited. They were mostly (86%) undergraduate students, Ph.D. students, researchers, professors attending every weekday the university spaces (classrooms, offices, departments) between the age 23 to 32 years old (μ=26 years old, SD=3). Of this participants, the 39% was under 25 (μ=23.44, SD=0.52), 43% between 25 and 30 (μ=27.2, SD=1.68) and only the 17% over 30 years old (μ=31.5, SD=0.57). The remaining sample size (14%) was composed of employees or freelancers elsewhere. Regarding the eligibility criteria,

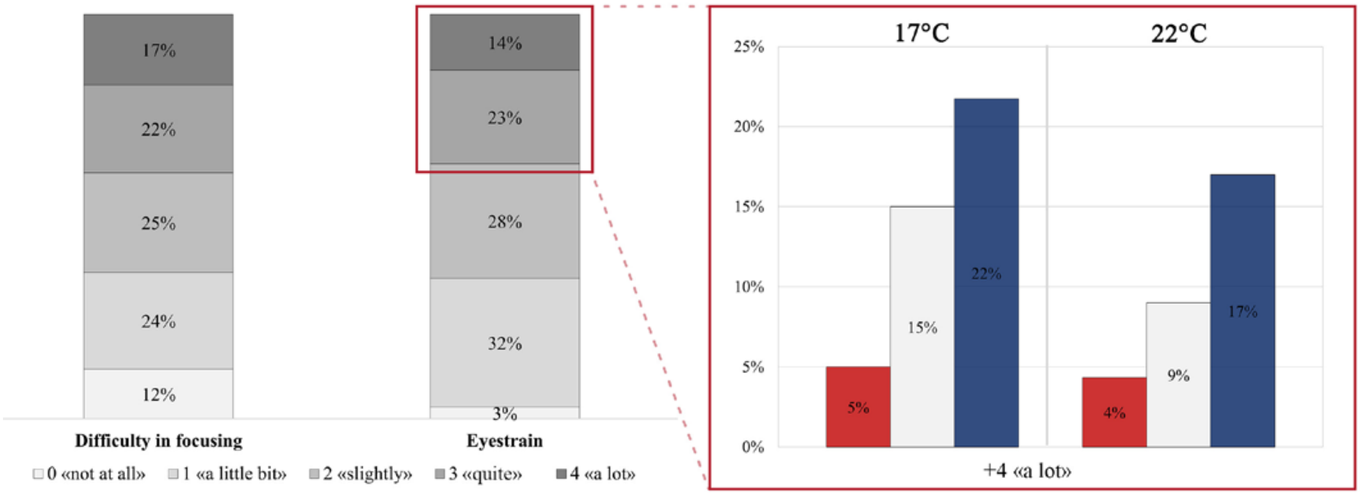

Fig. 5. *Results of the cybersickness ratings for "difficulty in focusing" and "eyestrain" disorders (a); "eyestrain" ratings among the test conditions during the IVE session (b).*

none of them suffer from colour blindness, and of all the participants, 48% having eyesight problems (myopia, astigmatism, hyperopia) wore corrective lenses to perform the tests in both scenarios.

To minimise the learning effect, participants performed all experimental tests with an interval of a week between December and January. Hence, they wore typical winter garments with a mean clo value equal to 0,90 and slight variability between the clothes throughout each test day.

Before each experimental session, 65% of all the subjects were involved in sedentary activities (<1,2 met). While the pre-experimental phase of 15 minutes allowed the subjects, who performed more intense activities prior to the tests (1,8 – 2,5 met and >2,5 met), to go back to a typical resting level.

It is important to note that, even if none of them had previous experience with IVEs, the overall group managed to finish the experiment, not suffering from cybersickness.

3.2. ECOLOGICAL VALIDITY

The Ecological validity of the IVE has been evaluated through self-reports on the VRSQ questionnaire.

Of all the participants, 96% did not experience dizziness (eyes closed) and vertigo due to the static conditions typical of the tests of this study. Between 41% and 58% of subjects rated the other disorders as general discomfort, fatigue, headache, the fullness of head, blurred vision as not significant («0=not at all» and «+1=a little bit»). Despite that, the survey received a quite rating (score «+3» and «+4») on the difficulty in focusing (at least 37%) due to slightly blurred images and eyestrain, as shown in Figure 5a through the mean percentage of votes.

Participants performed the productivity tests for each wall colour on the same day, with 5 minutes rest, and then were welcomed back to repeat the experience for the other temperature setup in the virtual environment a few days later. Indeed, an increasing percentage trend for the rating «a lot» (+4) given to the eyestrain symptom was discovered (Fig. 5b) during the progress of each test session. However, all participants fully complete the tests.

3.3. CONSTRUCT VALIDITY

3.3.1 PRODUCTIVITY

The Shapiro-Wilk test stated the normality of the results for each tested condition (p-value >0.05), then the distribution of errors detected in the proofreading task was considered. Among all the 12 errors contained in each text, subjects discovered a mean of 9.03 errors in the RE (sd=2.32) and 8.33 in the IVE (sd=2.28).

For the comparison approach between RE and IVE, a paired-samples t-test was conducted on the difference of errors (Δ) detected in the proofreading tasks for all the tested conditions. According to the results, the t-values and the p-values confirmed that the test environment (virtual or real) did not appear to influence subjects' productivity. Indeed, the difference of means of the errors (Δμ) presents non-significant values lower than 1.30.

The authors also calculated the Cohen's d effect size to analyse the size difference between the errors detected across the two tested environments. An overall "small" magnitude (0,20 ≤ d ≥ 0,50) was measured in five cases and a "negligible" effect (d <0,20) in one case.

Secondly, the results of the productivity test were compared within the experimental condition (three walls colour and two temperature set-point). A two-way repeated-measures analysis of variance (ANOVA) was conducted. The obtained F-ratios for both RE and IVE fall outside the critical region (F-ratio <4.35), and the p-values are above 0.05. Then, there were no mean differences in errors detected among the different tests.

3.3.2 THERMAL SENSATION

In order to look for an agreement between RE and IVE in the thermoception domain, the subjective ratings of thermal sensation votes (TSV) were compared. Figure 6 shows the number of TSVs expressed at each temperature set-point and coloured layout. Within each temperature level, no overall relevant differences might be highlighted in the stacked histograms between the real and the virtual office.

It is clear that temperature level has a significant influence on thermal sensation. Indeed, the median of the distributions corresponds to a slightly cool rating («-1») for the lowest set-point (17°C), while increases with the highest set-point (22°C), located around the thermal neutrality (score «0»). The Wilcoxon signed-ranks test confirmed the lack of statistically significant difference in terms of TSV between RE and IVE.

In addition, the distributions of thermal sensation reported in Figure 6 appear not to be affected by the coloured layouts in both RE and IVE within each temperature level, as also verified through the calculated Kruskal-Wallis H-ratio.

Hence, subjects' thermal sensation seemed not to be significantly affected by the main effect of colour (C) and the combination colour-temperature (C x T) in both tests environments. However, for temperature factor (T), the calculated Kruskal-Wallis H-ratio confirmed the relevant effect of temperature on subjects' thermal sensation.

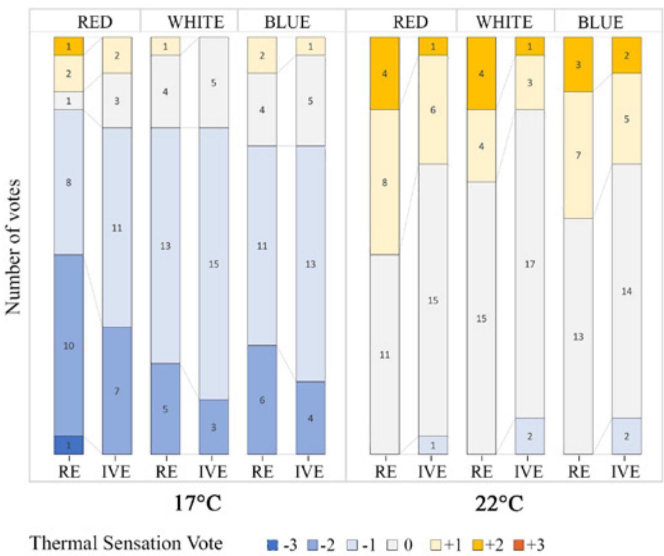

Fig. 6. *Number of votes for the thermal sensation votes (TSV) expressed among each experimental conditions.*

3.3.3 VISUAL SENSATION

In order to further support the construct validity of the modelled IVE, also subjects' visual sensation votes (VSV) were analysed. Figure 7 shows the number of VSVs expressed under each temperature set-point and coloured layout. Within each temperature level, no overall relevant differences might be highlighted between the real and the virtual office. Indeed, the median is located around the score "neither warmer nor cooler (+2)", which corresponds to a neutral white LED light with a 4000K correlated colour temperature.

The authors computed a statistical analysis to verify the previous hypothesis. The results of the Wilcoxon signed-rank test confirmed that there was no difference in terms of VSV between RE and IVE (μ_Δ=0) among each tested condition, due to the fact that the mean difference (Δμ) of the rating scores were less than 0.43.

In addition, the distributions of visual sensation reported in Figure 7 appear not to be affected by the coloured layouts in both RE and IVE within each temperature level, as confirmed by the nonparametric Scheirer-Ray-Hare

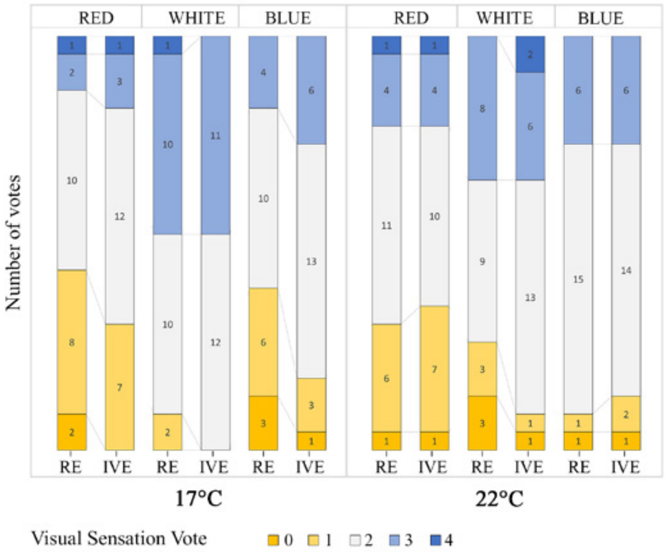

Fig. 7. *Number of votes for the visual sensation votes (VSV) expressed among each experimental conditions.*

test. Moreover, according to the statistical tests, subjects' visual sensation seemed not to be significantly affected by the main effect of colour (C), temperature (T), and their interaction (C x T) in both tests environments.

4. DISCUSSION AND CONCLUSIONS

The objective of this research is to provide a further contribution in terms of VR validation in the domain of buildings occupants' productivity, perception, and behavioural studies. The overall aim is to demonstrate that this tool is a suitable representation of physical environments and to fully exploit its many advantages (low cost, repeatability, and speed of execution), which allow overcoming the well-known limitations of the physical models (non-generalizable results, time/cost constraints).

Concerning the three VR "validation" aims, the main findings of this study are:

- The repeated-measure design research and the development of a fully realistic and detailed model allowed the creation of completely comparable scenes, thus supporting the internal validity.
- Participants felt a relevant sense of presence within the IVE. Indeed, the ecological validity of the IVE setting was confirmed by the cybersickness analysis, which revealed that the majority of subjects did not experience high disorders levels, while at least 37% assigned a quite rating to the «difficulty in focusing». Despite the fact that the VR headset caused an increasing percentage of the «eyestrain» symptom, all participants fully performed all the tests.
- The test environment (virtual or real) did not appear to influence subjects' productivity, thermal and visual comfort at each experimental setting (construct validity, part 1). A strong agreement was found between the collected data distribution (errors detection, TSV, VSV). Indeed, the statistical analysis confirmed that the differences for both errors and sensation votes across RE and IVE were not statistically significant.
- The experimental conditions (three colour layouts and two temperature set-point) had the same effect in both RE and IVE (construct validity, part 2). In particular, subjects' productivity, thermal and visual sensation in both test environments seemed not to be significantly affected by the main effect of colour (C), temperature (T), and their combination (C x T) except for the effect of temperature level on TSV, as expected.

The outcomes of the sample-wide analysis highlighted a strong agreement of the two tested environments revealing that VR is a potentially reliable tool to measure its real counterparts in terms of occupants' productivity, perception, and behaviour under different test conditions.

Despite the relevant results, more research is needed. For example, a wider range of thermal conditions could be tested to simulate both heating and cooling seasons. Even if the results were statistically significant, the sample size could be enlarged, also in terms of age distribution. Alternative work efficiency verification methodologies should be tested to get a suitable test duration consistent with the IVEs time exposure in order to limit the cybersickness disorders. Lastly, future investigations could accommodate the experimental design to test various sensory stimuli (thermal, visual, acoustic) and environmental layout (walls colour, lighting, design) to improve users' satisfaction, work productivity, and energy-related behaviour. This also suggests a potential use of VR since the early building design steps to acquire information about the end-users needs and preferences, thus enhancing the decision-making process supporting a human-centred design.

5. REFERENCES

[1] Yoshino H (2012) IEA EBC Annex 53: Total Energy Use in Buildings, analysis and evaluation methods, pp 1–15

[2] World Green building Council (2014) Health, Well-Being & Productivity in Offices. World Green Build Counc 1:46

[3] Al Horr Y, Arif M, Kaushik A, Mazroei A, Katafygiotou M, Elsarrag E (2016) Occupant productivity and office indoor environment quality: A review of the literature. Build Environ 105: 369–389. https://doi.org/10.1016/j.buildenv.2016.06.001

[4] Heydarian A, Pantazis E, Wang A, Gerber D, Becerik-Gerber B (2017) Towards user centered building design: Identifying end-user lighting preferences via immersive virtual environments. Autom Constr 8:56–66. https://doi.org/10.1016/j.autcon.2017.05.003

[5] D'Oca S, Hong T, Langevin J (2018) The human dimensions of energy use in buildings: A review. Renew Sustain Energy Rev 81:731–742. https://doi.org/10.1016/j.rser.2017.08.019

[6] Niu S, Pan W, Zhao Y (2016) A virtual reality integrated design approach to improving occupancy information integrity for closing the building energy performance gap. Sustain Cities Soc 27:275–286. https://doi.org/10.1016/j.scs.2016.03.010

[7] Blascovich J (2002) Social Influence within Immersive Virtual Environments. In: Schroeder R (ed) The social life of avatars. Springer, London, pp 127–145. https://doi.org/10.1007/978-1-4471-0277-9_8

[8] Saedi S, Rizzuto T, Zhu Y, Kooima R (2016) Measuring the Effectiveness of an Immersive Virtual Environment for the Modeling and Prediction of Occupant Behavior. Sustain Human–Building Ecosyst: 159–167

[9] Ozcelik G, Becerik-Gerber B (2018) Benchmarking thermoception in virtual environments to physical environments for understanding human-building interactions. Adv Eng Informatics 36:254–263. https://doi.org/10.1016/j.aei.2018.04.008

[10] Chen Y, Cui Z, Hao L (2019) Virtual reality in lighting research: Comparing physical and virtual lighting environments. Light Res Technol 51:820–837. https://doi.org/10.1177/1477153518825387

[11] Chamilothori K, Wienold J, Andersen M (2019) Adequacy of Immersive Virtual Reality for the Perception of Daylit Spaces: Comparison of Real and Virtual Environments. LEUKOS - J Illum Eng Soc North Am 15:203–226. https://doi.org/10.1080/15502724.2017.1404918

[12] Hong T, Lee M, Yeom S, Jeong K (2019) Occupant responses on satisfaction with window size in physical and virtual built environments. Build Environ 166. https://doi.org/10.1016/j.buildenv.2019.106409

[13] Yeom D, Choi JH, Zhu Y (2019) Investigation of physiological differences between immersive virtual environment and indoor environment in a building. Indoor Built Environ 28:46–62. https://doi.org/10.1177/1420326X17731945

[14] Emamjomeh A, Zhu Y, Beck M (2020) The potential of applying immersive virtual environment to biophilic building design: A pilot study. J Build Eng 32:101481. https://doi.org/10.1016/j.jobe.2020.101481

[15] Saeidi S, Rentala G, Rizzuto T, Hong T, Johannsen N, Zhu Y (2021) Exploring thermal state in mixed immersive virtual environments. J Build Eng 44:102918. https://doi.org/10.1016/j.jobe.2021.102918

[16] Salamone F, Bellazzi A, Belussi L, Damato G, Danza L, Dell'aquila F, Ghellere M, Megale V, Meroni I, Vitaletti W (2020) Evaluation of the visual stimuli on personal thermal comfort perception in real and virtual environments using machine learning approaches, Sensors (Switzerland) 20. https://doi.org/10.3390/s20061627

[17] Heydarian A, Carneiro JP, Gerber D, Becerik-Gerber B, Hayes T, Wood W (2015) Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations. Autom Constr 54:116–126. https://doi.org/10.1016/j.autcon.2015.03.020

[18] Saeidi S, Chokwitthaya C, Zhu Y, Sun M (2018) Spatial-temporal event-driven modeling for occupant behavior studies using immersive virtual environments. Autom Constr 94: 371–382. https://doi.org/10.1016/j.autcon.2018.07.019

[19] Saeidi S, Chokwitthaya C, Zhu Y, Sun M (2018) Spatial-temporal event-driven modeling for occupant behavior studies using immersive virtual environments. Autom Constr 94:371–382. https://doi.org/10.1016/j.autcon.2018.07.019

[20] ISO - International Organization for Standardization (2011) UNI EN 12464-1 Light and lighting. Lighting of workplaces. Indoor work places

[21] Unity (2021). https://unity.com. Accessed on May 7, 2021

[22] ISO - International Organization for Standardization (2004) ISO 8996:2004 Ergonomics of the thermal environment - Determination of metabolic rate

[23] ISO - International Organization for Standardization (2007) ISO 9920:2007 Ergonomics of the thermal environment — Estimation of thermal insulation and water vapour resistance of a clothing ensemble

[24] ISO - International Organization for Standardization (2019) ISO 10551:2019 Ergonomics of the physical environment -- Subjective judgement scales for assessing physical environments

[25] Kim HK, Park J, Choi Y, Choe M (2018) Virtual reality sickness questionnaire (VRSQ): Motion sickness measurement index in a virtual reality environment. Appl Ergon 69:66–73. https://doi.org/10.1016/j.apergo.2017.12.016