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Immersive virtual vs real office environments: A validation study for productivity, comfort and behavioural research

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A R T I C L E I N F O

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A B S T R A C T

The use of Virtual Reality (VR) to enhance research in the building sector is currently emerging, but validation studies are still limited. This work aims to provide a contribution in VR validation on comfort, productivity, and adaptive behaviour research in offices. 104 participants performed one test session in a real or a virtual room, three cognitive tasks and surveys (on immersivity, cybersickness, comfort, and intention of interaction). The validation process was addressed by evaluating the adequacy of VR in representing real-life scenarios and the benchmark of results. Findings confirmed the ecological validity of the model by an excellent sense of presence, graphical satisfaction, involvement, realism and low cybersickness levels. The absence of significant differences between the results on comfort, productivity, and behaviour, collected in the real and virtual settings, supported the criterion validity. Results highlighted the potentialities of applying VR to support a user-centred design and investigations on multi-domain comfort.

1. Introduction

Nowadays, most Europeans spend more than 20 h per day inside buildings [1], where almost all human activities take place from the professional to the personal one. As a result, during the last decades, there was a growing interest in the impact of indoor environmental conditions on individuals. This is a very relevant topic because the role buildings can play in users' productivity, behaviour, well-being, comfort, and health has never been more evident.

According to a user-centred design approach [2], the crucial aim should be to achieve an acceptable indoor environment through the improvement of the building design around end-users requirements. Indeed, human comfort, living conditions and work efficiency quality should be perceived as one indicator of the building's overall performance. It is well-established that building users' are exposed to several drivers (contextual, personal, indoor environmental quality, random) [3–6] that act simultaneously, thus complicating the impact of the built environment on the users [7]. This fact highlights the need for a strategy aimed at evaluating the effects of all these variables from the early design stage to optimise living and working conditions.

Indeed, early design decisions have a crucial impact on the project's life, costs and individuals' satisfaction [8]. Consequently, in the Architecture, Engineering and Construction (AEC) sector, the involvement of end-users has emerged via new technologies, such as Virtual Reality (VR) and Immersive Virtual Environments (IVEs). Their potentialities lie in: supporting experts to identify the pros and cons of design decisions while having a better understanding of the outcomes; enabling the revision of the planning and the monitoring of the progress more efficiently [9]; facilitating the communication of design details and scopes via the creation of immersive virtual models that allow stakeholders to experience an unbuilt or under maintenance indoor or outdoor environment from a first-person point of view [10].

In addition, in the past few decades, IVEs allowed researchers and designers to support and improve the acquisition and integration of human factors from the early design stage, for example, to measure end-user behaviour, receive feedback during design, and improve communication for a better understanding of the project itself [8] via multi-sensory 3D environments [11].

The use of these technologies is not only limited to the design phase but can also provide several advantages over other data collection methods in this research domain, such as traditional laboratory based-study.

Due to the relevant amount of time and resources needed to set up these physical spaces several troubles emerged: the impossibility of creating specific correlations for each design case, replicating specific

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Abbreviations

AEC	Architecture Engineering and Construction
GS	Graphical Satisfaction
INV	Involvement
IVE	Immersive Virtual Environment
RE	Real Environments
REAL	Experienced Realism
SP	Spatial Presence
VE	Virtual Environment
VR	Virtual Reality
TCV	Thermal Comfort Vote
TSV	Thermal Sensation Vote
TPV	Thermal Preference Vote
VCV	Visual Comfort Vote
VSV	Visual Sensation Vote
VPV	Visual Preference Vote

contexts, carrying out analysis for buildings still under design, and customising experimental models by modifying the multiple variables in a short time [12]. Indeed, VR is a low-cost technology, in terms of speed of execution and replication of tests. It allows the users to be immersed in a 1:1 scaled environment, while researchers and designers collect real-time feedback and easily control the design variables in terms of visual stimuli. Moreover, users can experience the so-called Acoustic Virtual Reality (AVR) [13], if VR is combined with acoustical stimuli, or mixed IVE (MIVE) [14] if the virtual environment is combined with a climatic chamber generating thermal stimuli. That is why IVEs are demonstrating their potential in data collection and examination in the multidisciplinary AEC field.

Despite its many advantages, the use of IVEs for studying productivity at work, comfort, and behaviour is still emerging and requires more research attention and validation to enhance the reliability and effectiveness of the collected data and related outcomes. A significant barrier to adopting these tools in building design and research is the limited amount of validation studies regarding their accuracy in the representation and comparison to real-life scenarios. An accurate representation of the indoor environment is crucial for obtaining valid user feedback [15], because the more the user feels present, the more the responses would match those in the physical environment. However, most research articles applied standalone IVE, without a comparison with its real counterpart, asking participants to self-report their sense of presence and immersivity, as in Refs. [16–20]. To the authors' knowledge, only a few experiments validated IVEs vs Real Environments (REs) in this research field, and especially:

- to evaluate the influence of the test environment on thermal comfort [14,21–23];
- to investigate users' thermally-driven [21] and lighting-driven [24, 25] behaviour;
- to explore the potential of AVR for indoor noise design protection [26–28];
- to assess the effects of the indoor building layout, such as indoor walls' colour [23,29,30], lighting status [7,8] and features [10,31], façade characteristics [32,33], biophilic exposure [34,35] on users' productivity, comfort and overall perceptions.

Thus, it is imperative to consolidate the validation domain of IVEs demonstrating the potential to represent real-life scenarios. In particular, the adequacy of VEs in replicating physical settings is mainly limited to making a comparison with in-situ settings by looking for any difference between the collected data from both experiments. However, it is important to systematically evaluate also the end-user experience and immersion within a VE, which is an often debated aspect [36] not fully addressed within the analysed research.

To contribute to this long-term goal and ensure higher levels of validation, this paper presents results from a comprehensive comparative study in the fields of comfort, productivity, and adaptive behaviour. In particular, 104 subjects performed a set of identical cognitive tasks in virtual and physical office environments with the same characteristics and climatic conditions (air temperature about 24 °C). The novelty of the presented research lies in the strict methodological approach used to investigate the validity of the modelled IVE, based on a double-fold and step-by-step validation. At first, the authors checked the ecological validity of the modelled IVE to ensure it can adequately reproduce the physical settings. It was tested by analysing the sense of presence, immersivity and cybersickness symptoms reported by the participants. Once the ecological validity is established, the authors proceeded by benchmarking the metrics of productivity, thermal and visual comfort and behaviour in real-world settings and with previous literature. If no statistical differences in the outcomes of the independent variables are detected and the cause-effect relationships or correlations agree with past studies, then, the criterion validity is established thus completing the overall validation of the tested IVE.

The rest of the paper is structured as follows: Section 2 summarises the research methodology, Section 3 covers the dataset analysis, the presentation and discussion of the results, and Section 4 reported the authors' conclusions and future research perspectives.

2. Materials and methods

The methodology was designed to provide a direct comparison of the real (RE) and the virtual (IVE) environments to investigate the adequacy of the virtual environment in the comfort, behaviour and productivity domain and to detect any changes within the subjective responses due to the change in the tested environment. An independent-measure research design was carried out in this study: each participant was randomly assigned to a virtual test session (group 1, $n = 52$) or an in-situ (group 2, $n = 52$) one. In this section, the experimental setup, the development of the virtual model, productivity tests and surveys are presented, followed by the experimental schedule.

2.1. Experiment setting

The tests were carried out in an office-like test room at the Department of Building and Civil Engineering and Architecture (Università Politecnica delle Marche, Ancona, Italy) with internal dimensions of 5.93 × 4.38 × 3.00 m (height).

The room was set up as shown in Fig. 1a to replicate an office working environment: the workstation included a computer, a keyboard, a mouse, and a monitor in the RE. The thermal environment depended only on the central HVAC system where the testing room was placed. During the experiment, the indoor air temperature was recorded by several measurement sensors (temperature range: from −40° to +125 °C and accuracy ±0.3 °C°) placed above the desk where the test was performed and located at the feet (0.10 m), waist (0.60 m) and head (1.10 m) of the seated participants to ensure the same thermal condition in both tested environments. In RE and IVE the indoor air temperature was on average equal to 24.10 °C (sd = 0.26) and 24.35 °C (dev.st. 0.32), respectively. Thus, no relevant differences were measured across the experimental sessions that could potentially harm the validation of the model from a thermoception point of view. To detect participants' energy-related intention of interaction a window, a fan, a heater, and an air conditioner were added to the room, but they were set off and did not influence the thermal environment. Indeed, the participants did not directly interact with the climatic systems; they only report the adaptive response they would have wanted to carry out to improve their thermal comfort induced by the HVAC of the room. Hence no thermal outcome was experienced by the subjects.

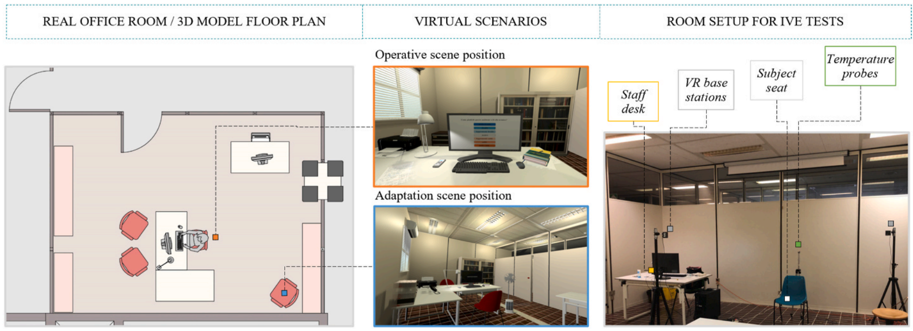

Fig. 1. (a) Floor plan of the real office room and 3D model; (b) Two scenarios of the immersive virtual environment; (c) Test room setup for the IVE experiments.

For the tests in the virtual environment, the room was reorganised with the proper equipment for the IVE visualisation which included the VR base stations and the workstations for the researchers, as presented in Fig. 1c.

2.2. IVE development

The second step in the workflow was to model the 20-square meters office room in a way that it can adequately replicate the real office space. Thus, 3D CAD software was used to build the room geometry (i.e., walls, floor, door) and furniture (i.e., chairs, desks, bookcases, and workstations). Once this step was completed, the model was imported into *Unity* software [37] to apply materials, lights and the first-player control to allow the users to experience the VE.

Before the office model was imported into Unity, the luminance parameter (L*) and chromatic components (a*, b*) of the CIELab model were detected using a spectrophotometer (*CM-2500d Konica Minolta*). This action was taken to ensure the correct representation of surfaces' materials and colour, thus, increasing the model realism. In particular, five measures were carried out (8 mm diameter), for each surface of the real office room: floor tiles, walls, desks, and chairs. Afterwards, the resulting L*a*b* parameters were mediated and then converted into RGB coordinates to be inserted within the Unity model.

Once the model and textures were completely set, the authors created two basic virtual scenarios: the first (Fig. 1b-down) allowed the subjects to have a complete view of the room far from the virtual workstation and to adapt to the VE, and the second one (Fig. 1b-top) to perform the test while virtually seating in front of the virtual workstation.

Necessary scripts were coded by using C# in Unity to sequentially and automatically visualise the scenes of the tasks to minimise the interactions with the researcher managing the test.

An *HTC Corporation VIVE PRO Eye* head-mounted display (1440 × 1600 resolution image per eye) and the *SteamVR* plugin [38] were used for immersing the participants in the virtual environment.

2.3. Experimental cognitive tasks

To get a valid and objective evaluation of the construct of "productivity", volunteers' productivity was assessed with objective measures as in Ref. [39]. Indeed, three cognitive functions were investigated due to their importance across a variety of tasks: *inhibition* by the *Stroop test* [40], *working memory* by the *OSPAN test* [41], and *task switching* by the *Magnitude-parity test* [42].

The *Stroop test* was developed to measure the ability to control attention and override habits and impulses. Thus, it displayed a total of 32 coloured words of colours (red, green, blue, pink and orange) disposed of in eight rows with four words each on a black background. To complete the task, the participants need to say the colour name of these words as fast as possible, ignoring the text of the word while the authors collected the execution time. For example, if the word "green" is printed in red ink, the correct answer is "red".

The *Magnitude-Parity test* aims to assess the ability to flexibly switch from one activity to another. It consists of a timed video based on a sequence of slides of 200 ms each. The digits from "1" to "9" except "5" were presented in black ink on a white background in the middle of the screen. The numbers were preceded by red or blue dots. According to the parity stimulus, participants expressed whether the displayed number is odd or even after the red dot and whether the displayed number is smaller or larger than "5" after the blue one (magnitude stimulus). The combination of parity-magnitude stimuli was displayed eight times each, for a total of 16 digits to be ranked.

Finally, the *OSPAN test* was adopted to evaluate the ability to keep information in mind and manipulate it. Like the *Magnitude-Parity test*, it consists of a sequence of slides. At first, a simple math operation was displayed in the centre of the computer monitor for 3 s and they were instructed to solve it by the mind. Then, in the second one (3sec) a possible solution to the previous equation was displayed and the subject has to tell whether it is true or false. Then, in the last slide (800 ms) a letter to be memorised was displayed. The combination of slides presenting the math equation-true/false-letter string was displayed in a set of five items. At the end of the five sets, the participants recalled all the five letters in the right order presented.

2.4. Survey instruments

In this study, a set of questions was conducted to collect the effect of individual features and further detect any difference across the RE and IVE tests, thus, supporting the criterion validity. The questionnaire consisted of two main parts for both the real and the virtual sessions. The first part was about basic socio-demographic information (gender, age, height, eyesight problems, educational level, previous experience with VR), and a list of clothes worn during the experiments to estimate the *clo* value according to standard UNI EN ISO 9920:2007 [20].

The second was to fill self-reports about thermal and visual comfort, and intention of interaction after completing the experimental cognitive tasks. The questions of the post-experimental survey are reported below in Table 1.

In particular, based on the standard UNI EN ISO 10551:2019 [43], three parameters were assessed for both thermal and visual comfort: Thermal/Visual Sensation Vote (TSV - VSV) from «very cold » to « very warm»; Thermal/Visual Comfort Vote (TCV - VCV) from «comfortable » to « extremely uncomfortable»; Thermal/Visual Preference Vote (TPV - VPV) from «much colder » to « much warmer».

During each session, adaptive strategies were recorded to study the occupant-building system interactions to improve thermal comfort. Indeed, according to the Theory of Planned Behaviour by Icek Ajzen [44], «*the intention of interaction is assumed to be the immediate antecedent of behaviour*», thus, the intention of interaction with a heater, fan, window, and air conditioning system was collected within the thermal environment. The thermal adjustments expressed were not provided in the physical environment or displayed in the virtual office upon users'

Table 1
Question and ratings of the post-experimental survey (factors marked with '*' were investigated only in the virtual environment).

Factor	Question	Rating scale
Thermal/Visual comfort	How do you judge this environment?	very cold/very warm (7-points)
	Do you find this.?	comfortable/extremely uncomfortable (5-points)
	Please state how would prefer to be now.	much colder/much warmer (7-points)
Intention of interaction	Would you interact with the highlighted building systems to improve your well-being?	yes - no
	If yes, please state your willing interactions	
*Graphical satisfaction (GP)**	I appreciate the graphics and images of the virtual model	totally disagree/totally agree (7-points)
*Spatial presence (SP)**	I perceived the office space as a place I visited rather than a photo I saw	totally disagree/totally agree (7-points)
	During the experience, I felt present in the office space	
	I perceived the virtual model as immersive	
*Involvement (INV) **	During the experience, I was not aware of the real world around me	totally disagree/totally agree (7-points)
*Experienced realism (REAL)**	I perceived the objects inside the virtual office as proportionally correct (i.e., they had about the right size and distance from me and other objects)	totally disagree/totally agree (7-points)
	I had the feeling of being able to interact with the office space (e.g. grab objects)	
	How realistic did you find the virtual model of the office space?	
*Cybersickness**	Did you experience.? GENERAL DISCOMFORT – FATIGUE - EYE STRAIN - DIFFICULTY IN FOCUSING – HEADACHE - VERTIGO	not at all/very much (7-points)

interaction with them (opening/closing window, switching fan, AC, local heater on/off).

There was a supplementary survey that subjects completed after experiencing the virtual environment to further verify the ecological validity of the model. According to the literature, well-established surveys to assess participants' sense of presence and immersivity in this field are the *Slater-Usoh-Steed* (used in Refs. [16–18,21,32]) and the *Igroup Presence Questionnaires* (*IPQ*) (used in Refs. [14,19,32,35,45]). Hence, the authors combined these two schemes to analyse four attributes: Graphical Satisfaction (GS), Spatial Presence (SP), Involvement (INV), and Experienced Realism (REAL) on a seven-point scale (from «totally disagree » to « totally agree»). Another key aspect was investigated: the "cybersickness" within the virtual environment. It was assessed on a five-point scale (from «not at all » to « very much») using the Virtual Reality Sickness Questionnaire (VRSQ) [46] and concerned six symptoms: general discomfort, fatigue, eye strain, difficulty in focusing, headache, and vertigo.

In general, due to the time constraints in VR experiments and the need to integrate the post-experimental survey within the model, the number of questions was revised and reduced to allow the participants not to exceed 25/30 min of exposure to VR.

2.5. *Experiment session*

The experiments took place as presented in Fig. 2. Each participant was recruited for a one-day test to experience the real (group 1) or the virtual environment (group 2), randomly assigned to ensure the internal validity of the research. At the beginning of each test visit, all participants were introduced to the test environment. During the pre-experimental phase, they signed a consent form, received the instruction about the experiment and completed the pre-experiment questionnaire through an online platform. This stage lasted about 15 min to allow them to get used to the environmental conditions and to reduce any fluctuation related to the 30 min-prior-test physical activity that might have influenced their metabolic rate [47].

The IVE session began with the head-mounted display setup and "orientation" session: the participants were asked to rest with their eyes closed for 30 s and adapted to the virtual scene for 3 min to reduce any psychological fluctuations related to the virtual environment exposure, and facilitate immersion, respectively [48]. Then, in both real and virtual settings, the volunteers performed three cognitive tasks (3 min). To reduce the order effect, counterbalance time-related factors and support internal validity, the authors randomised also the order of execution of the three tests (e.g. *M-P, OSPAN, Stroop* vs *Stroop, M-P, OSPAN*). Responses to the productivity tests were given by voice and recorded by the researchers.

Then, participants completed the final questionnaire that was administrated through an online platform in RE. On the other side in the IVE, the cognitive tasks and survey were integrated within the virtual model. Participants could see the tests and questions displayed on the virtual computer monitor as sequences of timed videos and images. In this way, the authors ensured the subjects had a fully immersive experience, without any break-in-presence [36] that can threaten the reliability and validity of the collected data.

The period of the test was limited to 25–30 min to reduce overall fatigue and exposure to the virtual environment, thus, avoiding the occurrence of any disturbances that could invalidate the test [49].

3. Results and discussion

The following paragraphs present the analysis and discussion of the two datasets (RE and IVE). The aim of this experimental study is double-fold: firstly, to evaluate the level of perceived presence-immersivity in the virtual scenarios and to examine whether the use of the VR tool leads

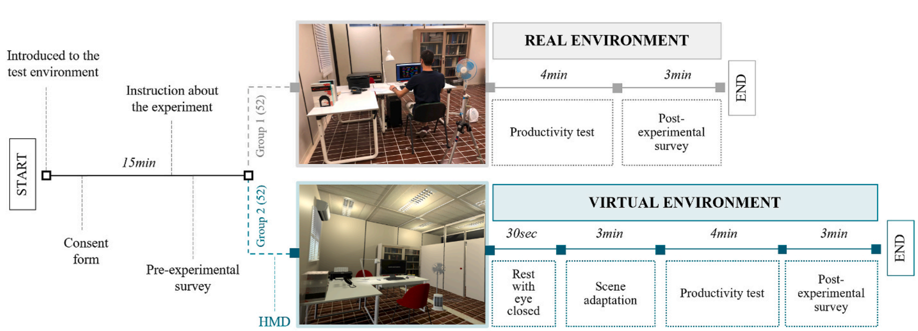

Fig. 2. Experimental schedule in the real and virtual environments.

to cybersickness (ecological validity), and secondly, to assess the adequacy of IVE in terms of productivity, comfort votes and interaction comparing the outcomes of the real and the virtual test sessions (criterion validity).

The parametric and non-parametric statistical analysis methods for independent samples were used for the hypothesis testing. All datasets were analysed through *RStudio* software [50] setting the significance level equal to 0.05 (5%).

3.1. Recruitment and sample analysis

In this study, to compare the responses of participants in the virtual and the real settings an independent-measure research design was carried out. Considering the central limit theory [51], the sample size was established to reach at least $n = 30$ subjects to get the normality of the distribution. Accordingly, two groups composed of fifty-two participants were recruited. A power analysis (effect size 0.50, $\alpha = 0.05$) through the G*Power software [52] was computed: the sample size was adequate to detect significant effects with a statistical power equal to 0.80.

Fig. 3a shows that the sample was well gender-balanced (50% male and 50% female) and it was mostly composed of young people (83%) under 30 years old (Fig. 3b). Most of the subjects were graduates (47%), 38% were university students and 14% had a higher educational level (PhD, post-graduate school, Fig. 3c). None of the subjects suffer from colour blindness and 42% of the sample had typical eyesight problems (myopia, astigmatism, hyperopia, or a combination of them, as shown in Fig. 3d), but all of them wore corrective lenses during the tests, to correctly perform the tasks and visualise the model. In addition, 56% of participants had had at least one previous experience with VR technology (Fig. 3e).

3.2. Ecological validity of the IVE

The presence and immersivity survey results from the test in VR (n = 52) were analysed through the indicators of Graphical Satisfaction (GS), Spatial Presence (SP), Involvement (INV), Experienced Realism (REAL) and the cybersickness disorders ratings. The assessment of Ecological Validity is a necessary step for experimental purposes, as it refers to the ability of virtual environments to adequately represent real settings and then proceed with the formal data analysis. If the Ecological Validity is not verified it is not possible to state that the subjects were properly immersed within the model and then to ensure the suitability and reliability of the results, for instance, in terms of cause-effect relationships. Indeed, generally, it is determined that the higher the values of the four attributes, the higher the participants perceived themselves as present within the environment, thus verifying the effectiveness of the study. Thus, this study compared the scores with the existing literature that applied VR technology and IPQ in the research field of human comfort and behaviour. A total of four previous studies [19,31–33] were considered. However, the attributes are measured with ordinal data that, depending on the experiment, may vary in terms of the 5-point or 7-point Likert scale. Therefore, the authors first rescaled the average ratings to a 5-point scale to allow the comparison. Fig. 4 summarised the comparison of the mean of the four attributes from the presence and immersivity survey. The reported values for this study (GS: 4.58, REAL: 4.47, SP: 4.21, INV: 4.15) are higher than the score corresponding to a moderate level (i.e., 4) on a 5-point Likert scale: the volunteers appreciated the graphics of the model (GS), reported that the virtual environment seemed real for them (REAL) that is why they felt involved (INV) and present (SP) within the virtual environment. The results are also higher than the mean scores from all the previous studies, except for SP which is almost similar to Ref. [19] (4.24). However, the difference is almost negligible (0.03), thus the authors concluded that the virtual model allowed the users to experience an overall excellent sense of presence and immersivity.

Another crucial aspect to evaluate in the VE is cybersickness, which occurs when there is any inconsistency between the visual sensations and the vestibular ones [53,54]. The results of the VRSQ reported that no subject suffered from ‘vertigo’ which states the absence of any difference between perceived and experienced movement because the test was carried out in static conditions. ‘Eyestrain’ showed a «moderate » effect for the 10% of participants probably linked to a ‘difficulty in focusing’ (25%), caused by the slightly blurred images presented by the head-mounted display. The other symptoms: ‘general discomfort’, ‘fatigue’ and ‘headache’ were negligible since 92–100% of scores were assigned to « not at all» and «slightly». Similar findings were reported in previous studies that carried out a sickness symptoms analysis after the experiments: moderate effects are usually highlighted for eyestrain [30, 55]. No general discomfort is usually experienced during the virtual tests [14,31,55] even if the majority of participants have never experienced the VR tool before as in the present study (44%, Fig. 3d).

3.3. Criterion validity of the IVE

According to the second aim of the study, the authors looked for a good agreement between the experiments carried out in RE and IVE. Thus, the outcomes of the independent variables (productivity, thermal and visual comfort and intention of interaction) are compared between the two environments through qualitative and statistical analysis. If the VR performs well, no significant differences will be discovered within the outcomes of the constructs. As a result, the adequacy of the tool in replicating real experimental situations will be confirmed.

3.3.1. Productivity

The dataset is assumed to be normal because the results of the three cognitive tasks belong to a ratio scale distribution and the sample size is greater than 30 (n = 104) [51]. Hence, the initial qualitative hypotheses, based on the mean and standard deviation analysis, were then evaluated with parametric statistical analysis. In particular, the *t*-test for two independent samples was applied. The null hypothesis states that there is no effect, no change, or no difference between the real and the virtual environment: if the computed t-value falls within the critical region (± 1.983 for df = 103, $\alpha = 0.05$) and the p-value is higher than 0.05, the authors could conclude that participants' productivity was not influenced by the tested environment.

Firstly, concerning the *Stroop test*, the number of errors in the colour naming, and the execution time in seconds were addressed. The qualitative analysis on the means of the two samples revealed approximately triple the error in the virtual condition ($mean_{IVE} = 0.31$, dev.st = 0.94) compared to the real one ($mean_{RE} = 0.08$, dev.st = 0.27). However, the result of the *t*-test did not reveal any statistically significant differences in the inhibition function.

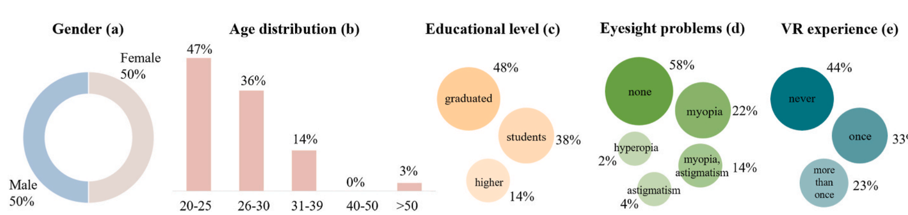

Fig. 3. General information about the sample: a) gender; b) age distribution; c) educational level; d) eyesight problems; e) experience with VR settings.

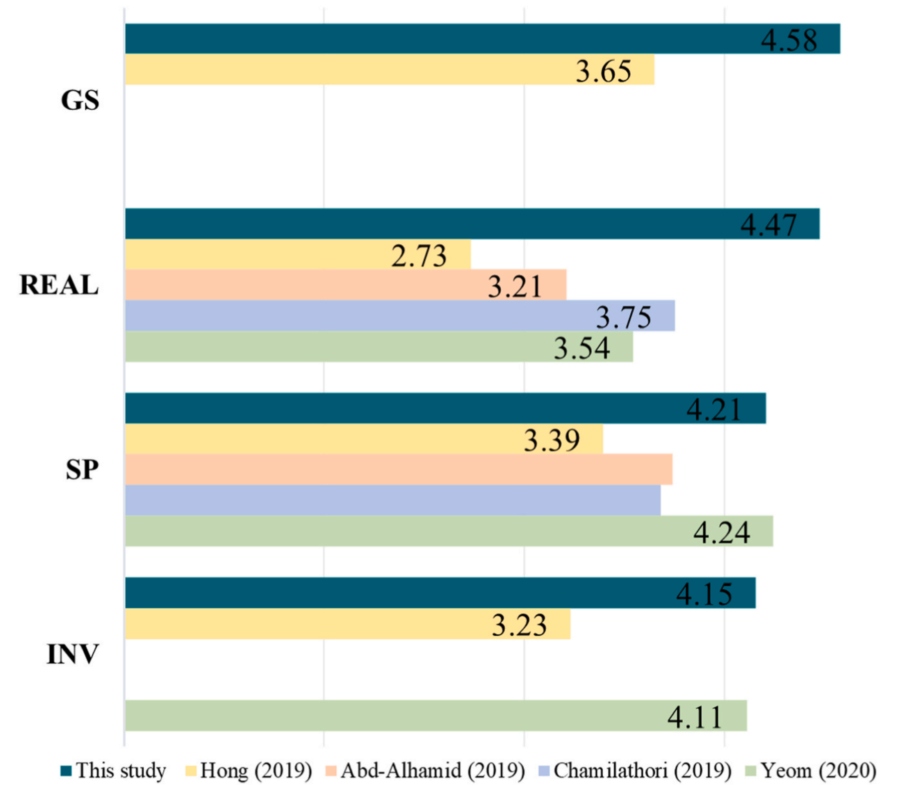

Fig. 4. Comparison of scores on a five-point scale of the four indicators: Graphical Satisfaction (GS), Experienced Realism (REAL), Involvement (INV), Spatial Presence (SP) [Yeom et al. [19], Chimalothori et al. [33], Abd-Alhamid et al. [31], Hong et al. [32]].

The same outcome was highlighted looking at the execution time with about 3 s of difference in the time the participants took to name the 32 colours ($mean_{RE} = 26.54s$, dev.st = 2.91s; $mean_{IVE} = 28.85s$, dev.st = 5.49s), but no difference between the two tested environments was discovered.

The errors in the subject classification of the digits even/odd and greater/lower than "5" were computed for the *Magnitude-Parity test*. In accordance with the statistical test, the qualitative analysis of the mean and standard deviations revealed no difference between RE and IVE: $mean_{RE} = 0.46$ (dev.st = 1.04), $mean_{IVE} = 0.40$ (dev.st = 0.60).

Lastly, the working memory task was analysed according to the automated *OSPAN test* development [41]. In particular, the authors calculated: the number of errors in the true/false string ($mean_{RE} = 0.29$, dev.st = 0.46; $mean_{IVE} = 0.35$, $dev.st_{IVE} = 0.65$), the correct order of the letters memorised ($mean_{RE} = 4.12$, dev.st = 1.34; $mean_{IVE} = 4.48$, dev.st = 0.98), and the OSPAN score, computed as the sum of the number of the right true/false and the letters correctly memorised ($mean_{RE} = 8.83$, dev.st = 1.48; $mean_{IVE} = 9.33$, dev.st = 1.08). Also for the *OSPAN test*, no relevant differences appeared within the mean and standard deviation values, as also confirmed by the further statistical analysis (t-values < t-crit, p-value >0.05).

To sum up, the outcomes revealed no influence of the environment typology on the subjects' cognitive functions.

The results of the statistical analysis are presented in Table 2.

Table 2
The results of the unpaired-sample *t*-test on the three cognitive tests.

Cognitive function test	Parameter	t-value	p-value	$\Delta\mu_{RE-IVE}$
Stroop	number of errors in the colour naming	1.701	0.092	−0.23
	speed of execution	1.741	0.084	−2.31
Magnitude-Parity	number of errors in the classification of the digits even/odd and greater/lower than "5"	0.347	0.729	0.06
OSPAN	the number of errors in the true/false string	0.521	0.603	−0.06
	the correct order of the letters memorised	1.588	0.115	−0.37
	OSPAN score (the sum of the number of the right true/false and the letters correctly memorised)	1.967	0.052	−0.50

3.3.2. Thermal and visual comfort

An agreement in the participants' ratings in both office rooms indicates the similarity of the real and the virtual environments concerning subjective comfort. To compare the ratings, the authors first computed a qualitative analysis of the overall trend of scores in percentage and then a statistical analysis was carried out to support the assumptions.

The scores of the comfort questionnaires are nonnumerical ordinal data, thus it was necessary to apply the non-parametric Mann-Whitney *U* Test, which properly considers that votes are organized in a fixed order corresponding to differences of magnitude. The null hypothesis states that there is no difference between the votes obtained in two tested environments, i.e., there is no tendency for the ranks in VE to be systematically higher (or lower) than the ranks in the RE. The ordinal datasets were rank-ordered, and Mann-Whitney U statistic computed. Since the two samples are both large ($n = 52 > 30$), the distribution of the U statistic tends to approximate a normal shape and the hypotheses can be evaluated using a Z-score statistic and the unit normal distribution to establish the critical region for this z-score (Z-crit = ± 1.96 for $\alpha = 0.05$) [51]. Whether the sample data produce a Z-score that falls outside the critical region and a p-value < α the null hypothesis is rejected.

Fig. 5 shows the percentage of votes across the real and the virtual tests for both thermal and visual comfort.

Concerning thermal comfort, in both RE and IVE the temperature set-

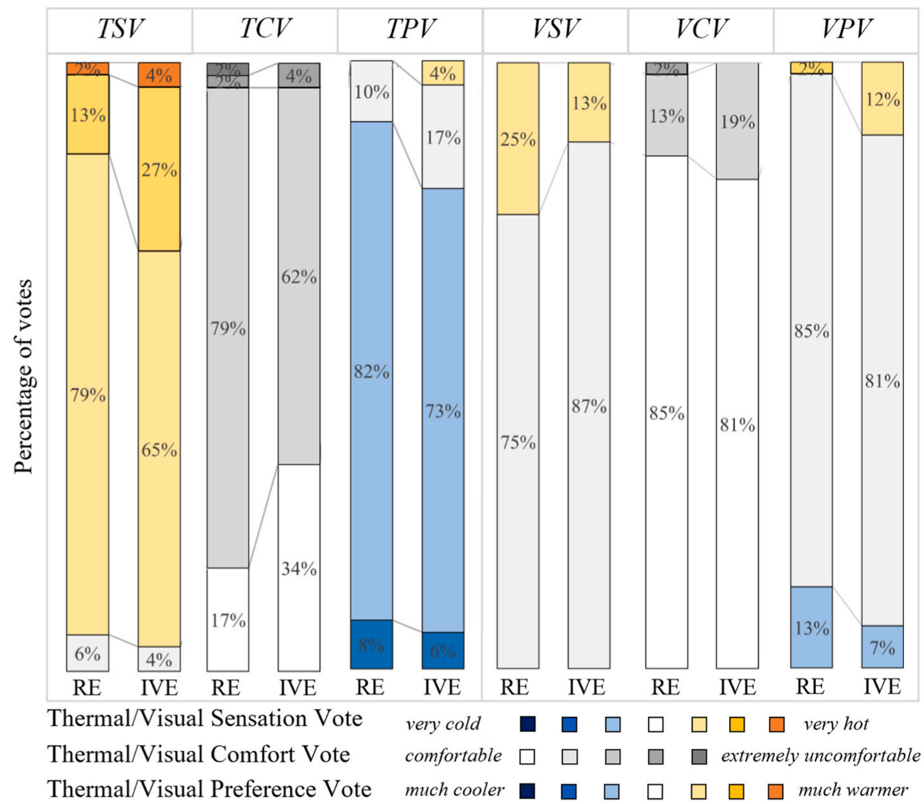

Fig. 5. Percentage of votes for the comfort parameters within the two tested environments (RE, IVE).

point has a significant influence on TSV: at least 94% of the subjects felt from «slightly warm » to « hot», thus, 66%–83% of them evaluated the thermal condition from «slightly uncomfortable » to « uncomfortable» (TCV), respectively. A possible explanation relies upon the fact that the indoor air temperature set-point, based on the central HVAC system of the testing room, was +4 °C away from the typical indoor winter thermal comfort temperature (20 °C). As a result, between 79% and 90% of the subjects reported they would prefer to feel at least « slightly cooler» and «cooler» (TPV). Hence, the outcomes of the qualitative analysis highlighted a correspondence between the real and the virtual environment in terms of thermal comfort feedback. This hypothesis was also confirmed by the statistical analysis: any significant difference between TSV, TCV and TPV in the two environments was discovered ($p > 0.05$, Z-score within ±1.96 boundaries, Table 3). In addition, despite the head-mounted display being an electronic device which could potentially warm up increasing the subjects' thermal perception, the observed TSVs in IVE were slightly (even not significantly) lower in comparison with those in the RE, where subjects did not wear the visor.

Then, the two conditions were compared concerning participants' perception in the domain of visual comfort, by using the same methodological approach. A congruence in VSVs has been discovered: the correlated colour temperature of the lighting was rated as being « neutral» and «slightly cool » for 60–79% of the subjects, in both RE and IVE. This result confirms that the subjects perceived the colour of light corresponding to 4000 K, which was the right colour of the light in RE from which the RGB value coordinates for the VE were derived. Moreover, the authors noticed that the participants got a rapid check of the virtual ambient light focusing on the light colour of the work lamp and the LED ceiling lighting before answering the questions in IVE. This interesting fact highlighted the effectiveness and adequacy of the surveys fully integrated within the IVE. Concerning the VCV, most of the subjects (75%–81%) felt « comfortable» in both RE and IVE, thus, between 58% and 69% of them would have not changed the visual settings. No statistical significance was discovered between the two environments concerning visual comfort for all three parameters (p-value >0.05, Z-score within ±1.96 boundaries).

Table 3
The results of the Mann-Whitney test between RE and IVE on the thermal and visual comfort (Z-crit = ± 1.96).

	Parameter	Sum of ranks RE	Sum of ranks IVE	U-value	Z-score	p-value
Thermal comfort	TSV	2512	2948	1134	−1,80	0.072
	TCV	2956	2504	1578	1,83	0.066
	TPV	2557.5	2902.5	1179.5	−1,54	0.123
Visual comfort	VSV	2925	2535	1547	1,84	0.064
	VCV	2683	2777	1305	−0,46	0.645
	VPV	2544	2916	1166	−1,83	0.067

Then, an overall agreement between RE and IVE was highlighted in terms of comfort. This result is not surprising. Indeed, previous literature supported the adequacy of using immersive environments in the thermoception [14,21,22] and visual perception [10,31] domains.

3.3.3. Intention of interaction

The number and type of intention of interaction with several control systems (heater, fan, window, air conditioning), reflecting the subjects' immediate response to the thermal environment, were also compared between RE and IVE. Generally, between 15% and 23% of the subject would have not changed their thermal condition, while the remaining 77% and 85% would have interacted with only one of the highlighted components to modify their thermal status. Fig. 6 presents the qualitative comparison of the type of interactions between RE and IVE. The analysis did not highlight relevant differences: between 71% and 81% of subjects reported the «opening the window » as the best strategy to improve their thermal sensation within the tested environment by decreasing the indoor temperature. This result completely agrees with the thermal comfort ratings: the subjects described the thermal condition as « slightly uncomfortable» (TCV) because it was at least « slightly

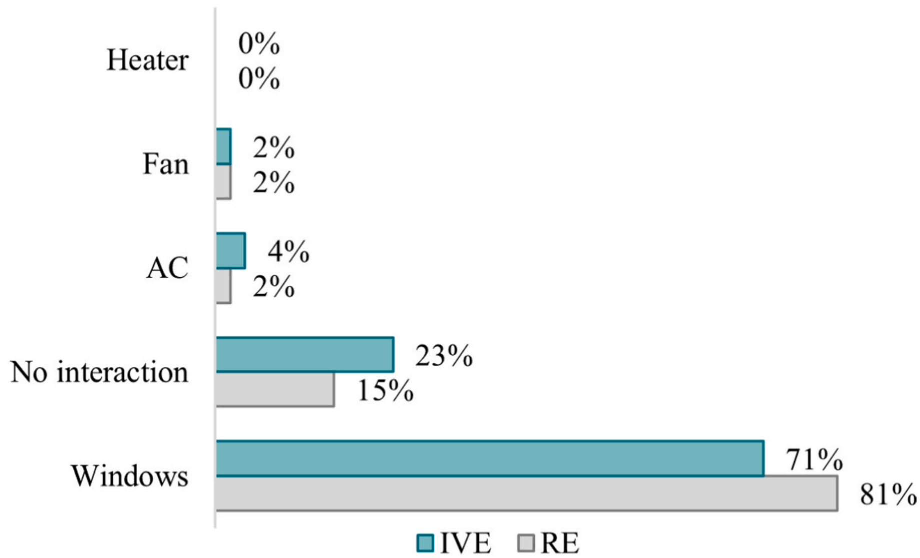

Fig. 6. Type of intention of interaction within the two tested environments.

warm» (TSV), thus, they would prefer to feel at least « slightly cooler» (TPV).

Finally, the hypothesis of the preliminary qualitative analysis was tested by the standardised Mann-Whitney test: a non-significant effect of the tested environment on the number ($U = 1456$, $Z = 0.98 < 1.96$; $p = 0.32 > 0.05$) and type ($U = 1273$, $Z = -0.68 > -1.96$; $p = 0.49 > 0.05$) of intention of interaction was detected. Following the only previous literature study in the thermally-driven behaviour domain [21], this result confirmed the promising application of VR for human-building interaction investigations.

4. Conclusions

This paper addressed the need for enhancing the validation of IVEs. The potential of these tools to represent real-life scenarios was explored to help overcome the significant barrier that still limits their application to support the AEC sector and research in the fields of comfort, productivity, and behaviour by ensuring reliable and effective data collection. In this paper, the adequacy of IVE was explored for an office space. A total of 104 participants, divided into two balanced groups, were recruited to perform one test session (in-situ experiment or virtual one) at a constant indoor air temperature (24 °C) while completing surveys (sense of presence and immersivity, cybersickness, thermal comfort, visual comfort and intention of interaction) and a set of three short-term cognitive tasks (OSPAN test, Stroop test, Magnitude-Parity test), considering the need of limiting the VE exposure time below 25/30 min.

The ecological validity was analysed through the sense of presence, immersivity and cybersickness ratings. The results from the analysis and the benchmark of the four attributes (GS, REAL, INV, SP) with similar past studies, revealed that the VE created an excellent level of presence and immersivity. This is a very relevant result because an accurate representation of the indoor environment is crucial for obtaining valid user feedback. Thus, the authors recommend creating a model with the highest level of detail to be reproduced with a proper visor (at least 1440 × 1600 resolution image per eye) and then ensuring that the average value of each indicator is higher than the value equivalent to the moderate-high level (i.e., 4) on a five-point Likert scale ranging from 1 to 5.

In addition, the cybersickness analysis not revealed high disorder levels, except for 25% who presented moderate 'difficulty focusing' caused by the slightly blurred images presented by the head-mounted display which caused 'eyestrain' for 10% of the subjects. Thus, the authors confirmed the ecological validity of the model. However, the literature analysis [30,55] revealed the same general trend linked to these symptoms. This fact suggests that head-mounted displays held some limitations: screen characteristics, such as resolution, luminance and contrast ratio widely depend on the available models which vary according to the budget [36]. As a result, some technological advancements of these devices should be addressed to obtain a more realistic illuminance and brightness, better-shaped images, and enhanced field of view which might improve participants' exploration of the model and potentially reduce the physical discomfort.

Concerning the assessment of the criterion validity, the authors compared the dataset of RE and IVE tests, looking for negligible differences in terms of productivity, comfort and intention of interaction. The main qualitative and statistical results allowed the authors to conclude that the tested environments did not influence users' productivity and overall feedback, as follows:

- No influence of the virtual environment on the subjects' executive functions (task-switching, inhibition, working memory) was discovered within the three cognitive tests because the number of errors and speed of execution in the IVE were strongly similar to those in the physical environment.
- A correspondence between RE and IVE was highlighted in terms of thermal comfort: 94% of the subjects evaluated the extreme thermal condition as at least « slightly warm» (TSV), then 66%–83% of them felt « slightly uncomfortable» (TCV), and the 79%–90% would prefer at least a «slightly cooler » temperature condition (TPV). An overall agreement emerged also in terms of visual comfort. In both tested environments, the subjects evaluated the correlated colour temperature of the lighting as « neutral» (VSV, 60–79%), and «comfortable» (VCV, 5%–81%), thus, between 58% and 69% of them would have not changed the visual settings (VPV). These results agree with previous literature studies that have already supported the adequacy of IVE in the thermoception [21,30] and visual perception [30–32] domains.
- In addition, the promising application of VR for adaptive behavioural investigations was also confirmed. There were no differences in terms of the number and type of intention of interaction with several control systems (heater, fan, window, air conditioning). Indeed, at least 77% of the subjects would have interacted with opening the window (71%–81%) as the best strategy to improve their thermal sensation.

Due to the VE time exposure constraints, this study only focused on three short-term cognitive tasks. However, the method to measure productivity strictly depends on the research purpose, thus future studies focused on productivity could be based on mid-term assessments (e.g., integrating the executive functions tests with reading passages and comprehension tasks), then revising the experimental schedule. In addition, another limitation of the work is that visual comfort was addressed by only focusing on participants' perceptions (VSV, VCV, VPV). Future activities should also integrate the main visual sensation, preference and comfort votes with glare and brightness assessments, to deepen the IVE validation concerning the visual domain. Lastly, additional studies in VR should be carried out to deepen the investigation of the influence of the thermal environment on users' cognitive functions. For example, by testing a baseline thermal condition (i.e., 20 °C) and a more extreme colder one (i.e., 17 °C) to establish a correlation between cognitive functions and indoor air temperature.

Based on the experimental outcomes, with comfort, behaviour and productivity being similar between IVE and RE, this study confirms that virtual reality and immersive virtual environments represent a promising approach to address the research supporting a user-centred design in the AEC sector. They could be used to explore a combination of various stimuli (thermal, visual, acoustic, olfactory) and environmental layouts (building types, colours of walls and lighting, size of windows, indoor design, and geometry) to address multi-domain and cross-effect investigations. Such applications have the potential to enhance well-living and working conditions in indoor environments using real-time simulation and feedback from the early design stages.

CRediT authorship contribution statement

Arianna Latini: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elisa Di Giuseppe:** Supervision, Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Marco D'Orazio:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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