Virtual reality as a new frontier for energy behavioural research in buildings: tests validation in a virtual immersive office environment

Abstract

Occupants' behaviour and strategies to encourage behavioural changes need to be addressed in workplaces to reduce energy consumption. In this study, the Theory of Planned Behaviour (TPB) was integrated for the first time with an office virtual environment (VE) to investigate the adequacy of the VE in the comfort and behaviour domain while understanding its effect in predicting individuals' energy-related intention of interaction with the building systems. One hundred four participants, randomly divided into two groups, were recruited to answer questionnaires (TPB, comfort, interactions, sense of presence and cybersickness). Two test sessions were conducted at a constant indoor air temperature: an in-situ experiment was compared with the virtual counterpart. Findings revealed an excellent level of presence and immersivity and the absence of high disorder levels. A good agreement between the two environments was highlighted in terms of thermal comfort, number, and type of interactions (one interaction focused on window opening for 71-81% of subjects). Moreover, no differences were discovered between the results of a multiple regression model in both real and virtual environments. In particular, the analysis identified the knowledge of energy consumption as the main predictor of behaviour because it accounted for about 12% of the variation in the intention of interaction in both tested environments. Thus, the suitability of the virtual environment could offer an effective tool for decision-makers and researchers to develop strategies aimed at designing more comfortable and less energy-consuming buildings.

Keywords: Immersive Virtual Environments, Office buildings, Indoor comfort, Intention of interaction, Theory of Planned Behaviour

1. Introduction

A Renovation Wave for Europe was proposed by the EU Commission in 2020 to allow buildings to be less energy-consuming while creating more liveable spaces. In this domain, an important target for researchers, policymakers, and public administrations is a clearer understanding of the factors driving energy consumption in the built environment. The aim is to develop suitable strategies to aid economic and environmental targets while increasing end-users comfort, satisfaction, health, and performance. However, technological progress and investments alone rarely guarantee low or net-zero energy in buildings because «human factors» play a crucial role, and while the awareness of their impact has improved, it is often ignored in building design. Indeed, it is well-established that occupants' behaviour is a major factor affecting the energy performance of buildings. It is important to notice that users' energy-related behaviour differs significantly between domestic and non-domestic use, where the dwellers directly pay for the energy consumption while the company provides free energy for workers. Employees seem less motivated to engage in energy-saving behaviour than households that are more willing to save energy in their daily lives. As a result, during the last years, energy consumption in commercial and services has increased, accounting for about 30% of European energy demand [1]. Due to the large amount of time spent in workplaces (60-70% every week), workers constantly try to provide comfortable working conditions [2]. Thus, a hot research topic has emerged to understand the factors affecting people's behaviour and willingness to save energy in workplaces. Accordingly, technological development promoting energy efficiency needs to be integrated with a programme to encourage behavioural changes that could be a potential solution to be adopted immediately.

Most of the research has already indicated that energy behaviour is a relatively complex task to understand because it depends on several drivers: internal (occupants' activities and preferences) and external (building, equipment, environment, time, contextual, random) factors. Thus, various theories and models have been introduced in this field, such as the Theory of Planned Behaviour (TPB) developed by Ajzen et al. [3]. It explains that human behaviour is guided by three factors: behavioural beliefs about the consequences of the behaviour itself, normative beliefs about the expectation of others over the users' behaviour, and control beliefs related to the presence of factors that may facilitate or limit the implementation of the behaviour. In particular: behavioural beliefs produce a favourable or unfavourable attitude toward the behaviour, normative beliefs result in perceived social pressure or subjective norm, and control beliefs determine perceived behavioural control. The combination of the attitude toward the behaviour, subjective norm and perceived behavioural control produces a behavioural intention. In general, the users' intention to perform a behaviour would be greater the more favourable the attitude, the less social pressure, and the greater perceived control. In addition, in the presence of an opportunity and sufficient control, building users are expected to finalise the intention, which is why it is assumed to be an immediate antecedent of the behaviour itself. Figure 1 shows a schematic representation of the TPB as developed by Ajzen et al. [3].

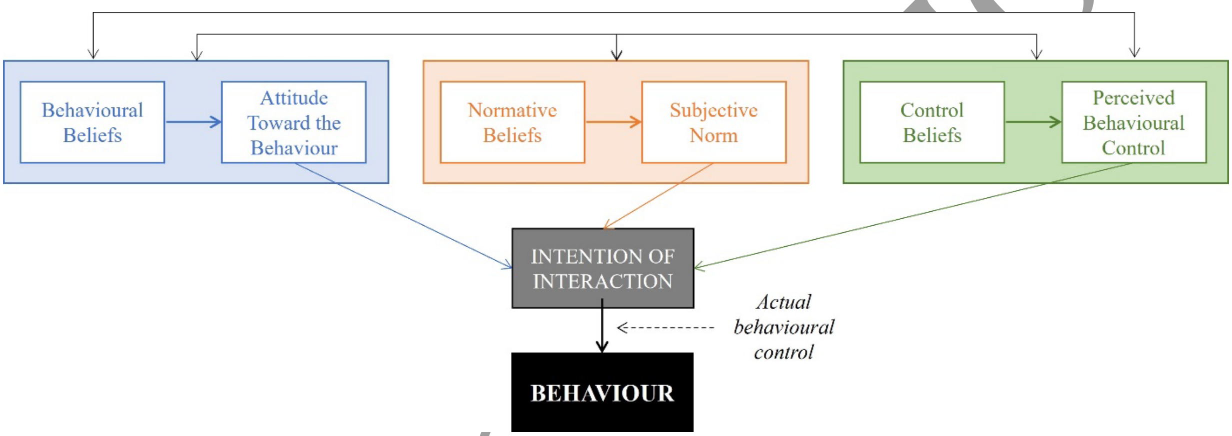

Figure 1 Schematic representation of the Theory of Planned Behaviour (Figure redrawn from Icek Ajzen [3])

However, to the authors' knowledge, only a few studies [2,4–7] have applied the TPB to environmental behaviours in workplaces. In general, several hundred office building occupants were surveyed (i.e. a university in Malaysia [5], companies in China [2], in the U.S. [6], and across the UK [4,7]) to examine how much the TPB constructs explain the variance in employees' energy-saving behaviour.

This research topic is still emerging. Moreover, an improvement in implementing suitable programs to understand energy behaviour and encourage occupants' sustainable choices in offices is needed. A proper strategy to pursue this goal could be the use of Virtual Reality (VR). This technology allows the researcher to create specific correlations for each office building configuration already in the early design stage. The end-user experience in energy-saving programs could be enhanced through suitable Immersive Virtual Environments (IVEs), which create a psychological state in which the users perceive themself as existing within the virtual space. Only a few studies examine the adequacy of VR in the occupant behaviour research domain focusing on blinds and lighting systems [8–11] and climatic equipment (heater, fans, air conditioning) [12,13], but the factors influencing the behaviour were not contextually examined.

Concerning these viewpoints, this research tries to contribute to the current literature by integrating, for the first time, the TPB with a virtual environment to understand individuals' energy-related intention of interaction with the building systems. This study compared results from a laboratory-based experiment in a real office room to those obtained in an equivalent immersive virtual model. The thermal comfort and interactions with the room components (a fan, a heater, an air conditioning system, and windows) of 104 participants were recorded to fit this purpose. The main goals of the study are to verify the adequacy of IVE in comfort and adaptive behaviour research and validate the integration of TPB within the IVE by exploring its suitability in predicting behavioural intention in workplaces through self-reports in both tested environments.

2. Materials and methods

The present study involved an independent-measure design experiment (52 subjects per group) in investigating the adequacy of the virtual environment in the comfort and behaviour domain. Two test sessions were conducted: each participant was randomly assigned to a virtual condition or «immersive virtual environment» (group 1) or an in-situ condition, or «real environment, RE» (group 2) session.

2.1 Test room

An office was set up like a test room located inside the Department of Engineering, Civil, Construction and Architecture (Università Politecnica Delle Marche, Ancona, Italy). The test room had an internal dimension of 5.93x4.38m and a floor ceiling height of 3.00 m. The room contained furniture to replicate an office working environment and was equipped with a computer station to carry out the tests and the equipment for the IVE visualisation (Figure 2). The thermal environment depends only on the central HVAC system of the room, and the indoor air temperature was recorded by several probes (temperature range: from +5° to +60° and accuracy ±0.3°) located at the feet (0.10m), waist (0.60m) and head (1.10m) of the seated participants and above the table where the test was performed. 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 reported the adaptive response they would have wanted to carry out to improve their thermal comfort induced by the HVAC of the room. So, no thermal outcome was experienced by the subjects. This strategy is supported by the TPB, which states that the intention of interaction is antecedent to the behaviour itself, and as the occasion occurs, the users would perform the intended behaviour.

2.2 Virtual environment

To create an IVE that can adequately replicate the double-occupancy office space, an extremely detailed 3D model was created using CAD software and afterwards exported to *Unity* software [14] to apply materials, lights and cameras. The luminance parameter (L*) and chromatic components (a*, b*) of the CIELab model were detected using a spectrophotometer (*CM-2500d Konica Minolta*) to address the correct representation of surfaces' colour and materials. Indeed, 5 measurements were carried out with a diameter of 8 mm for each surface of the office room: walls, desk, chair, and floor tiles. Then, the resulting L*a*b* parameters were converted into RGB coordinates for the Unity model.

The authors created two basic virtual scenarios (Figure 2): the first was located far from the virtual desk to have a complete view of the room to allow the adaptation to the virtual environment, while in the second, participants were virtually seated at their desks to perform the performance tasks and the questionnaires (operative phase). In order to achieve the highest level of realism and verify the external-ecological validity of the created model, the productivity tests and surveys were shown through the virtual computer monitor, then avoiding also the so-called «break-in-presence». Scripts were designed to visualise the scenes sequentially and automatically while collecting the participants' answers to minimise the interactions with the researcher managing the test. The *HTC Corporation VIVE PRO Eye* head-mounted display (1440 x 1600 resolution images per eye) allowed the visualisation of the virtual model.

To create a model coherent with its real office counterpart for validation, the climatic systems (a window, a heater, a fan, and an air conditioner) were also added in the virtual environment. After selecting their intention of interaction, the subjects did not experience dynamic visual changes and thermal outcomes as in the real environment.

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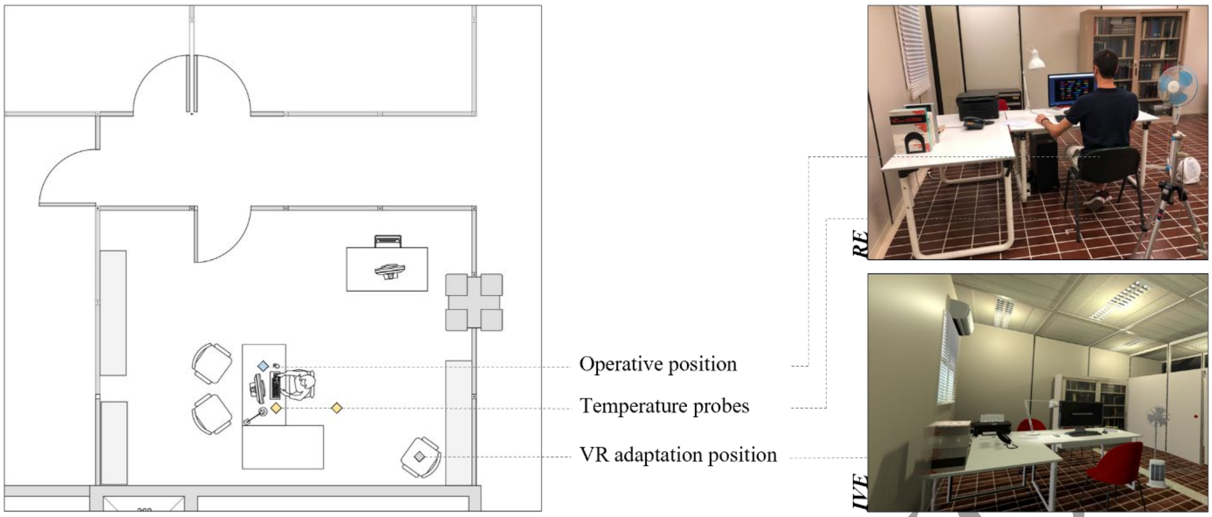

Figure 2 Test room setup, RE setting and IVE scenario

2.3 Survey

The survey consisted of three main sections for both RE and IVE tests: two for the pre-experimental phase and one for post-experiments. There were 24 questions in the pre-experimental questionnaire and 19 in the post-experimental one.

The first section included within the pre-test survey focused on socio-demographic questions (gender, age, height, eyesight problems, educational level) and garments worn during the test to estimate the clo value according to standard UNI EN ISO 9920:2007 [20].

The second section of the pre-experimental questionnaire was designed to contain four main parts associated with the Theory of Planned Behaviour constructs. It was intended to measure respondents' awareness of consequences, attitudes toward reducing energy use, knowledge about the energy consumption of electric appliances and perceived behavioural control. A seven-point Likert scale was adopted for the TPB questions asking participants to indicate their level of agreement for each indicator ranging from «totally disagree» to «totally agree». Table 1 presents the overall questions to investigate the TPB and the related literature references [15,16] adopted to develop the questionnaire. Anyway, the questions were revised to be suitable for the present research aim.

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Construct	Indicators		Ref.
Awareness of consequences (AC)	AC1	Interacting with the control systems to make myself comfortable in my workplace will influence MY COMFORT	D’Oca et a
	AC2	Interacting with the control systems to make myself comfortable in my workplace will influence ENERGY CONSUMPTION	
	AC3	Interacting with the control systems to make myself comfortable in my workplace will influence MY PRODUCTIVITY	
Attitude toward the reduction of the energy use (AT)	AT1	Saving energy in workplaces will help to protect the environment	Cibinskien et al.
	AT2	I typically perform energy-saving behaviours in my workplace	
	AT3	During the winter, I performed these adaptive actions to make myself comfortable: Adjusting/switching off the heating system when feeling too hot	D’Oca et a
	AT4	During the winter, I performed these adaptive actions to make myself comfortable: Adding an extra layer of clothing when feeling cold	
Knowledge about the energy consumption (KE)	KE1	I know how much energy the heater consumes	Cibinskien et al.
	KE2	I know how much energy the heating system consumes	
	KE3	I know how much energy the air conditioning consumes	
	KE4	I know how much energy the fan consumes	
Perceived behavioural control (PBC)	PBC1	I believe that I have control over the amount of energy consumed at work	Cibinskien et al.
	PBC2	I believe that I can avoid unnecessary power consumption at work (i.e. closing the windows when the heating system is working)	
	PBC3	Access is a main perceived impediment to interacting with the control system in my workplace	D’Oca et a
	PBC4	Other co-worker’s needs are a main perceived impediment to interacting with the control system in my workplace	

Table 1 Main construct and indicators associated with TPB survey questions and related literature references: S. D’Oca et al. [15], *A. Cibinskiene et al.* [16]

Lastly, the post-experimental questionnaire section included: comfort assessment and adaptive intention of interaction. The first part investigated thermal comfort parameters according to the standard UNI EN ISO 10551:2019 [17], as follows: Thermal Sensation Vote (TSV) from «very cold» to «very warm»; Thermal Comfort Vote (TCV) from «comfortable» to «extremely uncomfortable»; Thermal Preference Vote (TPV) from «much colder» to «much warmer». The second part focused on the adaptive strategies that subjects would have carried out to improve their comfort within the thermal environment. According to the TPB, the intention is assumed to be the immediate antecedent of the behaviour [18]; thus, the intention of interaction with a heater, fan, window, and air conditioning system was collected. Participants’ choices were not displayed in the virtual office or implemented in the physical environment to show a real status change (opening/closing window, switching systems on/off, etc.).

A final section in the post-experimental questionnaire was included during the test in the virtual environment to verify the ecological validity of the model. In particular, the Slater-Usoh-Steed and the Igroup Presence Questionnaires (IPQ) were combined to evaluate the sense of presence and immersivity according to four indicators: Graphical Satisfaction (GS), Spatial Presence (SP), Involvement (INV), and Experienced Realism (REAL) on a seven-point scale (from «totally disagree» to «totally agree»). The Virtual Reality Sickness Questionnaire (VRSQ) was also added to assess motion sickness [19] on a five-point scale (from «not at all» to «very much»). Six symptoms were investigated: general discomfort, fatigue, eye strain, difficulty in focusing, headache, and vertigo.

In the real office environment and the virtual pre-experimental phase, the questions were submitted through an online platform to minimise interactions with the researcher avoiding any influence on the subject’s answers.

For completeness, Appendix A reports the overall questionnaire.

2.4 Experimental procedure

Figure 3 shows the details of the experimental procedure. On each visit, participants were randomly assigned to experience the real (group 1) or the virtual environment (group 2).

At the beginning of each test session, all participants signed a consent form and received information about the test. Later on, a pre-experimental phase (15 minutes) was carried out to allow them to get used to the environmental conditions and complete the pre-experimental questionnaire. After that, in both RE and IVE sessions, participants

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performed a productivity task (3 minutes) to stay focused and simulate a traditional working scenario during the test session. However, no task performance assessment was later carried out in this study. Then, they answered a post-experimental survey.

In particular, in the IVE experiment, participants wore and adjusted the head-mounted display before the operative phase, rested with their eyes closed for 30 seconds and adapted to the virtual scene for 3 minutes. In this way, any psychological fluctuations related to the virtual environment exposure were reduced, and immersion was facilitated. Responses to the productivity test and questions displayed on the virtual computer monitor were given by voice and recorded by the researchers.

Each test session lasted about 20-25 minutes to reduce overall fatigue and exposure to the virtual environment.

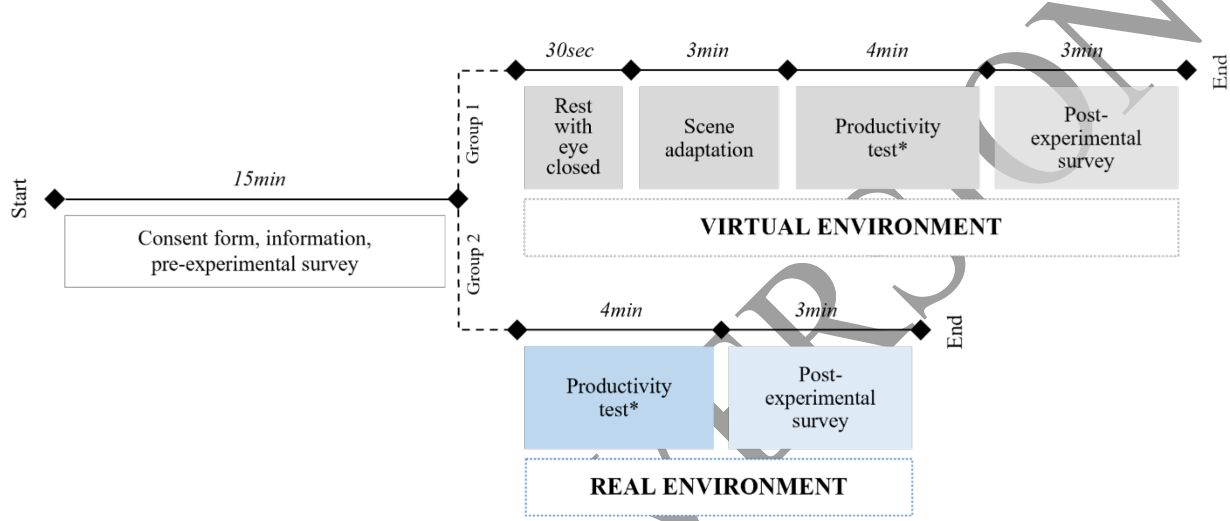

Figure 3 Experimental procedure in a real and virtual environment (*no performance analysis)

3. Results and discussions

In the following sections, the analysis of the two datasets (RE and IVE) is presented to investigate the ecological validity of the virtual model and establish the suitability of IVE in the behavioural research domain. Concerning the second point, the authors carried out a strict methodological step-by-step process to ensure the reliability of the results: the comfort parameters and the number and type of interaction were at first compared between the RE and IVE, then the ability of TPB integrated within the IVE to predict behavioural intention was analysed looking for any eventual difference with the RE.

3.1 Participants

The sample of 104 participants had a well-balanced male-female ratio (50-50%) and it was mainly composed of young people as follows: 48% between 20 and 25 years old (μ = 23.2; SD =1.3), 35% between 26 and 30 (μ = 27.5; SD = 1.6), 21% between 31 and 39 (μ = 33.3; SD = 1.9) and only the 6% over 50 years old (μ = 40.7; SD =2.9). Most subjects were already graduated from university (45%), 40% were selected among university students, and 14% had a higher educational level (PhD, graduate school). 58% of participants had had at least one previous experience with VR technology. 42% of the sample had eyesight problems (myopia and astigmatism), but all of them wore corrective lenses during the tests to achieve a good model visualisation and correctly perform the test. The authors computed a power analysis (effect size 0.50, α = 0.05) through the G*Power software [20], confirming that the sample size was adequate to detect significant effects due to a statistical power equal to 0.81.

3.2 Ecological validity

The ecological validity of the created virtual environment was evaluated through the self-reports on the sense of presence and immersivity indicators (Graphical Satisfaction, Spatial Presence, Involvement, Experienced Realism) and the cybersickness disorders from group 2 performing the IVE experience.

In order to verify the immersivity level and the effectiveness of the study, the four indicator scores were compared

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with the ones from existing literature using the VR tool in the same research domain [21–24]. The type of adopted scale (i.e. Likert, five-point, seven-point) for each question may vary depending on the experiment. Thus, the average scores obtained were rescaled to a five-point scale. The mean scores are reported in relevance order in Table 2. The values are generally higher than a moderate level (i.e. 4) on a five-point scale ranging from 1 to 5. In particular, the participants appreciated the graphics of the model (GS), experienced a very good realism (REAL) and felt involved within the virtual environment (INV). In addition, a very good spatial presence was reported as the mean value for *SP* is 4.47, which is higher than [21] (3.39), [23] (3.68), [22] (3.74), and almost similar to [24] (4.24). Due to a negligible difference equal to 0.03, the virtual environment offered the users an excellent sense of presence and immersivity.

Classification		Year	*GS*	*REAL*	*INV*	*SP*
This study		2022	4.58	4.47	4.15	4.21*
Previous studies	[19]	2019	3.65	2.73	3.23	3.39
	[20]	2019	-	3.21	-	3.74
	[21]	2019	-	3.75	-	3.68
	[22]	2020	-	3.54	4.11	4.24*

Table 2 Comparison of scores on a five-point scale of the four indicators: Graphical Satisfaction (GS), Experienced Realism (REAL), Involvement (INV), Spatial Presence (SP)

According to the Virtual Reality Sickness Questionnaire results, no subject has suffered from vertigo since the test was conducted in static conditions. General discomfort, fatigue and headache symptoms were negligible since between 92% and 100% of the subjects assigned a score of «not at all» and «slightly». Moreover, 10% of them reported «moderate» eye fatigue due to a «difficulty in focusing» (25%) caused by the slightly blurred images presented by the head-mounted display.

3.3 Comfort and interaction analysis

The authors looked for a good agreement between the real and virtual experiments by qualitatively comparing the outcomes of the thermal comfort votes and intention of interaction.

At first thermal comfort (TSV, TCV, TPV) was assessed (Figure 4). The average value of the indoor air temperature during the test sessions was 24.45°C (SD = 0.52). Figure 4 shows the participants' percentage of votes across the real and the virtual experiments. As expected, the temperature significantly influences TSV in both environments: at least 94% of the subjects felt from «slightly warm» to «hot». Therefore, the thermal condition was evaluated as not fully comfortable (from «slightly uncomfortable» to «uncomfortable») by 66%-83% of the subjects, respectively, because the selected temperature set-point was +4°C away from the usual winter thermal comfort temperature (20°C). Thus, according to the TPV, the majority (between 79% and 90%) of the subjects would have wanted to feel at least «slightly cooler» and «cooler».

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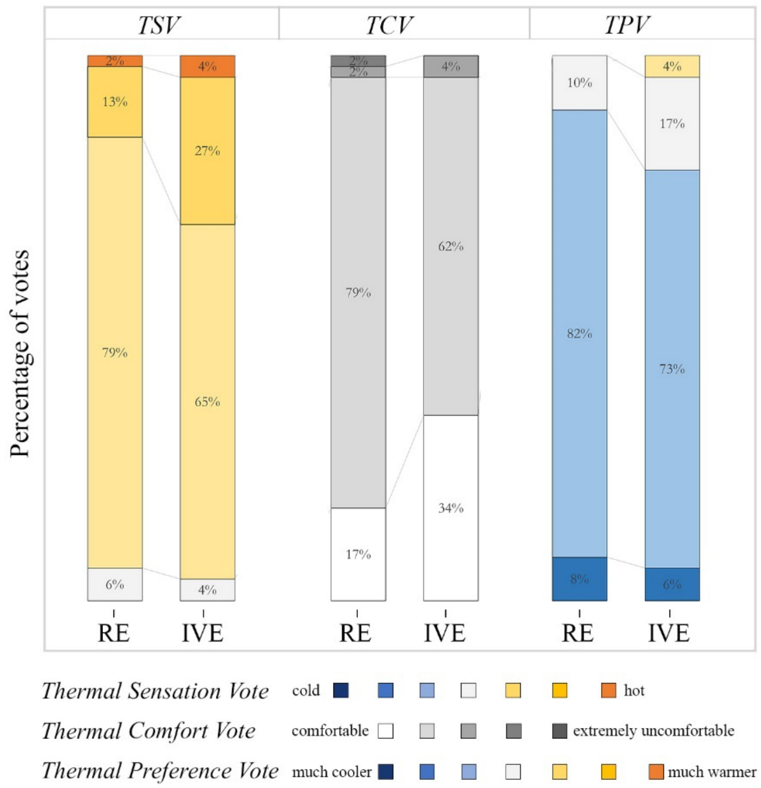

Figure 4 Percentage of votes for the thermal comfort parameters

Secondly, the authors analysed participants' number and type of intention to interact with typical thermal control systems (heater, fan, window, air conditioning) within both environments. Generally, only one intention per participant was recorded in both the real and virtual settings: between 77% and 85% of participants would have modified their thermal condition by interacting with one of the highlighted components. This result is in agreement with the TPV scores. The type of interactions was also compared. The qualitative analysis (Figure 5) did not highlight a difference between RE and IVE: between 71% and 81% of subjects highlighted opening the window as the best strategy to improve their thermal sensation, decrease the indoor temperature and enhance air change. As a result, the authors concluded that the virtual reality tool performs well because no significant differences were discovered across thermal comfort and interactions. The results allowed the authors to conclude that VR properly performs because no significant differences were detected in terms of thermal comfort and intention of interaction between the real and the virtual environment, in line with previous studies (i.e. [12]).

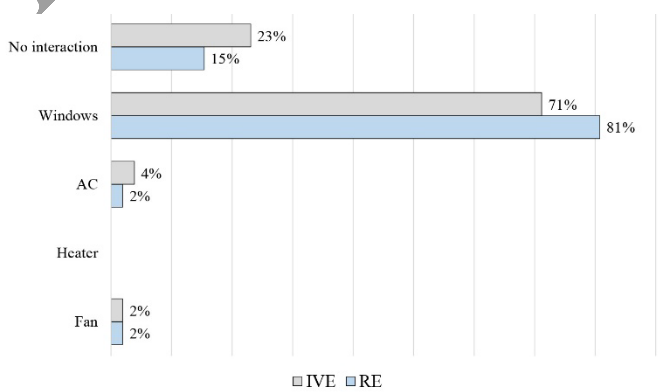

Figure 5 Type of intention of interaction within the two tested environments

3.4 TPB analysis

Finally, once the perfect match between RE and IVE in terms of thermal comfort parameters, number and types of interactions was demonstrated, the suitability of integrating TPB within an immersive environment was explored. Thus,

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as part of the validation process, the authors looked for a correspondence between the RE and IVE in terms of the ability of TPB constructs to predict behavioural intention.

First, this paragraph presents an overview of the data via qualitative analysis. Secondly, it was necessary to carry out a specific factorial analysis to ensure that the dataset of the four constructs (AC, AT, KE, PBC) is suitable to analyse the intention of interaction. Lastly, after ensuring the adequacy of the dataset for the research purpose, the results of the VE were compared to the real one via regression model to detect if TPB integrated within an IVE can adequately predict the same behavioural intention as in RE.

At first, a qualitative analysis of the TPB self-reports on the overall sample size (n=104) was conducted. All the subjects agreed that energy-saving in workplaces would lead to a positive outcome (AT1, 99%). Even if only 20% to 35% of them know how much energy the surrounding electric appliances (heater, heating system, air conditioning, fan) consume (KE), they confirm to carry out an energy-saving behaviour during the winter (AT2), such as adjusting or switching off the heating equipment when feeling hot (AT3, 100%) or adding an extra layer of clothing when feeling cold (AT4, 91%). Access (PBC3) and other co-workers' needs (PBC4) were perceived as the main impediment (100% and 95%, respectively) to interacting with the control system. Thus, less than 50% believed to have control over the amount of energy consumed (PBC1) and avoid unnecessary power consumption at work (PBC2). Despite that, at least 95% were aware of the consequences of interacting with the control systems in terms of comfort, energy consumption and productivity (AC).

Secondly, a Confirmatory Factor Analysis (CFA) was computed to evaluate the model's internal consistency and validity and ensure that the dataset is reliable. At first, two items, marked with an asterisk in Table 3, were dropped (AT4, PBC4) due to factor loadings (indicating the correlation between the item and the construct) lower than the threshold value for a sample of 100 respondents. Other lower values (AC1, AT3, italics font) were retained because it is recommended to have at least three items measuring each construct and their elimination neither increase nor decrease the reliability of the model itself (see next steps). As a result, the overall measurement items have significant construct validity. An adequate fit of the data was then confirmed according to the chi-square statistics, and four of the five fit indices respected the threshold values but fell short of the recommended cut-off for the SRMR.

		Construct validity	Model-fit				
Construct	Item/ questions	Factor loading	Chi-square to the degree of freedom	Comparative Fit Index	Tucker Lewis Index	Root Mean Square Error of Approximation	Standardized Root-Mean-Square Residual
Awareness of consequences (AC)	*AC1*	*0.50*	1.89 ($\chi 2$ = 106.28, df = 61)	0.93	0.91	0.08	*0.10*
	AC2	0.68					
	AC3	0.83					
Attitude toward energy-saving (AT)	AT1	0.92					
	AT2	0.55					
	AT3	*0.30*					
	AT4*	0.003*					
Knowledge about the energy consumption (KE)	KE1	0.83					
	KE2	0.96					
	KE3	0.96					
	KE4	0.83					
Perceived behavioural control (PBC)	PBC1	0.83					
	PBC2	0.77					
	PBC3	0.67					
	PBC4*	0.30*					
Threshold values		≥ 0.55 [23]	≤ 3.00 [24]	≥ 0.90 [24]	≥ 0.90 [24]	≤ 0.08 [24]	≤0.08 [24]

Table 3 The result of the main standardised factor loadings, reliability and convergent validity according to the cut-off values ([25,26])

The Composite Reliability (CR) and Average Variance Extracted (AVE) values were all greater than the recommendation, thus supporting the reliability and convergent validity of the model (Table 4).

Moreover, the square root value of the AVE of each construct (Table 4, bold font) was greater than the correlation among the constructs in the same row and column. According to the Fornell-Larcker criterion, the discriminant validity

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was established, confirming that each construct is unique and truly distinct from the others [27].

In conclusion, the measurement model (CFA) confirms that the overall AC, AT, KE, and PBC contribute to analysing the intention of interaction with the building systems of the total sample size (n=104).

Construct	Reliability	Convergent validity	Discriminant validity			
	Composite Reliability	Average Variance Extracted	AC	AT	KE	PBC
Awareness of consequences (AC)	0.71	0.51	**0.71**			
Attitude toward energy-saving (AT)	0.64	0.50	0.68	**0.69**		
Knowledge about the energy consumption (KE)	0.94	0.81	0.10	0.64	**0.90**	
Perceived behavioural control (PBC)	0.80	0.64	0.21	0.23	0.04	**0.80**
Threshold values	≥ 0.60 [25]	≥ 0.50 [25]				

Table 4 The result of the reliability, convergent and discriminant validity

Finally, after verifying the suitability of the measurement model, a stepwise multiple linear regression analysis ($\alpha = 0.05$) was undertaken to explore the ability of TPB constructs to predict behavioural intention based on the four constructs (AC, AT, KE, PBC) in both tested environments. The analysis was carried out in both groups separately (n=52), and then the results were compared. The constructs were entered into the model in the following order: awareness of consequences, attitude toward energy saving, knowledge about the energy consumption of the equipment, and perceived behavioural control. The significance level was set equal to 0.05 (5%). Table 5 shows that only when knowledge about energy consumption is combined with the awareness of consequences and attitude toward energy-saving (Model #3) does the predictive power (R^2) of the regression model increase. According to the R^2 value, Model #3 accounted for about 17% of the intention in interaction in both RE and IVE. Perceived behavioural control did not substantially improve the previous result (Model #4). Thus, a final regression model (Model #5) with knowledge about energy consumption as the only predictor shows a significant relationship in both cases. The authors concluded that no difference was detected across the two environments concerning the ability of the TPB constructs to predict the intention of interaction, thus supporting the adequacy of VR. Knowledge about energy consumption alone accounted for approximately 12% of the variation in the intention of interaction. However, only a few subjects knew how much energy the electric appliances (heater, heating system, air conditioning, fan) consumed.

Model #	Predictors	R^2		F-statistics		p-value	
		RE	IVE	RE	IVE	RE	IVE
1	AC	0.02	0.03	0.33	0.35	0.45	0.44
2	AC + AT	0.10	0.09	0.87	0.82	0.52	0.57
3	**AC + AT + KE**	0.17	0.17	1.96	1.95	**0.04**	**0.04**
4	**AC + AT + KE + PBC**	0.17	0.17	1.96	1.95	**0.04**	**0.04**
5	**KE**	0.12	0.11	3.33	3.34	**0.01**	**0.01**

Table 5 Multiple linear regression analysis in RE and IVE: significant p-value (< 0.05) are in bold font

4. Conclusions

Understanding the factors affecting individuals' behaviour and attitude to saving energy is beneficial to encouraging behavioural changes and reducing energy consumption in workplaces. In this study, the Theory of Planned Behaviour was integrated for the first time with an office virtual environment to understand individuals' energy-related intentions of interaction with the building systems. A total of 104 participants, divided into two balanced groups, were recruited to answer questionnaires (TPB, comfort, intention of interaction, sense of presence, and cybersickness). Each group randomly performed one test session at a constant indoor air temperature (24°C): an in-situ experiment was compared with the virtual counterpart of an office room. The data were analysed to verify the adequacy of IVE in adaptive behaviour research: ecological validity, thermal comfort and number and type of interactions comparison, and the ability of TPB integrating within the IVE to predict behavioural intention in both tested environments.

In particular, the analysis and the comparison with past studies of the four indicators (graphical satisfaction,

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experienced realism, involvement, and spatial presence) revealed that the virtual environment created an excellent level of presence and immersivity, and most subjects did not report high disorder levels.

Secondly, a good agreement between the real and the virtual environment was discovered in terms of thermal comfort and the number and type of interactions. In both environments, the temperature has a significant influence on thermal sensation (at least 94% of the subjects felt from «slightly warm» to «hot»), and the selected temperature condition was evaluated as not fully comfortable because the set-point was +4°C away from the usual winter thermal comfort temperature (20°C). Thus, the majority (between 79% and 90%) of the subjects would have wanted to feel at least «slightly cooler» and «cooler». Therefore, opening the window was highlighted as the best strategy to improve the thermal sensation by decreasing the indoor temperature and enhancing air change in both RE and IVE.

After establishing a good model-of-fit (CFA analysis), multiple regression models of the environments were compared to evaluate the suitability of the TPB in IVE in predicting participants' intention of interaction. The comparison of the results did not reveal differences between RE and IVE, thus, supporting the adequacy of the integration of TPB within the VR technology. In particular, the analysis identified the knowledge of energy consumption as the main predictor, even if only a few subjects knew how much energy the electric appliances consumed. This implies that a higher knowledge about this topic could significantly positively affect energy-related behaviour, allowing individuals to interact correctly with the building equipment to make them comfortable while saving energy in the workplace.

In conclusion, the suitability of the virtual environment could offer an effective tool for decision-makers and researchers to develop strategies aimed at designing more comfortable, liveable and less energy-consuming buildings. However, future studies should be conducted after adjusting the TPB survey to include other predictors in the model, such as personal and social norms, habits in energy-saving behaviours, and time availability. Thirdly, the data were collected on a hundred subjects, which may restrict the generalizability of the results, but the findings may be effective in the university-specific contest where individuals are mainly students with limited access and knowledge about the building systems. Lastly, an educational strategy to improve people's awareness to use and save energy efficiently while creating more liveable and comfortable spaces should be carried out and then make a comparison between non-trained occupants and trained ones in terms of the intention of interaction and energy-saving practices.

Author Contributions

Arianna Latini: Investigation, Formal analysis, Writing - original draft, Writing - review & editing. Elisa Di Giuseppe: Conceptualization, Methodology, Writing - original draft, Writing - review & editing. Marco D'Orazio: Supervision, Funding acquisition, Conceptualisation

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Appendix A

Factor	*Question*	*Rating scale*
Pre-experimental questions		
Demographical information	Please specify your: ● Gender ● Age ● Height ● Weight	Short open-ended questions
Educational level	Please select your educational level ○ Not graduated from university ○ Graduated ○ PhD, post-graduate school	
Health status and eyesight problems	● Do you suffer from body temperature-altering illness? ● Do you suffer from visual defects? If yes, do you have corrective lenses?	yes - no
Activity	A half-an-hour ago, you were: ○ Playing sport ○ Walking ○ Seating ○ Standing	
Garments	Please tick all the clothes you are wearing during this test □ Undershirt □ T-shirt □ Shirt □ Sweater □ Jumper/Hoodie □ Coat □ Tights □ Socks □ Short skirt □ Long skirt/trousers □ other …	
TPB: Awareness of consequences (AC)	Interacting with the control systems to make myself comfortable in my workplace will influence ● my comfort ● energy consumption ● my productivity	totally disagree/totally agree
TPB: Attitude toward the reduction of the energy use (AT)	● Saving energy in workplaces will help to protect the environment ● I typically perform energy-saving behaviours in my workplace ● During the winter, I performed these adaptive actions to make myself comfortable: adjusting/switching off the heating system when feeling too hot ● During the winter, I performed these adaptive actions to make myself comfortable: adding an extra layer of clothing when feeling cold	totally disagree/totally agree
TPB: Knowledge about the energy consumption (KE)	● I know how much energy the heater consumes ● I know how much energy the heating system consumes ● I know how much energy the air conditioning consumes ● I know how much energy the fan consumes	totally disagree/totally agree
TPB: Perceived behavioural control (PBC)	● I believe that I have control over the amount of energy consumed at work ● I believe that I can avoid unnecessary power consumption at work (i.e. closing the windows when the heating system is working) ● Access is a main perceived impediment to interacting with the control system in my workplace ● Other co-worker's needs are a main perceived impediment to interacting with the control system in my workplace	totally disagree/totally agree
Post-experimental questions		
Intention	Would you interact with the highlighted building systems to improve your well-being? If yes, please state your willing interactions	yes - no
Thermal comfort	● *TSV* How do you judge this environment? ● *TCV* Do you find this..? ● *TPV* Please state how would you prefer to be now.	very cold/very warm comfortable/ extremely uncomfortable much colder/ much warmer
Graphical satisfaction (GP)	I appreciate the graphics and images of the virtual model	totally disagree/totally agree
Spatial presence (SP)	● I perceived the office space as a place I visited rather than a photo I saw ● During the experience, I felt present in the office space ● I perceived the virtual model as immersive	totally disagree/totally agree
Involvement (INV)	During the experience, I was not aware of the real world around me	totally disagree/totally agree
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) ● 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?	totally disagree/totally agree

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