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Immersive Virtual Reality for Buildings Occupants' Work-Efficiency, Comfort and Behavioural Research

Definition, Validation and Application of an Experimental Framework

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Contents

Abstract

Currently, people spend most of their time in enclosed spaces. The indoor environments where they live, and work shape their well-being, comfort, behaviour, perceptions and work efficiency. Even if the human dimension is at the forefront of concern in building design and regulation, the comprehension of human responses to indoor environmental factors is oversimplified.
A crucial aspect is to create sustainable and conducive indoor environments for the health and well-being of the people. However, this is quite complex because individuals are exposed to several indoor variables at a time.
A growing body of research is demonstrating the relevant impact of the environmental conditions on individuals' comfort, work efficiency and behaviour but there is a scarcity of multi-domain analysis looking for the effect of all these variables at a time. A significant barrier to the acceleration of knowledge in this field is the difficulty of controlling and testing visual stimuli in laboratory-based studies in terms of the amount of time and resources needed for the setup which limits the generalizability of the results to real-life contexts.
To this end, Virtual Reality (VR) and Immersive Virtual Environments (IVE) are suggested as alternative methods to facilitate the exploration of this research domain and leverage the adoption of advanced methodologies and experimental approaches to address and improve the human dimension in buildings. To date, there is a lack of a protocol and standardized methods to carry out experiments in VR and collect reliable data. These issues prevent the diffusion of VR for the comprehension of human-dimension and support evidence-based design.
As a result, this thesis proposed a novel experimental framework to organise, carry out and enhance the adoption of VR technology on work efficiency, comfort and behavioural research. Firstly, the aim is to support researchers in how to strategically and effectively adopt VR technology. The second and third objectives are intended to demonstrate the effectiveness of such methodological approach and its potential to support multi-domain studies.
To address these challenges a step-by-step experimental framework was defined. Secondly, an experimental activity to validate the framework and examine the suitability of the protocol and VR as a research tool was carried out by generating an immersive virtual office model and comparing it with its real counterpart. Finally, the framework and the model were applied to investigate the influence of indoor environment characteristics in multi-domain investigations.
The outcomes of the present thesis revealed the potential of the developed framework as an effective and replicable tool. Namely, this valuable instrument has the potential to ensure the validity and generalizability of the research findings thus supporting the adoption of VR technology as a "data collector" mitigating the drawbacks of VR-based studies. The finding demonstrated the practical opportunity to expand the use of virtual environments to support the research in the built environment, building design practises and theories on human-centred comfort, work efficiency and behaviour avoiding the time and cost-consuming physical settings.

Research method

The outcome of the present doctorate thesis is threefold: the development, validation and application of a methodological framework ready to support the research field on human comfort, work efficiency and behaviour in indoor built environments. The framework was practically conceived to be further implemented and support evidence-based design guidelines of the indoor built environment, in the direction of more comfortable and supportive environments as identified by current building standards and global concerns.

The research question that contains the aim of the thesis and the research gaps can be expressed as follows:

What is the most effective way to use Immersive Virtual Reality as a research tool to investigate human-building interaction and support the realisation of user-oriented indoor environments?

The thesis led to the collection of three years of experience in coupling human-building interaction, comfort, work efficiency and behaviour research with technological innovation finding the *trait d'union* in the Virtual Reality framework. These activities resulted in seven papers which are published in international scientific journals according to ANVUR journal classification for the sector 08/C1 or are in the last stages of the publication process. These articles were considered due to the fundamental and relevant role of the author of this thesis in their development and generation steps.

Hereunder are presented the publications related to some of the parts and chapters of the present thesis:

Part III and Part V: Chapter I

- Latini A., E. Di Giuseppe, M. D'Orazio, Development and application of an experimental framework for the use of virtual reality to assess building users' productivity, Journal of Building Engineering 70 (2023) 106280. doi: 10.1016/j.jobe.2023.106280.

Part IV

- Latini A., E. Di Giuseppe, M. D'Orazio, Immersive virtual vs real office environments: A validation study for productivity, comfort and behavioural research, Building and Environment 230 (2023) 109996. doi: 10.1016/J.BUILDENV.2023.109996.
- Latini A., E. Di Giuseppe, M. D'Orazio, Virtual reality as a new frontier for energy behavioural research in buildings: tests validation in a virtual immersive office environment, Rivista TEMA (Technologies, Engineering, Materials and Architecture) 9(2) (2023), doi: 10.30682/tema090001

Part V: Chapter II

- Latini A., Di Loreto S., E. Di Giuseppe, M. D'Orazio, Di Perna C., Crossed Effect of Acoustics on Thermal Comfort and Productivity in Workplaces: A Case Study in Virtual Reality, Journal of Architectural Engineering 29(2): 04023009 (2023), Online ISBN 978-981-19-8769-4, doi: 10.1007/978-981-19-8769-4_12

Part V: Chapter III

- Latini A., S. Torresin, T. Oberman, E. Di Giuseppe, F. Aletta, J. Kang, M. D'Orazio, Effects of Biophilic Design intervention on university students' cognitive performance: An audio-visual experimental study in an Immersive Virtual office Environment, Building and Environment 250 (2024). 111196, doi: 10.1016/j.buildenv.2024.111196
- Latini A., S. Torresin, T. Oberman, E. Di Giuseppe, F. Aletta, J. Kang, M. D'Orazio, Virtual Reality application to explore indoor soundscape and physiological responses to audio-visual Biophilic Design interventions: An experimental study in an office environment, Journal of Building Engineering (2023). under review
- Latini A., Marcelli L., E. Di Giuseppe, M. D'Orazio, Using Virtual Reality to investigate the impact of greenery elements in office environments: an eye-tracking pilot-study on cognitive tasks, visual attention and distraction, Applied Ergonomics (2023). under review

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Part I: Introduction

1.1. Context and background

The building and construction supply chain represents one of the world's largest industry sectors [1]. Buildings are designed by people and for people to live and work in [2], and building occupants constantly affect and are affected by buildings, in a bidirectional relationship. Indeed, evidence suggests that on one side occupant behaviour has significant impacts on building use and energy consumption [3] and on the other changes in the built environment impact the human state of mind and corresponding reactions [4]. As an example, the precondition for human activity is the building design which might, for example, either support or limit individual tasks while shaping occupants' perceptions, experiences, and behaviour.

Considering the relevant contribution of the building sector and the current environmental concerns, buildings have the potential to facilitate the shift toward a more sustainable paradigm coupled with technological innovation. The new generation of smart buildings has the potential to decrease energy use and improve indoor quality levels [5]. However, technological progress and investments alone rarely guarantee low or net-zero energy in buildings because «human factors» play a crucial role.

As a result, the creation of positive impacts on people by providing long-term value and quality of life is fundamental to reducing operating use and energy-related costs while optimizing well-being and work efficiency.

Currently, professionals, researchers and policy makers believe that the most effective way to enhance building performance and achieve energy efficiency at a large scale is through the advancement of building codes and standards [6] and increased attention to the human dimension [7].

Thus, a shift forward in the inclusion of the human dimension in building performance assessments and practice emerged. Evident is the rise of concern of building rating (e.g., ASHRAE Std. 55, EN 16798-1:2019, ISO 7730), and certifications (e.g., LEED, WorldGBC), which originally focused on Indoor Environmental Quality (air quality, thermal comfort, lighting, acoustics), interior layout and ergonomics, while are now increasingly shifting to health and wellbeing issues (e.g., WELL), thus catalysing a global interest and scientific attention to the suitability of the building sector.

A worldwide imperative for the Architectural, Engineering and Construction sectors is the application of a user-centred or human-centred design approach [8]. By giving end-users extensive attention at each stage of the design process and building life cycle, it will be possible to create comfortable and supportive indoor environments that inspire, energize, and support people using it.

However, understanding and empowering the so-called human-building interaction is often oversimplified in the building life cycle, due to the stochastic, complex, and interdisciplinary nature of occupants' comfort and behaviour [9].

Indeed, it is well-established that building users are exposed to several drivers (contextual, personal, indoor environmental quality, random) [10–13] that act simultaneously, thus complicating the impact of the built environment on the users [14]. It means that their perception, comfort, and work efficiency are multimodal and influenced by the combination of stimuli associated with different domains, namely thermal, acoustic, visual, and air quality [15]. To establish an acceptable indoor environment, the effects of all the sensory variables and environmental factors that can realistically be found within buildings should be considered in a multisensory integration [16]. In response, multi-domain approaches to support an understanding of indoor environmental effects and behavioural research [13] have been proposed as one of the main areas of focus of IEA EBC Annex 79 [17].

Over the past years, many efforts have been devoted to studying the human dimension of indoor environmental stimuli mainly acknowledging the impact of environmental factors on individuals in isolation. A recent literature review by Chinazzo et al. [16] defined the quality criteria of existing multi-domain studies identifying also the characteristics of study conduction. Nonetheless, multi-domain assessment of indoor environmental characteristics remains in large parts understudied above all in comparison with single-domain studies. Therefore, crucial gaps in scientific knowledge exist due to the need to boost human comfort research through multi-domain analysis. ASHRAE Guideline 10P [18] emphasized the interactions among indoor environmental factors and recommended that more detailed research might be conducted. Indeed, the observed discrepancies between predicted and reported occupant satisfaction, comfort and work efficiency could be explained by a lack of multisensory integration [16].

The possibility of accounting for the centrality of multi-domain approaches in indoor building context and scientific research opens the way to new opportunities: a deeper understanding of human responses (i.e., comfort, work efficiency, behaviour) to their complex surrounding environment and a more tangible possibility of ensuring sustainable and conducive buildings to the health and well-being of the people. Collected and interpreted measures will be the optimised evidence basis to marry enhanced design practices and guidelines on this topic [13]. These "proofs" from scientific research will be translated into design guidelines and building standards to encourage not arbitrary design choices in a variety-built environment practice. Additionally, sufficient insight and adequate representation of the complex human dimension in building simulation tools could contribute to filling the gaps between the designed and actual energy performance [7]. Including human knowledge in building systems and maintenance is also the key aspect of delivering user-centred and personalised building systems capable of supporting the optimal operation of building, reducing energy consumption and increasing efficiency [5].

What is the reason for the high attention these topics receive? The response to this question lies in the increasing portions of people's lives spent inside buildings.
Nowadays, people are spending more than 20 hours per day inside buildings [19], where almost all human activities take place from professional to personal ones. Over the last decades, there has been a growing interest in the impact of indoor environmental conditions on individuals.
This is a very relevant topic, as the role that indoor environments can play on users' health, well-being, comfort, behaviour, and work efficiency has never been more evident. It was estimated by the World Health Organization, that 19% of the factors influencing individuals' health and well-being are directly related to the characteristics of the built environment [2].
In addition, adults spend a significant amount of their time in working environments (60-70% every week) [2] where they constantly try to provide comfortable and supportive working conditions. The workplace environment can be beneficial or detrimental to occupants' satisfaction, performance, and well-being [20]. Thus, a hot research topic has emerged to comprehend the influence of workplace environmental factors and design that could allow to enhance rather than degrade workers' experiences. Namely, in Europe, office buildings are the second largest section of the non-residential market for new construction [21,22]. Thus, this work of thesis addresses office environments where employees spend most of their time working at a desk work-station performing activities such as reading, writing, and typing on computers [23].
In recent years, the increasing awareness of benefits deriving from enhanced work efficiency shifted higher emphasis on providing valuable indoor environmental quality within office buildings. In particular, workspace design affects not only people's well-being but also their work performance linked to business-oriented outputs and is especially relevant in personnel costs [24]. Workers' salaries and benefits typically account for 90% of a company's costs [25,26]. The comfort factors of office users regard physical comfort and functional comfort [26]. They refer to biological responses (e.g., light, indoor air quality, climate, noise, ergonomics) and the suitability of work environments for work tasks (e.g., disturbances and distractions). Even a slight improvement in comfort can have a fundamental impact on individual task-related performance.
In particular, after the COVID-19 pandemic, people are reconsidering the functionality and utility of their working environments wondering if they correctly answer their needs as their home workplaces do during the smart working periods [27]. Simultaneously, designers, facilities managers, and researchers have the opportunity to influence and revolutionize workplace design since office environments built only to maximize space efficiency are no longer desirable. In light of growing concern about the factors affecting work efficiency, each organisation should ensure the most comfortable, pleasant and efficient working conditions in the long term.
A challenge in how to objectively and rigorously insight and quantify the features that improve comfort, behaviour and work-efficiency in indoor office spaces arises. In this context, take actions based on comprehensive multi-domain evidence are required to extensively improve the human dimension outcomes while maximising building efficiency.

1.2. Problem statement

Considering the potential impact of individuals on buildings and vice versa, empowered data, theories, guidelines, and models are essential to leverage human dimensions in significantly reducing building energy use and improving indoor quality of life during the entire building life cycle.
More than ever, the imperative challenge is improving the understanding of human needs, comfort, work efficiency and behaviour while encouraging the reduction of operating costs and energy and developing suitable strategies to aid economic and environmental targets.

Two main factors underpin the challenge observed in building occupants' work-efficiency, comfort and behavioural research, as discussed hereunder:

- A paucity of multi-sensory/multi-domain assessment in empirical investigations to support evidence-based design guidelines, building performance models and theories.
- Manipulations of indoor environment variables are often costly and logistically challenging to implement in real monitoring campaigns or laboratory experiments which lead to human responses that may not be fully generalizable to real-life contexts.

Empirical assessments are at the base of evidence-based practices and theories on the human dimension and of mathematical equations for building performance simulation programs.
A fundamental role is played by in-field monitoring campaigns or laboratory experiments with controlled environmental conditions [28]. By conducting experiments in these research facilities, scientists can gather comprehensive data about humans and buildings. Different sources of data storage include, for example, built environmental measures (e.g., CO2, air temperature sensor, humidity, light, air velocity sensors), wearable sensors for physiological measures (e.g., electro-dermal activity, skin temperature, heart rate) [29,30] and surveys to evaluate subjective sensations of occupants [3,31]. Experimental processes are carried out every day by researchers, but only comprehensive assessments could bring valuable results in the long term in the field of human-centred comfort, work efficiency and behaviour studies.
However, data collection is the most time-consuming and costly phase of a research project, and, due to the complexity and variety of variables included in the human-building context, researchers may find it difficult to conduct a comprehensive analysis. Indeed, it is common to conduct investigations for each stimulus, taking into account, for example, visual, thermal, acoustic, and air quality separately.
Thus, several troubles emerged: findings remain tenuous due to the unique site-specific nature of each study, the impossibility of replicating a wide range of contexts, carrying out analysis for buildings still under design, and customising experimental models by modifying the multiple variables in a short time [32,33]. These criticalities limit the generalizability of the results to real-life contexts thus evaluations of human responses could not be free from ecological validity issues and produce evidence that is increasingly complex and sometimes contradictory.
By incorporating more technological innovations into empirical assessment methods, it is possible to gather a significantly higher amount of data which might produce better knowledge suitable to define design guidelines and user-centred building systems.

Virtual Reality (VR) and Immersive Virtual Environments (IVEs) provide a promising approach to solving these issues.
The Oxford English Dictionary first used the term "virtual reality" in the 1980s but, at first, the devices were not efficient, cumbersome, and expensive. At the end of the century, as underlying technologies have become more established, the use of the term has shifted. Indeed, the US National Research Council stated [34]: «VR refers to a set of techniques for creating synthetic, computer-generated environments in which human operators can become immersed. In VR systems, human operators are connected to computers that can simulate a wide variety of worlds, both real and imaginary, and can interact with those worlds through a variety of sensory channels and manipulators. [..] More sophisticated systems, such as those used for pilot training and immersive entertainment experiences, can include head-mounted displays».
Recent significant strides in hardware and software, allowed VR to decrease in size, become cost-effective and provide the users a greater immersion in terms of sight, hearing and the possibility to interact with virtual objects. Thanks to the technological advances in audio, graphics and rendering, Immersive Virtual Environments (IVEs) have been developed and widely used from simple means of entertainment into effective and reliable allies in research. Due to these significant strides, VR embraces

several fields (e.g., medical disorders treatment, industrial applications, training experience) attracting the attention of professionals and academia and allowing the tool to transcend the technology field.
The built environment and VR technology have been the focus of recent research.
The Architectural, Engineering, and Construction sectors have acknowledged VR for its capacity to create multisensory 3D environments that immerse the user in a virtual world [35]. VR can help to visualise the design of a site/building before its construction, resulting in cost savings and better outcomes, above all in case BIM submissions are converted into VR. The 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 [36]; 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 [37].
Well-developed IVE could ensure a sense of presence with high ecological validity, playing a leading role in the evaluation and prediction of real-world human responses [38].
The use of these technologies is not only limited to the design phase but can also provide several advantages over other traditional data collection methods in this research domain, such as traditional empirical assessment. Much more complex, immersive, and expansive design possibilities are offered by IVEs. Indeed, by involving study participants in complex physical and social environments that are ecologically valid, researchers can improve their comprehension of environmental designs.

The human-building research core process is drastically changed by VR and IVE. Researchers and designers are observing an increase in support and improvement concerning the acquisition and integration of human factors from the early design stage. These new technologies are low-cost, and have lots of benefits, 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, measure end-user behaviour and easily control the design variables in terms of visual stimuli [39]. Moreover, users can experience the so-called Acoustic Virtual Reality (AVR) [40], if VR is combined with acoustical stimuli, or mixed-IVE (mIVE) [41] if the virtual environment is combined with a climatic chamber generating thermal stimuli.
The widespread use of VR technology has resulted in studies actively evaluating and verifying its utility and applicability on occupants' work efficiency, comfort and behavioural research in built environments. Figure I - 1 shows a bar chart about the evolution of the number of scientific papers published over the last two decades. The chart is based on a database of 2.613 scientific document results obtained with the Scopus database.

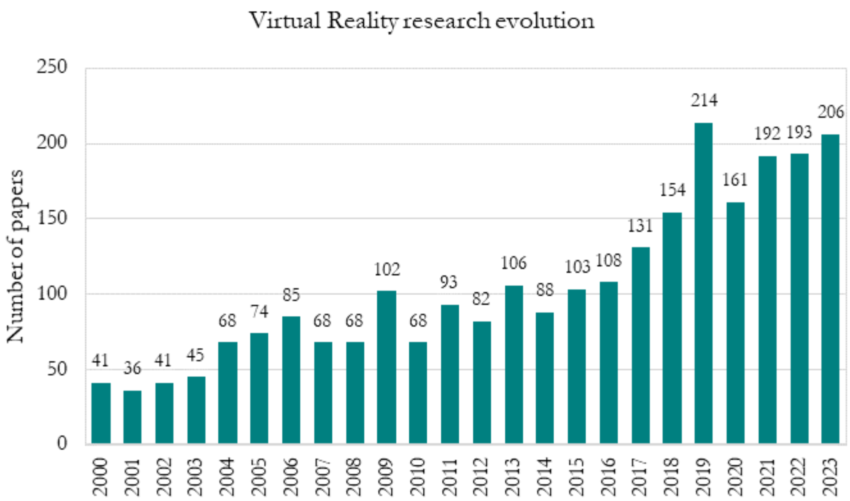

Figure I - 1 Evolution of the Virtual Reality-related scientific paper production according to Scopus Database with TITLE-ABS-KEY ("virtual reality" OR "immersive virtual environment" AND "building" AND "comfort" OR "work" OR "behaviour")

Researchers have argued that virtual reality may support innovative activities by allowing experimentation in-depth and the involvement of all in the innovation process [42]. That is why IVEs are demonstrating their potential in data collection and examination in the multidisciplinary Architectural, Engineering and Construction field.

However, VR is still a newly emerging technology at the beginning stages of exploration for scientific research.
Namely, by simulating actual building spaces and visual elements, VR can be adopted to achieve effective evidence-based design, proving its reliability in scientific experiments. Few efforts have been made to use VR mock-ups for healthcare facility evidence-based design (e.g., [43,44]). Despite the rapidly growing trend and the demonstrated benefits of using VR, its adoption to advance the field of human-building insight, enhanced design guidelines and user-centred systems remains limited above all in multisensory research (Figure I - 2).
A key challenge preventing VR from becoming more widespread in evidence-based indoor design practises to foster occupants' work efficiency, comfort, and behaviour, is the lack of an established protocol for conducting rigorous experiments in virtual settings. This lack of consistency could be translated into a critical weakness in building standards criteria which currently do not include evidence-based outcomes established by VR experiments.
As VR is one of the many forms of the current digital transformation, the topic should gain momentum and increase the interest of academic researchers. Such a step is essential to help bridge the gap between VR-based research and practice in providing human-dimension theories, at the base of decision-making, design guidelines, and user-centred services.

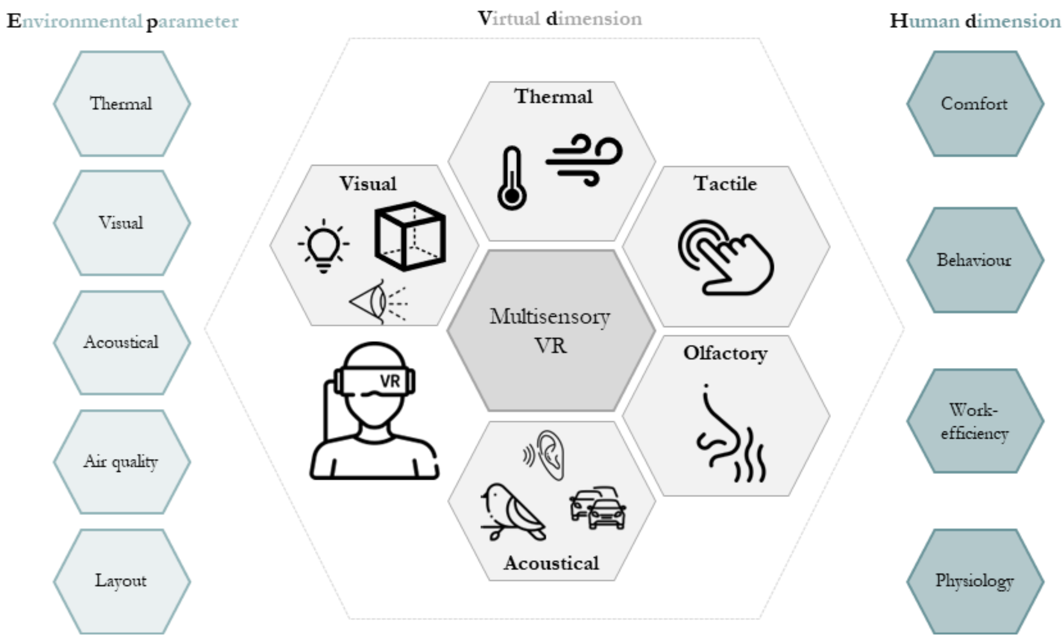

Figure I - 2 Multisensory VR for investigations on human dimensions

1.3. Thesis objective

The context analysed in the previous chapter forms the basis for the present work.
The costly and logistically challenging real-life environmental manipulations, which limit multi-domain assessments in empirical investigations and the generalisability of results, represent important stumbling blocks in supporting the realisation of user-oriented, comfortable and supportive indoor environments. Thus, this thesis sought to develop a novel experimental method integrating meaningful data collection approaches in the field of human-centred comfort, work efficiency and behaviour into innovative Virtual Reality technology.
Due to the lack of a defined and standardized experimental framework, the present thesis seeks to address the following research question:

What is the most effective way to use Immersive Virtual Reality as a research tool to investigate humans-buildings interaction and support the realisation of user-oriented indoor environments?

The novelty of the present research lies in developing, validating and testing a methodological multidisciplinary framework for Virtual Reality-based research on users' comfort, work efficiency and behaviour. This framework includes recommendations on timing and planning for the experiments,

construction of the dependent variables, development of scenarios, running the evaluations and analysing data to show how researchers could obtain evidence-based feedback for design.
In order to answer this question and extend the validity and generalizability of the present work, this thesis encompasses many additional research objectives presented in different parts of the thesis:

1. To develop an experimental framework suitable to support building occupants' work efficiency, comfort and adaptive behaviour research via VR (Part III: Definition of an experimental framework for IVR applications). The human-centred approach is highly valued throughout the work to develop a framework that can adequately identify and exploit human-building relationships.
2. To demonstrate the suitability of the framework through the validation of virtual reality as an experimental tool against its real counterpart (Part IV: Validation of the experimental framework).
3. To demonstrate the applicability of the framework in the fields of work efficiency, comfort and adaptive behaviour by investigating the influence of indoor environment characteristics on users in multi-domain investigations (cross-modal and combined effect studies) (Part V: Applications of the experimental framework in the fields of work-efficiency, comfort and adaptive behaviour, Chapter I: Investigation of users' response to varying thermal environment in a mixed-IVE Chapter II: Identifying the effect of indoor noise through Acoustic Virtual Reality Chapter III: Exploring the impact of virtual audio-visual Biophilic Design interventions).

A summary of how the aforementioned objectives addressed by this thesis is presented in the next paragraph.

1.4. Thesis outline

The thesis consists of six parts that flow through the topics highlighted hereunder.

- Part I: Introduction gives a comprehensive overview of the background and context in which the present thesis takes shape, picturing the research gap in Virtual Reality adoption to support human dimension research in buildings and underlining the purpose and the structure of the present thesis.
- Part II: Human dimension research in buildings: Immersive Virtual Reality applications in the fields of work efficiency, comfort and adaptive behaviour is the foundation for the present work. It provides the state-of-the-art information about Immersive Virtual Reality applications in the fields of work efficiency, comfort and adaptive behaviour focusing on its suitability as a research tool and describing the most frequently used data collection methods for investigating the human dimension in buildings.
- Part III: Definition of an experimental framework for IVR applications describes a novel experimental procedure developed by coupling well-known validation types to carry out research studies, VR essential parts, and methods for data collection in the field of human-centred comfort, work efficiency and behaviour, to produce trustworthy data suitable to allow the researcher to make general conclusions and further support building design practises and theories.
- Following the identified framework as an important research method, Part IV: Validation of the experimental framework examines its adequacy to allow Immersive Virtual Environment validation against its real environments for empirical research on building occupants' work-efficiency, comfort, and behaviour.
- The methodological foundations for the rest of this thesis are built upon the findings of the previous section, which support the use of the developed experimental method in subsequent empirical studies. Indeed, Part V: Applications of the experimental framework in the fields of work-efficiency, comfort and adaptive behaviour uses the novel VR-based framework to assess the extent of human responses to changes in thermal and acoustical environments, in single-domain studies, and visual and acoustical biophilic patterns in multi-domain assessment to demonstrate the multifold potential and relevance of the research framework developed in the present thesis.
- Lastly, Part VI: Conclusions, limitations and future perspectives concludes the thesis with an overview of the achievements and impact of the present work and discusses promising future research perspectives.

To summarize the core content of this thesis, Figure I - 3 presents an overview of the thesis outline and the conducted studies, including the research methods, aims, and sample size, which will be further discussed in the following sections.

Part I

Introduction

- Context and background
- Problem statement
- Thesis objective
- Thesis outline

Part II

IVR applications in the fields of work efficiency, comfort and adaptive behaviour

- Suitability of IVR as a research tool
- Data collection methods in IVR

Part II

Definition of an experimental framework

- The experimental framework
- Dependent variables

Part IV

Validation of the experimental framework

Immersive virtual vs real office environments — I — 104* participants

- The creation of the IVR model
- Ecological validity of the IVE
- Criterion validity of the IVE (work efficiency, comfort and adaptive behaviour)

Part V

Application of the experimental framework

Investigation on users' response to varying thermal environment in a mixed-IVE — R — 104* participants

- Ecological validity of the IVE
- Temperature effect on thermal and visual comfort
- Temperature effect on adaptive behaviour
- Temperature effect on work efficiency

Identifying the effect of indoor noise through Acoustic Virtual Reality — I — 104 participants

- Ecological validity of the IVE
- Acoustical effect on thermal comfort
- Acoustical effect on work efficiency

Exploring the impact of virtual audio-visual Biophilic Design interventions — R I — 198 participants

- Ecological validity of the IVE
- Effect of audio-visual connection with nature on cognitive performance
- Effect of audio-visual connection with nature on soundscape assessment
- Effect of audio-visual connection with nature on physiological response
- Physiological parameters and soundscape assessment relationship
- Effect of visual connection with nature on visual attention (adaptation phase)
- Effect of visual connection with nature on visual distraction from task execution (operative phase)

Part VI

Conclusions, limitations and future perspectives

- Main achievements
- Impacts on academia, building design, standards and society
- Current limitations
- Future research perspectives

Experiments in real environments
Experiments in virtual environments
Cross-modal effect stimuli experiments
Combined-effect stimuli experiments
Multi-domain
R Repeated-measure design experiments
I Independent-measure design experiments
* Common participants between studies

Figure I - 3 Outline of the thesis and overview of the studies conducted

Part II: Human dimension research in buildings: Immersive Virtual Reality applications in the fields of work efficiency, comfort and adaptive behaviour[1]

Although a substantial amount of research has produced metrics regarding human comfort, work efficiency and behavioural patterns, determining which attributes of the indoor environment matter most to building occupants, there is a limited and inadequate understanding of how multiple indoor environmental conditions influence occupants. A significant barrier to the acceleration of knowledge in this field is the difficulty of controlling the variation of indoor environmental conditions in multi-domain studies based on real environment experiments. This is an acknowledged issue. To this end, virtual environments are suggested as an alternative method that can facilitate the exploration of this research domain and leverage the adoption of innovative and advanced methodologies, tools and experimental approaches to address and improve users' well-being, behaviour and working efficiency in buildings.

Virtual Environments can be experienced through various VR systems: non-immersive (e.g., screen-based interaction with 3D graphics), partially immersive (e.g., visors, CAVE), and fully immersive [45]. This thesis deals with the application of fully immersive systems which support the stereoscopic view of a scene. Namely, binocular head-based VR technology, such as Head Mounted Displays (HMDs) will be addressed and further adopted. These delivery technologies were chosen because of the significant development in HMDs over the last few years and their widespread availability to users and researchers.

To identify the gaps in the current research status and guide the development of the framework on the topic, Part II: Human dimension research in buildings: Immersive Virtual Reality applications in the fields of work efficiency, comfort and adaptive behaviour of the present thesis provides state-of-the-art about Immersive Virtual Reality applications in the fields of work efficiency, comfort and adaptive behaviour.
Specifically, this chapter addresses questions pertaining to the suitability of Virtual Reality and fully Immersive Virtual Environments as a research tool to support human dimension topics.
Moving to relevant research methods for investigating the human factors in indoor office environments, this chapter will report the adoption of Virtual Environments (VR) in empirical work efficiency, comfort and adaptive behaviour research, and outline different approaches for quantifying the effects of indoor environmental characteristics on individuals.
The state-of-art brings forward the need to further knowledge on the multi-domain investigations on occupants and to identify promising research methods that will be used in the present thesis to advance this knowledge.

2.1. Suitability of IVR as a research tool

Recently, there has been a growing trend towards the use of virtual representations in human-dimension research.
The application of IVEs for occupants' comfort and adaptive behaviour research was addressed in the recent comprehensive review by Alamirah et al. [46] that focused on the technologies, and the related concepts (i.e., immersion, presence, users' experience, ecological validity), validation experiments, single and multi domains studies. Other systematic reviews focused on VR applications in the architecture, engineering and construction sectors [35,36] or on more specific subjects, such as biophilic design [47], visual perception [48], and energy-related behaviour [49].

Four are the main concept and characteristics related to VR and hence essential towards validation of its conclusions, as hereunder discussed:

- <u>Immersion</u> indicates «state in which a participant becomes attracted and involved in a virtual space of an activity to an extension that his or her mind is separated from the physical space he or she is being active in» [47]. The level of immersion strictly depends on visual realism, display parameters,

[1] This section is based on A. Latini, et al. 2023 "Development and application of an experimental framework for the use of virtual reality to assess building users' productivity", Journal of Building Engineering, 70: 106280

haptics, and sound [45]. It is also linked to the degree of the user's interaction with the virtual environment and to the realism of the study [50].

- Presence is concomitant with immersion since it refers to «the sense of being in an environment» [47]. The idea of presence in virtual environments is the sense of being in places where the VR suggest, rather than the physical location. Sense of presence within a VE is mainly investigated with self-reporting questionnaires.
- Users' experience: could be influenced by the narrative used during or before the experiments (i.e., introductory demo sessions, short adaptation phases) and by cybersickness which describes symptoms (e.g., headache, nausea, or dizziness) experienced by users during VR sessions [51].
- Ecological validity indicates the ability to make general conclusions from experimental results equivalent to those conducted in real-life situations as well as the realistic behavioral response of participants. It is a crucial point, namely for researchers that using VE as a predictive tool [47]. Comparing the results of an experiment conducted in both a real and virtual environment is a common method for testing ecological validity. The absence of statistical difference between the outcomes validates the VE and allows researchers to generalize the findings [50].

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.
To the authors' knowledge, only a few experiments validated IVEs on occupants' work-efficiency, comfort and behavioural research in office virtual environments via a comparison with their real counterparts.
The adequacy of virtual environments in replicating physical settings was assessed by looking for the reliability of the collected data. As presented in Figure II - 1 and extensively reported in Table II - 1, the literature analysis revealed that single-domain research is the most widespread study design type in validation studies (47%). Namely, the authors assessed the potential of VR to adequately replicate the effect of indoor environmental conditions: indoor air temperature [52–54] (e.g., hot and cold environment), visual conditions [14,39,55] (e.g., light intensity) and indoor layouts [53,56,57] (e.g., wall colour, biophilic design) were varied. 47% of the studies did not consider environmental conditions variations, thus RE and IVE were compared in the same controlled conditions (e.g., equal indoor temperature, light settings).
Few multi-domain validation studies (i.e., [53]) were carried out by combining thermal and visual stimuli (combined-effect study type) and additionally assessing the cross-modal effect of the thermal domain on visual response. The cross-modal effect study type is when one stimulus influences a non-related response, which is usually triggered by another stimulus (e.g., when light influences thermal responses) [16].
Virtual environments were validated against their real counterparts mainly considering the reliability of the outcomes concerning thermal [52,53,55,58,59] and visual comfort [14,53,59–61] (36%), tasks related to work efficiency [39,53,56,57,59,62], occupants' perceptions [37,56,57,61–63] and physiological parameters [54–56,58].
Fewer attempts of validation concerned the thermal (14%) and lighting (7%) behaviour of individuals (i.e., [52,59] and [60], respectively).
In addition, participants were asked to rate their sense of presence and immersivity and cybersickness disorders through well-established surveys (e.g., Slater-Usoh-Steed, the Igroup Presence Questionnaires, ITC-Sense of Presence Inventory, Virtual Reality Sickness Questionnaire). Indeed, an accurate representation of the indoor environment and non-relevant disorder levels are crucial metrics for obtaining valid users' feedback, because the more the user feels present and healthy, the more the responses would match those in the physical environment.

In most cases, the differences in results between the virtual and real environments were not significant providing evidence that IVEs can be effective tools to study user thermal [52–54,59], visual response [14,53,59,60] and behavioural response [59,60] and to measure perceptual [61,63] and task accuracy [39,53,56,59]. Fragmental outcomes were detected considering the physiological response of subjects with significant differences between real and virtual scenarios detected in some cases [54,57,58], and absent in others [56]. Some incongruency between in-situ and IVE exposures was detected also in perceptual responses [57,60] and rarely in task outcomes [57].

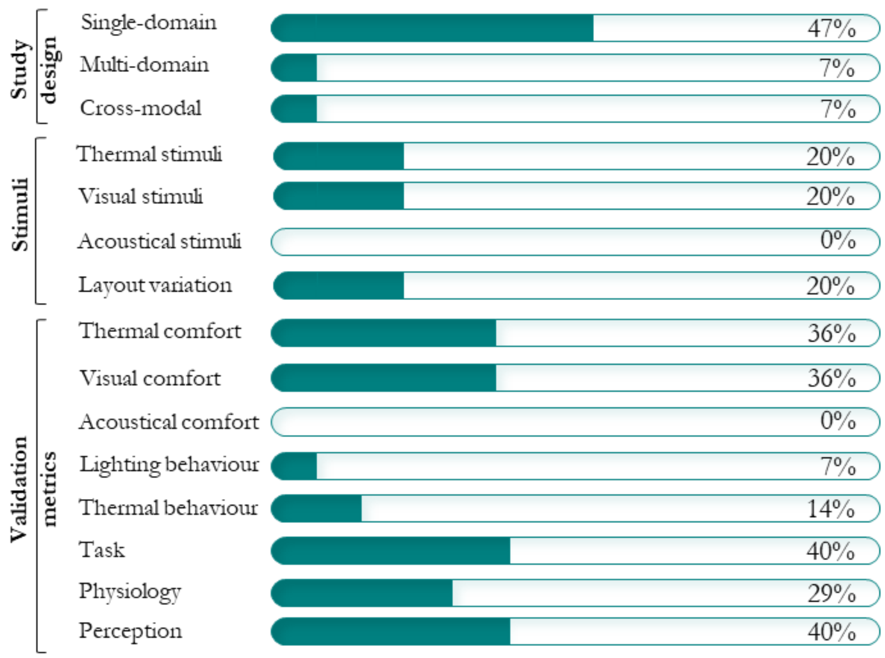

Figure II - 1 Evidence map of VR-validation studies on occupants' work-efficiency, comfort and behavioural research in office virtual environments

		Environmental condition variations				Validation metrics								VR assessment	
Source	Year	Thermal	Visual (light)	Acoustic	Layout	Thermal comfort	Visual comfort	Acoustical comfort	Lighting behaviour	Thermal behaviour	Task	Physiology	Mood Percept.	Presence Immers.	Cyber sickness
[39]	2015		√								√			√	
[60]	2015						√		√				√	√	
[52]	2018	√				√				√					
[56]	2018				√						√	√	√		
[58]	2019					√						√			
[61]	2019						√						√	√	√
[63]	2019												√	√	
[37]	2019												√	√	
[62]	2019										√		√	√	√
[55]	2020		√			√						√			
[57]	2020				√						√	√	√		
[53]	2021	√			√	√	√				√				√
[54]	2021	√										√		√	√
[14]	2021		√				√							√	
[59]	2023					√	√			√	√			√	√

Table II - 1 Summary of VR-validation studies on occupants' work-efficiency, comfort and behavioural research in office virtual environments

On the other side, most of the research articles applied standalone IVE, without its real counterpart, and evaluated its suitability via questionnaires asking participants to self-report their sense of presence and immersivity and cybersickness disorders (e.g., [64,65]).

The literature analysis (Figure II - 2) revealed that a wide range of studies (78%) addressed single-domain research considering (Table II - 2) the influence of different artificial and natural lighting statuses [8,65–67] correlated colour temperature [68–70], viewing location [71] or façade characteristics (i.e., window to wall ratio, outside view) [72–80] and indoor settings (i.e., green elements [32,81–90] layout [76,91]) as evaluation metrics on individuals' responses.

Multi-domain approaches remain still in part understudied (5%) in a limited number of studies combining thermal-visual stimuli [68,69].

Few studies addressed crossed-modal effects (15%) considering the effect of visual condition (e.g., colour) on thermal comfort [68,69,74] and vice versa [69,92], and the effect of acoustics on thermal [15] and visual comfort [93].

The authors were interested in adopting VR settings to facilitate the investigation of the effect of indoor environmental conditions on office building occupants. Namely, the perceptual responses of individuals were the most investigated factor (63%) [8,32,67,69,71–73,75,76,79–85,88–91,94–97] followed by task accuracy [15,66,70,73,77,81,85,88–92,94–96,98] (40%), physiology measures [32,69,71,72,80–83,85–87,91,96,97] (35%), behavioural analysis on lighting settings [8,64,66,67,94,99] (20%) and thermal comfort [15,64,68,69,74,87,92] (18%). Visual and acoustic comfort (14%) are less investigated in virtual office environments, with few studies concerning different lighting [64,69,78,92] [70] [93] and noise conditions [15,93,95–97]. Behavioural analysis regarding thermal settings [64] (5%) is the least addressed metric by VR-based standalone studies.

The methodology and outcomes of these studies highlighted that VR offers researchers a unique opportunity to conduct experiments in immersive environments supporting the understanding and description of the drivers of occupants' comfort, work efficiency and adaptive behaviours in buildings.

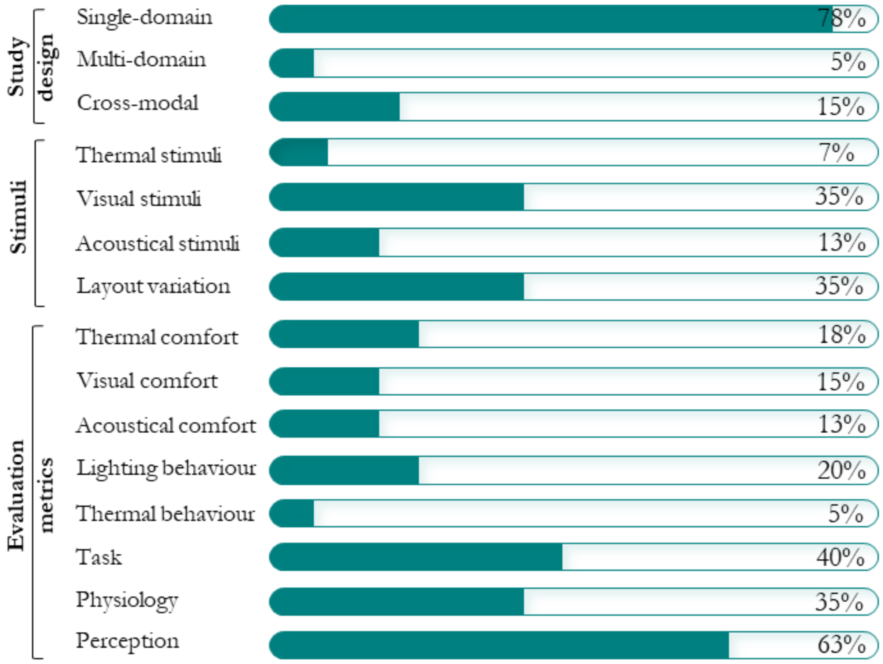

Figure II - 2 Evidence map of VR standalone studies on occupants' work-efficiency, comfort and behavioural research in office virtual environments

		Environmental condition variations				Evaluation metrics								VR assessment	
Source	Year	Thermal	Visual (light)	Acoustic	Layout	Thermal comfort	Visual comfort	Acoustical comfort	Lighting behaviour	Thermal behaviour	Task	Physiology	Mood Percept.	Presence Immers.	Cyber sickness
[66]	2016		√						√		√				
[99]	2016								√						
[8]	2017		√						√				√		
[68]	2017	√	√			√									
[65]	2018		√						√					√	
[67]	2019								√				√		
[100]	2019								√						
[64]	2019					√	√		√	√				√	
[72]	2019											√	√		
[81]	2019				√						√	√	√		
[95]	2019			√				√			√		√		
[80]	2019		√									√	√		
[90]	2019				√						√		√	√	
[84]	2020				√								√		
[79]	2020				√								√		
[71]	2020		√									√	√		√
[91]	2020				√						√	√	√		
[73]	2020		√								√		√	√	
[32]	2020				√							√	√		
[82]	2020				√							√	√		
[69]	2021	√	√			√	√					√	√		
[85]	2021										√	√	√		
[83]	2021				√							√	√		
[74]	2021		√		√	√								√	
[96]	2021			√				√			√	√	√		
[75]	2021		√										√		
[97]	2021			√				√				√			
[94]	2021								√		√		√		
[76]	2022		√		√								√		
[86]	2022				√							√			
[87]	2022				√	√						√		√	√
[98]	2022										√				
[88]	2022				√						√		√	√	
[93]	2022			√			√	√					√		
[70]	2022		√				√				√			√	
[15]	2023			√		√		√			√			√	√

[92]	2023	√			√	√	√	√		√	√
[77]	2023		√					√	√		
[89]	2023			√				√	√		
[78]	2023		√			√					

Table II - 2 Summary of VR standalone studies on occupants' work-efficiency, comfort and behavioural research in office virtual environments

2.2. Data collection methods in IVR

Although the results are promising in terms of encouraging the adoption of this technology to measure building occupants' work efficiency, comfort and behaviour, it is essential to discuss how metrics data are collected during these experiments.

The most widespread evaluation metrics in this research domain are subjective approaches.
Individuals' comfort is typically assessed through onsite post-occupancy surveys that focus on self-reported perception. The surveys are typically developed according to well-established standards, such as ISO 10551:2019 [101], ANSI/ASHRAE 55:2004 [102] for sensation, preference and comfort ratings or ISO 12913-2: 2018 [103] and ITU-R BS 1116-3: 2015 [104] for the acoustical field-study. Perceptual and mood response is mainly investigated with the Positive and Negative Affect Schedule (PANAS) [105], and State-Trait Anxiety Inventory (STAI) [106] for psychological responses.
In particular, the literature analysis revealed inhomogeneous approaches to the administration of the survey. Most of the studies administrated questionnaires at the end of the experiment, after removing the head-mounted display [14,39,52,53,56,57,62,64,70,73,82,83,99], others during the experiment session verbally [37,41,65,71,75,80,96] or, in a few cases, interactively using the controllers [55,91,93,107]. Concerning the former approach, participants' perceptions might not be realistic because their ratings, which refer to the virtual environment, are given in the real world [46]. The latter could potentially harm the immersion level throughout the tests, thus, influencing the test's reliability [46].
In addition, some studies [32,69,71,72,80–83,85–87,91,96,97] integrated the subjective approach of surveys with objective methods. Indeed, users' physiological responses throughout the experimental session were also recorded, such as the heart rate, skin conductance and temperature, and electroencephalogram, to be correlated with comfort and overall perceptions.

Concerning experiments studying users' work efficiency, this is usually objectively assessed via reading passage tasks, which are common obligations for office work and easy to reproduce in IVEs [39,52,53,60,64,67,94,99]. Only a few studies focused on objective measures across different tasks in cognitive performance using the Stroop test [56,62,71,73], visual [39,56,82,95,108] or auditory memory task [93,96], general visual tests [57] and arithmetic sums [82,109].
Sometimes these tests are combined with subjective measures asking users to estimate their task fatigue and workload stress while performing cognitive tests productivity. The NASA-Task Load Index (TLX) self-diagnosis questionnaire [110] is commonly adopted. Productivity tasks are presented with different methods, e.g., on the virtual computer monitor [15,39,52,59,62,64,67,73,92,95] on virtual papers [53,60,94,99], slides [57] or via headphones [93,96].

Finally, to better understand the influence of preliminary design decisions on occupants' adaptive behaviour, some experiments in IVE addressed the complexity of the human-building interaction domain. The majority of the reviewed papers focused on blinds and lighting adjustment [8,60,64,66,67,94,99]. Meanwhile, only a few papers relied on physical monitoring activity of indoor environmental conditions (air temperature, air velocity, relative humidity) while detecting participants' control decisions on climatic systems (heater, fans, air conditioning) to achieve better indoor comfort [52,59,64,92]. Sometimes participants experienced a dynamic visual change after expressing the intended behaviour and could also perceive the thermal outcome [52,64]. The overall aim was to collect occupancy-related data to understand individuals' behaviour. The results will allow for better integration of occupancy information in the building energy design process, thus, reducing the performance gap between the simulated and real energy consumption.

2.3 Concluding remarks

The VR-based studies presented in this section share eight main shortcomings that can guide future research efforts on the topic and that were considered as a basis for the definition of the experimental framework.

First of all, the challenge in using such innovative technologies lies in obtaining research findings that are valid, reproducible, and generalizable from virtual to real environment case studies. 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.

Secondly, most studies adopted VEs in isolation, without the comparison with a real counterpart, and analysed users' sense of presence and immersivity and cybersickness disorders to support the suitability of the tool. However, the analysis of such assessment metrics is not uniform and in some case studies the level of presence, immersion and disorders were not explicitly measured.

Thirdly, single-domain research is the most widespread across VR-based validations and standalone approaches. IVE-based multi-domain work-efficiency, comfort and behaviour experiments are limited and mainly centred on thermal and visual stimuli. None included acoustic in their experimental designs.

Fourthly, IVEs-based experiments have been effectively carried out to study primarily the influence of visual domain and indoor layout variations on individuals' perception, performance tasks, physiological measures and comfort. A possible explanation is that virtual settings facilitate the modification of the visual dimension, which reduces time and effort constraints (e.g., artificial and natural lighting statuses, illuminance level, and colour temperature are one-click update metrics).

Fifthly, a limited amount of research was conducted on the adaptive behaviour analysis concerning the visual domain (e.g., lighting intensity set-up, blinds adjustment). The assessment of thermal settings behaviour was not thoroughly investigated (e.g., thermostat and air conditioning adjustment).

Sixthly, surveys were administrated with inhomogeneous approaches: in the real environment, verbally or interactively during the tests which might limit the authenticity of the virtual environment. Therefore, it is crucial to create a seamless transition between the virtual experience and the questionnaire to guarantee that the information collected is trustworthy while maintaining immersion and a sense of presence throughout the experiment.

Seventhly, most of the experiments analysing participants' work efficiency adopted reading passage tasks and isolated cognitive tests: none of them focused on a comprehensive evaluation of human cognitive functions.

Lastly, the study samples were typically limited in size and were homogenous resulting in a lack of diversity and representativeness of the entire population, thereby limiting the generalizability of the outcomes.

To conclude, despite a growing interest in VR-based study to support building occupants' research on comfort, work efficiency and behaviour, the development of a mature and holistic science of human-centred indoor environments is still impeded by the lack of an agreed-upon conceptual framework.

The present thesis aims to address this research gap by developing a systematic methodology for data collection in the field of human-centred comfort, work efficiency and behaviour via VR technology, which is necessary for the generalizability of research findings.

Part III: Definition of an experimental framework for IVR applications[2]

The state-of-the-art in Part II: Human dimension research in buildings: Immersive Virtual Reality applications in the fields of work efficiency, comfort and adaptive behaviour identified some research gaps and challenges that are essential to address the central question of the present thesis. These research aspects relate to the design and methods of the VR-based research on building occupants' work efficiency, comfort and behaviour, as well as the content of the investigated metrics. The methodological approach in the present thesis was determined by these shortcomings to ensure the validity and generalizability of the findings in this research domain adopting VR technology.

This part of the thesis presents the consequent methodological decisions and research methods that were adopted in this work to overcome the aforementioned research gaps.
This chapter begins with on outline of the novel experimental framework developed by coupling well-known validation types to carry out research studies and VR main attributes. The aim is to produce trustworthy data suitable to allow the researcher to make general conclusions and further support building design practises and theories.
The next paragraph provides a comprehensive explanation of the relevant constructs and metrics that are essential for reliable data collection in the field of human-centred comfort, work efficiency and behaviour.
Lastly, the novelty of this approach and the future direction of the thesis is presented.

3.1. Background and aim

Recent advancements in VR technology offer a unique opportunity to support and expand the research in the built environment as properly designed indoor spaces are vital components for living and working. The overall aim is to discover, through the VR tool, the relationships among the changes and characteristics of the indoor spaces, in terms of layout (windows size, walls and light colour) and stimuli (thermal, visual, acoustical), with users' comfort and perceptions, productivity and adaptive behaviour.
Even if VR has been widely presented as a proper tool, a correct experimental procedure to effectively and efficiently structure the VR application is still missing.
Concerning the need and relevance of a strict measure protocol, this thesis aims to develop a comprehensive experimental framework for organising and enhancing the application of VR to enhance comfort, productivity, and adaptive behaviour research.
The proposed experimental framework aims to overcome the many limitations mentioned in the state-of-the-art. It establishes a pre- and post-trials procedure, based on well-known validation types of the research study (internal and external validity) and measurement (content, face, and criterion validity) (see Figure III - 1). The former allows a strict experimental design to produce trustworthy data, the latter to organise the measurements, correlate the results with existing studies, and make general conclusions looking for a cause-effect relationship between variables.

3.2. The experimental framework

In the early design stage, after the definition of the research purpose, the researcher should build the tool to measure the construct of interest. For instance, there is no objective, observable entity called "productivity" or "comfort/well-being" that can be directly measured, thus, specific tests and surveys should be properly produced.
To get valid results, the content of these instruments must cover all the relevant parts. Indeed, according to existing literature, standards, and theories:

- to deal whit the time constraint of VR exposure, individuals' productivity should be assessed with objective measures: asking workers to self-estimate their productivity should be a more suitable practice in long-term studies typical of RE experiments. Well-established literature [111,112] suggests measuring the three domain-general cognitive functions that are important across a variety of short-term tasks: *working memory*, which refers to the ability to keep

[2] This section is based on A. Latini, et al. 2023 "Development and application of an experimental framework for the use of virtual reality to assess building users ' productivity", Journal of Building Engineering, 70: 106280

information in mind and manipulate it, *inhibition*, which refers to the ability to control attention and override habits and impulses, and *task switching,* which refers to the ability to flexibly switch from one activity to another.
- Self-reports from participants should be based on the indicators of each construct: sensation, evaluation, and preference for comfort; spatial presence, graphical satisfaction, realism, and involvement for the sense of presence and immersivity factors; disorders for the cybersickness measure. To face the limit in VR time exposure, the researcher might need to revise the number of questions, meanwhile paying attention to developing effective and complete surveys coherent with the research purpose.
- Questionnaires should collect users' personal information (gender, age, educational level) which may explain the findings or some cause-effect relationships as potential confounding variables.

Thus, the outcomes of the developed instruments (tests and subjective votes) become the indicators of the constructs that the researcher wants to study and the more they represent the constructs, the greater the **content validity** [113].

Then, a strict study protocol should be developed to ensure the suitability of the experimental design supporting the **internal validity**. Researchers can conduct *repeated-measures* or *independent-measure* design research having the same group of individuals participate in all of the different treatments or have a different group in each treatment condition, respectively. Each experimental procedure has advantages and disadvantages that must be weighed in the early planning phase. Indeed, it is necessary to counterbalance time-related factors, order effect, individual differences and other biases that can be a threat to internal validity by managing the order of the tests [114]. In addition, the participants' group should be well-balanced in terms of gender and demographics, for example, to allow the generalisation of the results to a wider population. The sample size should be also adequate, due to its relevant effect on the results. Indeed, researchers should carry out a power analysis to ensure its adequacy in detecting significant effects based on the statistical power and the effect size.

Before the experimental session begins, content and internal validity should be assessed through a pilot study able to screen and overcome any problems with the created tool and protocol (**face validity**).

Once the trial design is concluded, the experiment sessions take place. Between the early definition of the experimental design from a theoretical point of view (content, internal, and face validity) and the empirical analysis of the data after the trials, researchers can find the fourth step: **external-ecological validity.** It refers to the ability of virtual environments to adequately represent real settings. This validity is an intermediate point because there are two inner steps: the need to provide a higher level of immersion during the test through the experimental procedure and virtual model development, and, afterwards, the analysis of the self-reports about the sense of presence, immersivity and the cybersickness disorders.

For example, it is suggested to:
- Create an extremely detailed model in all its relevant features, such as objects, materials and lights, to be experienced through a suitable and effective head-mounted display in terms of resolution image per eye.
- Integrate and administrate the questionnaires inside the virtual model to ensure a fully immersive experience for the user and then reliable collected data. Since subjects provide feedback inside the virtual environment, authors will be allowed to avoid the *break-in-presence* [46] which can threaten the validity of the experiment.
- Test all the relevant constructs for the evaluation of the VE, thus, supporting the content validity: cybersickness, sense of presence and immersivity according to the well-established surveys: *Virtual Reality Sickness Questionnaire*, *Igroup Presence Questionnaires* and *Slater-Usoh-Steed.* To verify the ecological validity is important that the majority of the subjects do not experience high disorder levels and to detect a good level of sense of presence and immersivity. Concerning the latter, the authors suggest comparing the average value of each indicator to other literature studies that used the same tool, such as [61–63,73] and afterwards to ensure that they are higher than the value equivalent to the moderate-high level (i.e., 4) on a five-point Likert scale ranging from 1 to 5.

- Limit the exposure time to the virtual model below a recommended time interval of 25/30 minutes, to avoid the occurrence of any disturbances that could invalidate the test due to discomforting participants [49,68,108]. VR-induced symptoms are a recurrent issue in VR experiments and might depend on poor virtual experiments [41], the quality of hardware (HMD characteristics) and personal susceptibility to motion sickness [68]. Longer exposure time can be adopted but researchers should be aware of the risk of carrying out long-term studies that might generate higher disorder levels. Long-term experiments could be divided into shorter test sessions providing a break between them, but the researcher should avoid the removal of the head-mounted display so as not to affect participants' immersivity.
  Despite that, the experimental schedule should always include, at the beginning of the experiment, 30 seconds of rest with eyes closed to reduce any psychological fluctuations related to the VE exposure, and 3/4 minutes of virtual scene adaptation to facilitate immersion (visual and acoustical) [91].

After the trials, once the ecological validity is established, the researchers should establish the **criterion-concurrent validity**. Within IVE validation studies to examine the adequacy in replicating real experimental situations and the reliability of the research, the outcomes of the constructs (i.e. comfort, productivity and behaviour) need to be compared between the two procedures (RE – IVE). Otherwise, VR standalone studies can be compared to the ones from previous research activities and accepted as being valid using a similar measurement methodology [115]. An example is a thermal comfort and adaptive behaviour correlation, the hue-heat hypothesis, or the disrupting effect of noise on productivity. If the tool (virtual reality) performs well a high correlation should be discovered in both cases, in terms of variables' behaviour or cause-effect relationships.

	PRE-EXPERIMENTAL PHASE			POST-EXPERIMENTAL PHASE	
	Content	**Internal**	**Face**	**Ecological**	**Criterion**
Description	The test content is fully representative of what it aims to measure according to standards and theories	The researcher can reasonably draw a causal link between the treatment (independent variable) and the dependent variable	The content of the test appears suitable to its aims	The researcher can apply the findings (variables behaviour, cause-effect relationship) of the study to a broader context (settings, people, time)	The tool provides an accurate representation (similar results) of the outcome it is designed to measure
Strategies	Definition of the construct (i.e. comfort, performance, cybersickness, sense of presence and immersivity, behaviour) Identification of the indicators Well-established test and survey construction to assess the indicators on the base of standards and previous-literature	Independent-measure (comparable control group *vs* treatment group) or dependent-measure design Randomly assign and equally distribute participants to the sample groups to eliminate order effects, time-related factors and selection bias Suitable and well-balanced sample size according to the power analysis	Perform a pilot study to screen and overcome any problems	Creation of an extremely detailed model Survey integrated and administrated in the virtual model to enhance immersion Analysis of the self-reports about the sense of presence and immersivity and the cybersickness disorders → compare the mean values of each indicator of the sense of presence and immersivity to the one from previous studies: results should be higher than a critical moderate value → detect low disorders level associated with cybersickness Limit the exposure time (15/20min) but include rest with eye closed (30sec) and adaptation phase (3/4min)	Participants experienced a new tool methodology (IVE). The outcomes of each construct indicator need to be compared between the IVE and a "gold-standard" (real settings for validation studies or other previous studies in IVE for VR standalone ones). If the tool (virtual reality) performs well, good agreement (variables behavior, cause-effect relationship) is expected between the two procedure scores using the same measurement methodology

Figure III - 1 The experimental framework: description and strategies

Figure III - 2 summarises the approaches to include the developed framework in the research design and conduct studies in fully immersive virtual environments.

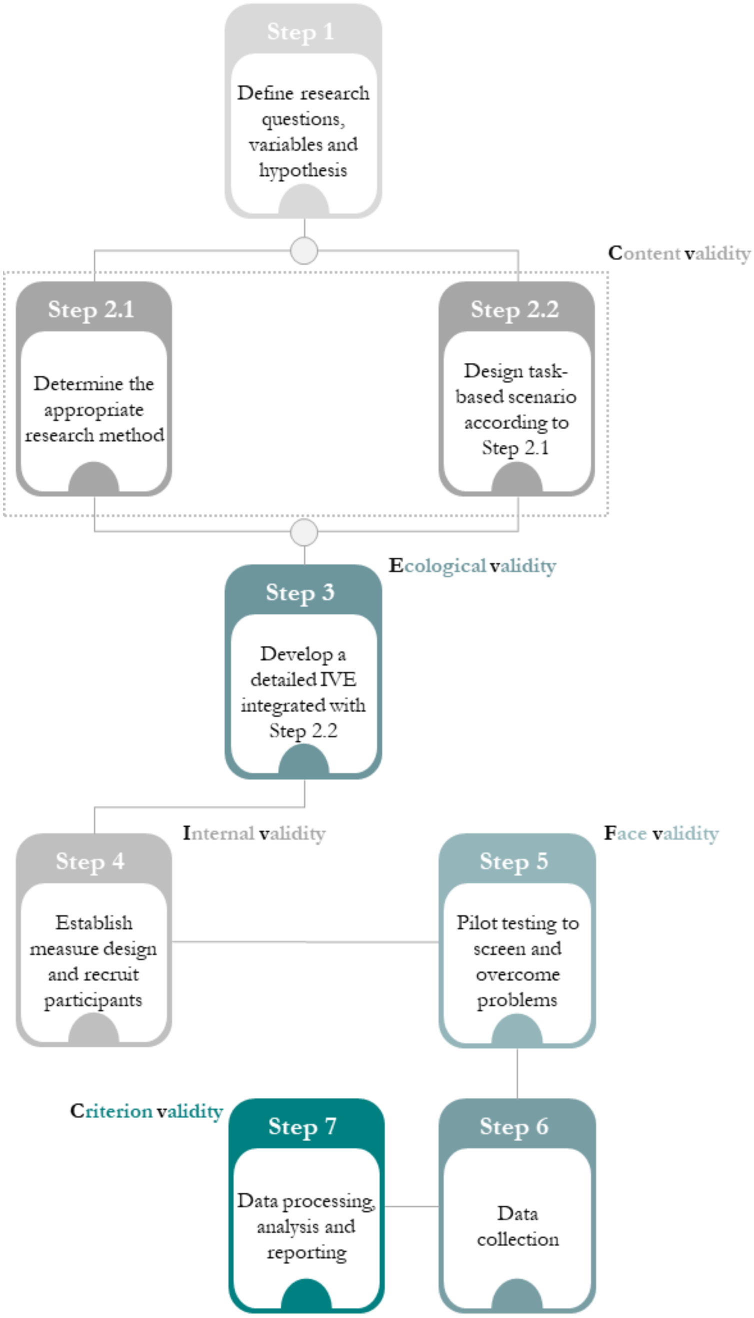

Figure III - 2 Approach to include the developed framework and conduct research in fully IVE

3.3. Dependent variables

Regarding the selection of dependent variables, the review of methods for quantifying the effects of the indoor environment on occupants' comfort, work efficiency and behaviour in Section 2.2 showed the need for robust variables in VR research.

Consequently, the present paragraph presents the employed objective and subjective measures (i.e., cognitive task performance, physiological parameters, self-reports data) based on existing literature, relevant standards, and theories to deal with content validity (Section 3.2).

To examine the effect of the independent variables, the data collected during the experimental activity at a global level include individuals' cognitive performance and behaviour, while comfort, immersivity and cybersickness attributes in post-experiment.

Additionally, at a local level, environmental and physiological measures are carried out to understand the interaction underlying a specific environmental exposure-response relationship.
An overview of variables collected at each stage of the thesis research project and insight potentials can be found in Figure III - 3.

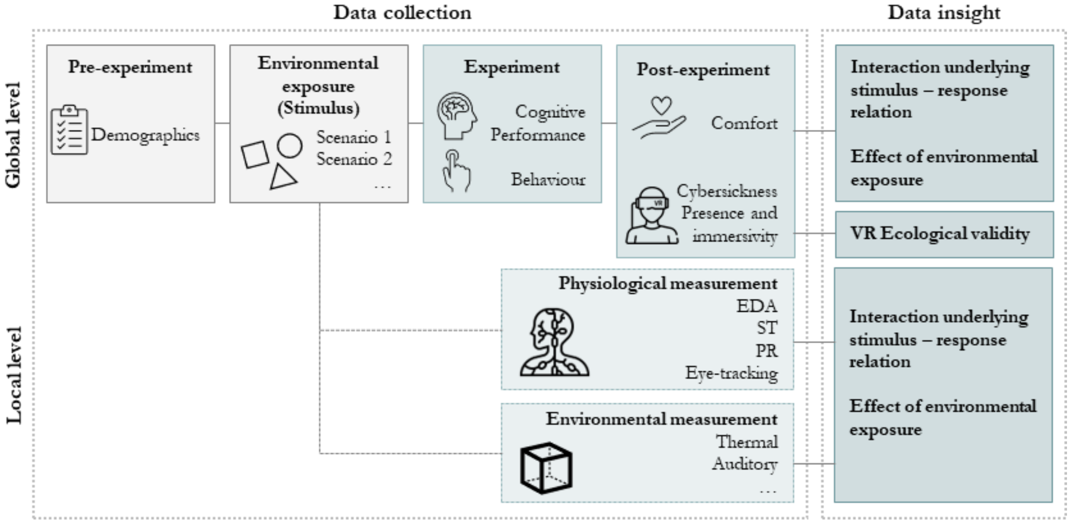

Figure III - 3 Overview of the collected data during the experimental phases of the research activities

The next sub-paragraphs explain in detail the dependent variables useful for building occupants' work-efficiency, comfort and behavioural research and how they can be integrated with the VR-experimental activity.
These approaches will be adopted throughout the experimental methods of the present thesis.

3.3.1. Cognitive tests

To objectively assess the productivity supporting the content validity of the developed model, three specific tests were carried out to investigate the related executive functions: the *Magnitude-parity test* [116] for *task switching*, the *OSPAN test* [117] for the evaluation of the working memory, and the *Stroop test* [118] for inhibition.
The *Magnitude-Parity test* was performed through a timed video composed of a sequence of slides (200 ms). The digits from "1" to "9" except "5" were used as stimuli. All numbers were presented in black colour on a white background, in the middle of the screen preceded by coloured (red and blue) disks, presented in the centre of the screen too for 200ms. Participants were asked to tell whether the displayed number is odd or even after the red dot is displayed (parity stimulus), and whether the displayed number is smaller or larger than 5 after the blue disk (magnitude stimulus). The dot-number strings were presented eight times for each stimulus, for a total of 16 digits to be ranked.
Also, the *OSPAN test* consists of a sequence of images of short duration: in the first slide (3sec) the participants saw one simple math operation, centred on the computer monitor, to be solved by the mind; the second slide (3sec) shows a number proposed as a possible solution to the previous equation. The subject was asked to tell aloud whether the solution is true or false. Immediately after, in the last slide (800ms) they saw a letter to be memorised. The operation-true/false-letter strings were presented in a set of five items. At the end of each complete set, the participant was instructed to recall all the letters in the order presented.
Finally, the *Stroop test* was presented as a picture composed of a total of eight rows with four words on each row. Four colours: Red, Green, and Blue, representing the three components of the RGB model, pink and orange were displayed on a black background. Subjects were asked to name the colours of the words as fast as they could, while their execution time was collected. For example, if the word "red" is printed in blue ink, the correct answer is "blue".
Responses to all three cognitive tests were given by voice (Figure III - 4).
To support internal validity, the execution of the three tests needs to be randomised (e.g. *OSPAN, M-P, Stroop* vs *M-P, OSPAN, Stroop*) to counterbalance the order effect and time-related factors. Moreover, in the case of repeated-measure design research where the subject performs the test under two or more environmental stimuli, a different version of the three tests was developed, with the same difficulty level.

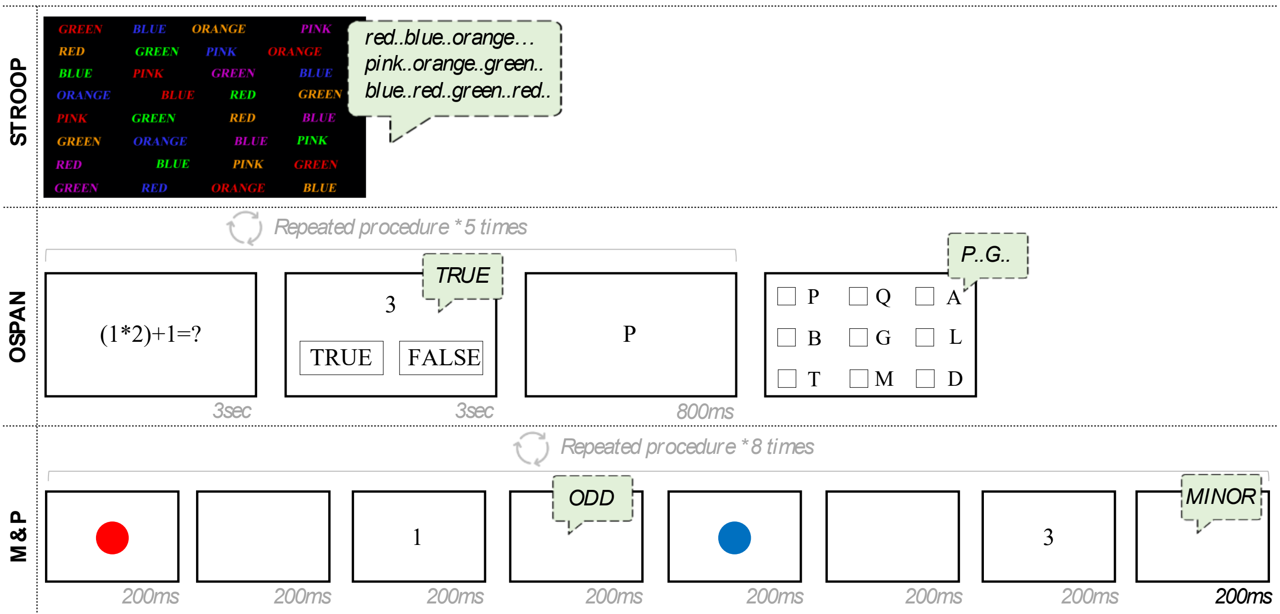

Figure III - 4 Instructions and sequences of the slides for the three cognitive tests

The data collected from cognitive tasks and eye-tracking measures were extracted and analysed for each participant as follows.
For the instructions of each test, the time to complete the reading of the slides was calculated. The errors in the subject classification of the digits even/odd and greater/lower than “5” were considered for the Magnitude-Parity test. Concerning the OSPAN test, results were analysed by calculating the number of errors in the true/false string, the correct order of the letters memorised and the OSPAN score, computed as the sum of the number of the right true/false and the letters correctly memorised. The above-mentioned cognitive metrics were used as an index of inhibition, task-switching and working memory capacity. Lastly, in the Stroop test, the number of errors in the colour naming, and the execution time in seconds were computed.

3.3.2. Questionnaires

During the experimental activity, participants were asked to respond to a questionnaire consisting of two main parts: a pre-experimental survey and a post-experimental one after exposure to environmental stimuli.

3.3.2.1 Pre-experimental questionnaire

The former concerns basic socio-demographic information (gender, age, eyesight and hearing problems, educational level).
To understand an individual’s experience within the IVE, questions (from “never” to “every day” scores), that focused on daily sedentary activity and habits with some medium, such as watching TV, playing video games, and experience with VR are included [39].
A list of clothes worn during the experiments to estimate the *clo* value according to standard UNI EN ISO 9920:2007 [20] was also added to understand the connection with thermal comfort, for example.
These questions were useful to collect the effect of individual features and further detect any difference across the tests, thus, supporting the criterion validity.
Table III - 1 reports the overall questions to investigate participants’ basic demographics and relevant generalities.
In addition, participants were asked to indicate the characteristics of their working environment and the most wanted elements in the office, in terms of access to natural light and ventilation, the presence of indoor green plants and natural or urban landscape views. The level of satisfaction with the visual design and acoustic characteristics of their work/study places was also investigated.

Construct	Indicators/question	Rating scale	Thesis section
Demographical information	Please specify your: ● Gender ● Age	Short open-ended questions	Part IV Part V: Chapter I Part V: Chapter II

	● Height ● Weight		Part V: Chapter III
Educational level	Please select your educational level ○ Not graduated from university ○ Graduated ○ PhD, post-graduate school		Part IV Part V: Chapter I Part V: Chapter II Part V: Chapter III
Health status and eyesight problems	● Do you suffer from body temperature-altering illness? ● Do you suffer from visual problems? If yes, do you have corrective lenses? ● Do you suffer form hearing problems?	yes - no	Part IV Part V: Chapter I Part V: Chapter II Part V: Chapter III
Activity	A half-an-hour ago, you were: ○ Playing sport ○ Walking ○ Seating ○ Standing		Part IV Part V: Chapter I Part V: Chapter II
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 …		Part IV Part V: Chapter I Part V: Chapter II
Workplaces characteristic	Select the characteristics that are present in your workplace: □ Access to natural light □ Natural elements (e.g., potted plants, living wall) □ Operable windows that allow natural ventilation □ Natural materials (e.g., wood, natural stone) □ Co-working spaces □ Natural sounds (e.g., bird song) □ Anthropic sounds (e.g., traffic) □ Outdoor view (urban landscapes) □ Outdoor view (natural landscapes)		Part V: Chapter III
	Select the characteristics that you would like to introduce in your workplace: □ Access to natural light □ Natural elements (e.g., potted plants, living wall) □ Operable windows that allow natural ventilation □ Natural materials (e.g., wood, natural stone) □ Quieter environment (from external sources) □ Quieter environment (from internal sources) □ Outdoor view (urban landscapes) □ Outdoor view (natural landscapes)		Part V: Chapter III
	I am satisfied with the design of my workplace	totally disagree/totally agree (7p)	Part V: Chapter III
	I am satisfied with the acoustical features of my workplace		Part V: Chapter III

Table III - 1 Pre-experimental survey questions on basic demographics and other general constructs

Concerning human-building interaction and adaptive behavioural assessment, a specific section was designed to contain four main parts associated with the Theory of Planned Behaviour constructs [119]. 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 III - 5 shows a schematic representation of the TPB as developed by Ajzen et al. [119].

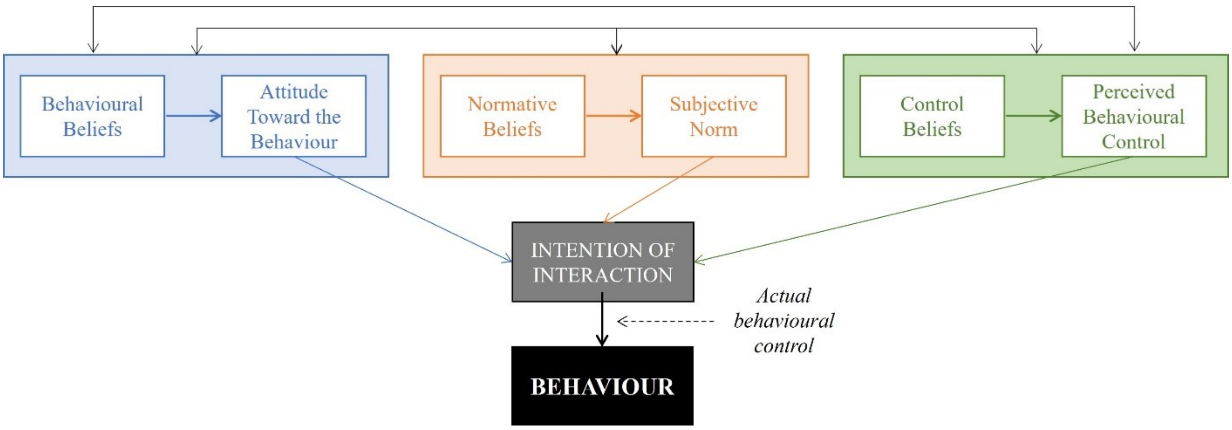

Figure III - 5 Schematic representation of the Theory of Planned Behaviour (Figure redrawn from Icek Ajzen [3])

It was of interest 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 III - 2 presents the overall questions to investigate the TPB and the related literature references [120,121] adopted to develop the questionnaire. Anyway, the questions were revised to be suitable for the present research aim.

Construct	Indicators/question		Ref.	Thesis section
Awareness of consequences (AC)	AC1	Interacting with the control systems to make myself comfortable in my workplace will influence MY COMFORT	[120]	Part IV: Validation of the experimental framework
	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	[121]	
	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	[120]	
	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	[121]	
	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	[121]	
	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	[120]	
	PBC4	Other co-worker's needs are a main perceived impediment to interacting with the control system in my workplace		

Table III - 2 Main construct and indicators associated with TPB survey questions and related literature references

The pre-experiment questionnaire was completed through an online platform to minimise interactions with the researcher avoiding any influence on the subject's answers.

3.3.2.2 Post-experimental questionnaire

While exposed to each stimulus, after the operative phase, it was of interest to ask participants to complete a post-experiment questionnaire which included five sections: thermal, visual, acoustical comfort, perceived affective quality of the soundscape, the intention of interactions with building thermal systems, sense of presence and immersivity, and cybersickness disorders.

Participants' self-reports about thermal and visual comfort were collected. In particular, based on the standard UNI EN ISO 10551:2019 [101], three parameters were investigated 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».

To measure the effect associated with the noise stimulus, the standards ISO 12913-2: 2018 [103] and ITU-R BS 1116-3: 2015 [104] were adopted. Subjects were asked to rate how much they could distinguish the five sound sources and the overall quality of the virtual sound environment (pleasant, relaxing, peaceful, boring, chaotic) on a seven-point Likert scale. The Acoustic Comfort Vote was investigated ranging from «comfortable» to «extremely comfortable» in addition to the perceived effect of noise on work-efficiency.
Moreover, participants were invited to rate the perceived affective quality of the soundscape through the following eight perceptual attributes using a five-point Likert scale (from «strongly agree» to «strongly disagree»): pleasant, exciting, eventful, chaotic, unpleasant, monotonous, uneventful, and calm [122]. Due to the absence of an indoor soundscape assessment model for office buildings (such as present for residential buildings [123]), the model developed by Axelsson et al. [124] and ISO/TS 12913–2 technical specification [122] for (outdoor) urban environments were adopted. The choice is justified by the fact that at least the two main perceptual dimensions can be considered generalizable, with the first referring to the degree of pleasantness or comfort of the environment and the second referring to the degree of saturation of the environment with sounds or events (i.e., eventfulness or content).

It was of interest in the behavioural domain, to record the adaptive strategies to study the occupant-building system interactions to improve thermal comfort. Indeed, according to the Theory of Planned Behaviour, «the intention of interaction is assumed to be the immediate antecedent of behaviour» because people are expected to carry out their intentions when the opportunity arises. 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' 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 state of the art presented in Section 2.2, well-established surveys to assess participants' sense of presence and immersivity in this field are the *Slater-Usoh-Steed* and the *Igroup Presence Questionnaires* (*IPQ*). 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 Likert 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) [125]. The investigated symptoms were reduced from nine to six: general discomfort, fatigue, eye strain, difficulty in focusing, headache, and vertigo.

The questions of the post-experimental survey completed throughout the experimental activities described in Part IV: Validation of the experimental framework and Part V: Applications of the experimental framework in the fields of work-efficiency, comfort and adaptive behaviour, are reported in Table III - 3.

Factor	Question	Rating scale	Thesis section
Thermal/Visual comfort	How do you judge this environment?	very cold/very warm (7p)	Part IV Part V: Chapter I Part V: Chapter II
	Do you find this..?	comfortable/ extremely uncomfortable (5p)	
	Please state how would prefer to be now	much colder/ much warmer (7p)	
Sound distinction	Can you distinguish the following sound types within the present virtual environment..? ● mechanical system noise ● human-based sound sources ● machine noise	not at all/a lot (5p)	Part V: Chapter II

	● acoustical effect ● phone rings		
Sound evaluation	Please judge to what extent the attributes listed in the following are applicable to the acoustic environment you are experiencing ● pleasant ● relaxing ● paceful ● chaotic ● boring	totally disagree/totally agree (7p)	Part V: Chapter II
Perceived affective quality of the soundscape	Please judge to what extent the attributes listed in the following are applicable to the acoustic environment you are experiencing ● pleasant ● exciting ● eventful ● chaotic ● unpleasant ● monotonous ● uneventful ● calm	totally disagree/totally agree (7p)	Part V: Chapter III
Effect on performance	The ambient sound can influence my work-efficiency	totally disagree/totally agree (7p)	Part V: Chapter II
Acoustic Comfort Vote	How do you feel in the present virtual environment concerning the sound quality?	comfortable/extremely comfortable (5p)	Part V: Chapter II
Intention of interaction	Would you interact with the highlighted building systems to improve your well-being? If yes, please state your willing interactions	yes - no	Part IV Part V: Chapter I
Graphical satisfaction (GP)*	I appreciate the graphics and images of the virtual model	totally disagree/totally agree (7-points)	Part IV Part V: Chapter I Part V: Chapter II Part V: Chapter III
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		
Involvement (INV)*	During the experience, I was not aware of the real world around me		
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?		
Cybersickness*	Did you experience..? ● general discomfort ● fatigue ● eye strain ● difficulty in focusing ● headache ● vertigo	not at all / very much	

Table III - 3 Questions and ratings of the post-experimental survey (factors marked with '*' were investigated only in the virtual environment)

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 minutes of exposure to VR.

3.3.3. Physiological parameters

While the participants were immersed in VR, three physiological signals were occasionally recorded on the Empatica Health Monitoring Platform using the EmbracePlus wearable device [126]:

- Electro-Dermal Activity (EDA) (measure range: 0.01 to 100 μS) is the physiological response reflecting sweat glands activity and is sensitive to the activation of the sympathetic nerve due to psychological stimuli [127,128]. It is adopted as an indicator of psychological and physiological arousal and to assess stress [23]. Indeed, if the subject experiences an increase in stress level due to the activation of the sympathetic nerve, EDA increases and promotes the sudomotor [83,129]. On the contrary, lower EDA values indicated a more relaxed status.

- Pulse Rate (PR) (measure range: 24 to 240 bpm; accuracy: 3 bpm in case of no motion) refers to the rate at which blood pulses through the arteries per minute and changes as the sinoatrial node of the heart activates the autonomous nervous system [130]. Similarly to heart rate, it is commonly adopted as an objective measure of psychological stress [23,128]. At a stable status, if the subject is in a calm or relaxed state, the pulse rate slows down as the parasympathetic nerve is activated, when the sympathetic nerves are activated, the heart rate increases [131].
- Skin Temperature (ST) (measure range: 0 to +50 ◦C; accuracy: ± 0.1°C from 30°C to 45°C) is a physiological response that changes as the peripheral blood vessels contract or relax [132]. When stress activates the sympathetic nervous system a reduction in peripheral circulation occurs causing a reduction in skin temperature [23]

Additionally, at a local level, participants' raw eye-tracking data (i.e., blink, pupil diameter, fixations and saccades metrics) were collected with an eye-tracking system embedded in the VR headset. Namely, the objective was to measure mental workload across different tasks and environmental stimuli. For this purpose, the most frequently used metrics include:

- **Number of blinks**: it is an involuntary metric whose frequency reduces as cognitive load increases [133,134]. Indeed, during attention-demanding tasks to extract and process critical task-relevant, eye blinks tend to be inhibited to maximize stimulus perception [135,136].
- **Pupillary dilation** is another effective metric for cognitive load assessment as pupils tend to dilate as a reaction to mental demands and emotional arousal [133–135,137–141].
- **Number of fixations/Fixation count:** a fixation is a short period during which an individual gaze remains relatively stable and focused on a specific point of interest to process visual information [142]. The number of fixations entails several meanings depending on the content and the task performed which might involve different levels of attention, mental processing and comprehension, for example. Literature reported that more fixations reflect higher cognitive load [143,144] and engagement in the scene [145].
- Similarly, the **fixation duration** is linked to the time for information processing: a longer fixation duration indicates a higher mental load in extracting information during reading task [133], visual search task [135] [143] and working memory [143] and visual interest toward the scene [145].
- The **number of saccades** (rapid movements of the eyes as they shift from one point of interest to another) increases in the presence of higher cognitive load in information processing and task performance as the ability to shift gaze effectively to relevant information decreases [135,143].

It was of interest to couple quantitative eye-tracking data (e.g., blinks, pupil dilation, fixation and saccade) with the visualization of eye-tracking records by using eye movement heatmaps. Within the **heatmaps,** a colour degree from light green to red is assigned depending on the degree of accumulation of fixation and the related duration, the higher the visual attention the warmer the colour [146]. Thus, they provide information about visual attention to patterns displayed while performing a task [143,147].

3.4. Concluding remarks

The definition of the novel experimental framework to carry out VR research studies on occupants' work-efficiency, comfort and behaviour overcomes the limitation of methodological approaches of the current literature in this field. This experimental method has the potential to offer high mobility, facilitating the replication of the tests while collecting trustworthy data suitable to allow the researcher to make general conclusions and further support building design practises and theories.
The challenge lies in applying this experimental approach to obtain research findings that are valid, reproducible, and generalizable from virtual to real environment case studies.
Thus, the methodological approach used in the present thesis is linear.
It starts with the validation of this virtual reality-based experimental method is tested against a real environment (Part IV: Validation of the experimental framework), providing an essential reference for the suitability of the framework and the adequacy of virtual reality technology in reproducing real empirical settings, addressing a critical gap in the existing literature.
Then, it continues with research that examines the relevance of the proposed tool and research objectives to set the foundation for a comprehensive assessment of human dimensions in indoor environments. Through a series of investigations, this thesis systematically seeks to demonstrate the wide range of applications of the framework to support the criterion validity of VR in quantifying the effect of environmental conditions on occupants.

Part IV: Validation of the experimental framework[3]

Given the relevance of validity issues, Bishop and Rohrmann [148] suggested that a standard procedure for the effective implementation of VR modalities and new methods is the empirical validation of such novel tools and approaches.
Hence, the present chapter presents the results of an experimental study that investigates the adequacy of the experimental framework for building occupants' work-efficiency, comfort and behavioural research. This chapter aims to validate the methodological instrument and a virtual reality office model, as a suitable experimental tool against its real counterpart to be used in the empirical studies that support answering the core research question of this thesis.

Structurally, this chapter consists of six sections. After the statement of the aim, the second section describes the real environment. The third section reports the workflow for the generation of the virtual model at the base of the following empirical studies of this thesis. The fourth section presents the experimental study that used the virtual office environment and the corresponding real environment to test the participants' comfort, work efficiency, behaviour, sense of presence and cybersickness in VR. The fifth section describes the findings of this first experimental study investigating the criterion validity of the created virtual model. Lastly, a summary of the findings and the focus of the following chapters is presented.

4.1. Background and aim

Suitable Immersive Virtual Environments have the potential to create a psychological state in which the users perceive themself as existing within the virtual space.
Part II: Human dimension research in buildings: Immersive Virtual Reality applications in the fields of work efficiency, comfort and adaptive behaviour stated that 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 the end-user experience and immersion within a VE, which is an often debated aspect [46] not fully addressed within the analysed research.
Virtual environments were validated against their real counterparts mainly considering the reliability of the outcomes concerning, in order of relevance, thermal and visual comfort, tasks related to work efficiency, occupants' perceptions, and physiological parameters. Fewer attempts of validation concerned the thermal and lighting behaviour of individuals.
In addition, the factors influencing the behaviour were not contextually examined. Indeed, to the authors' knowledge, only a few studies [149–153] have applied the Theory of Planned Behaviour (see Part III: Definition of an experimental framework for IVR applications, Section 3.3.2) to environmental behaviours in workplaces. In general, several hundred office building occupants were surveyed (i.e. a university in Malaysia [151], companies in China [150], in the U.S. [152], and across the UK [149,153]) to examine how much the TPB constructs explain the variance in employees' energy-saving behaviour. This research topic is still emerging and 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 VR.

As extensively discussed in Part II: Human dimension research in buildings: Immersive Virtual Reality applications in the fields of work efficiency, comfort and adaptive behaviour and briefly highlighted in this introduction, it is imperative to consolidate the validation domain of IVEs demonstrating the potential to represent real-life scenarios in comprehensive assessment to adequately support the research on occupants' comfort, work efficiency and behaviour.
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.

[3] This section is based on:
A. Latini, et al. 2023 "Immersive virtual vs real office environments: A validation study for productivity, comfort and behavioural research". Building and Environment, 230: 109996
A. Latini., et al. 2023 "Virtual reality as a new frontier for energy behavioural research in buildings: tests validation in a virtual immersive office environment. Technologies, Engineering, Materials and Architecture (TEMA)

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. Moreover, this research tries to contribute to the current state-of-the-art by integrating, for the first time, the TPB with a virtual environment to understand individuals' energy-related intention of interaction with the building systems.
According to the developed framework (Part III: Definition of an experimental framework for IVR applications), firstly, the authors checked the ecological validity of the modelled IVE to ensure it could 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 author proceeded by benchmarking the metrics of work-efficiency, 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.
Figure IV - 1 shows the overall process for the validation of the virtual office environment.

1 Visual stimuli in the real and virtual environment

- ▶ **Real environment** (RE) — selection of the experimental office space
- ▶ **Immersive Virtual Environment** (IVE) — creation of the virtual model as faithful replication of real office

2 Validation of the experimental framework

- ▶ **Reported presence and immersivity** — evaluation of perceived presence in the IVE
- ▶ **Reported cybersickness** — evaluation of perceived sickness after using VR headset
- ▶ **Task accuracy** — evaluation of accuracy in RE and IVE across three cognitive tests
- ▶ **Perceptual accuracy** — evaluation of perception in RE and IVE (thermal comfort, visual comfort)
- ▶ **Behavioural accuracy** — evaluation of adaptive behavioural strategies in RE and IVE (TPB, behaviour)

Figure IV - 1 Illustration of the methodological approach in the study presented in Part IV to validate the immersive office environment.

4.2. Description of the real environment

In order to test the accuracy of virtual reality as an experimental tool, subjective evaluations and task accuracy of real office space and its representation in virtual reality were compared.
The criteria that were established for the selection of the test room were a small-to-medium size and accessibility to allow the measurement of the material properties of the main surfaces and the control of the room furniture, to accommodate similar real and virtual scenarios.
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). The test room has a width of 5.93m, a length of 4.38 and a height of 3.00m.
The room was set up as shown in Figure IV - 2 to replicate an office working environment: the workstation included a computer, a keyboard, a mouse, and an indoor microclimate station.
The blu-point highlighted in the room was selected as the viewpoint for the participants in the real environment (Figure IV - 2a), as well as for the position in the virtual scene (Figure IV - 2b).

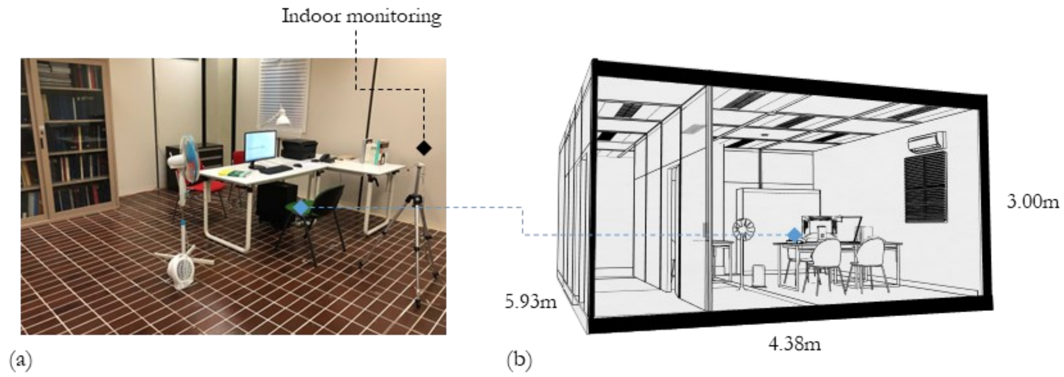

Figure IV - 2 Photogram of the test room corresponding to the Real Environment (a), illustration of the interior in the 3D model (b)

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 (0.10m), waist (0.60m) and head (1.10m) 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 reported 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.

4.3. Workflow for the generation of the immersive model

The second step in the workflow was to model the 20-square-meter 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 [154] 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. Figure IV - 3 presents the generation of the texture to be integrated into the virtual model.

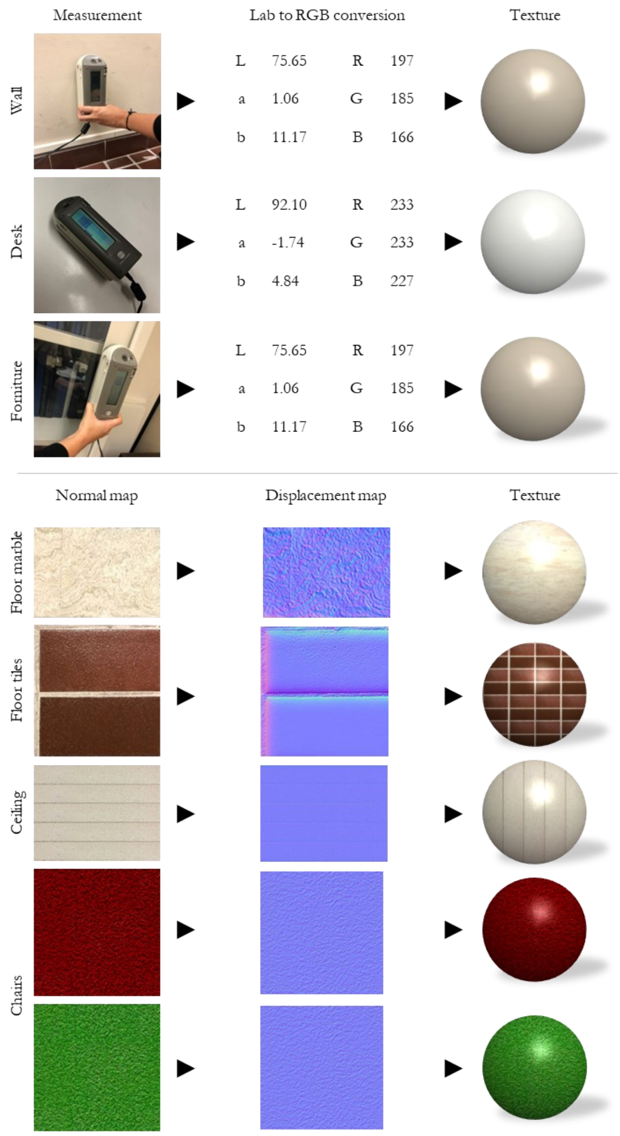

Figure IV - 3 Generation of the texture for the virtual model

Once the model and textures were completely set, the authors created two basic virtual scenarios (Figure IV - 4a,b): the first 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 to perform the test while virtually seating in front of the virtual workstation. In neither of the two basic scenarios was it possible for subjects to view virtual hands, as no direct interaction with the model was allowed and the overall test session was verbally solved. Indeed, the productivity tests and questions of the surveys were shown through the virtual computer monitor, respectively, as attached timed videos and sequences of images, to provide the highest level of realism, to support external-ecological validity.
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.
The IVE model was experienced through the *SteamVR* software plugin [155] combined with one of the most common technologies regarding head-mounted displays: the *HTC Corporation VIVE PRO Eye*. It has a 1440 x 1600 resolution image per eye, a pixel density of 615 PPI, a screen Dual OLED 3.5" diagonal, a maximal illumination of 125.73 cd/m^2, a refresh rate of 90 Hz, a field of view of 110° per eye and an adjustable interpupillary distance from 60.7 to 73.5 mm). To visualise the scenes, the height of the camera was set at 1.10m height from the ground based on the average eye height of a seated person.
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 Figure IV - 4c.

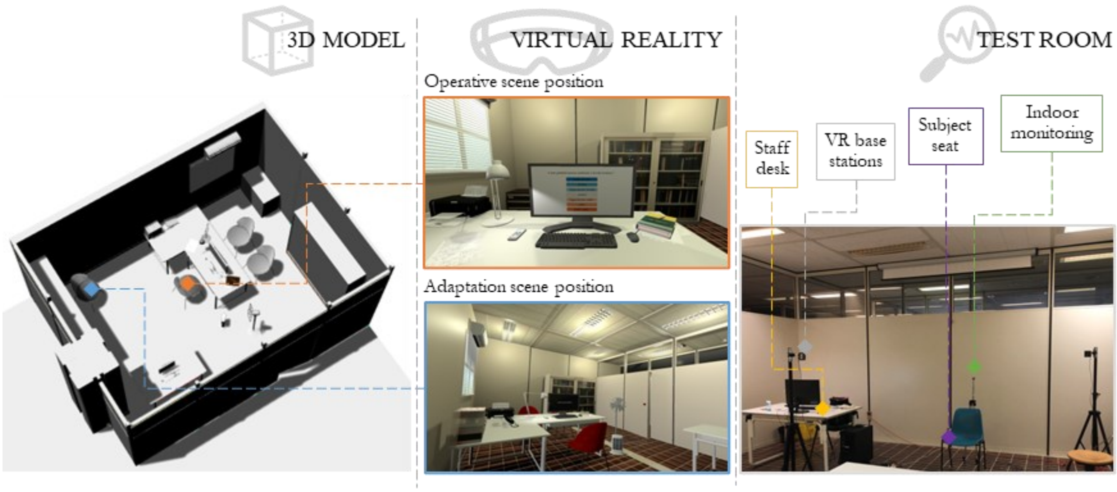

Figure IV - 4 3D model of the office room (a), the virtual model with the positions for the adaptation phase and the operative phase (b), the test room setup (c)

4.4. Experimental design

The experiments took place as presented in Figure IV - 5 and followed the prescription established by the experimental framework (Part III: Definition of an experimental framework for IVR applications). 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 instructions about the experiment and completed the pre-experiment questionnaire through an online platform. This stage lasted about 15 minutes to allow them to get used to the environmental conditions and to reduce any fluctuation related to the 30 minutes-prior-test physical activity that might have influenced their metabolic rate [102].

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 seconds and adapted to the virtual scene for 3 minutes to reduce any psychological fluctuations related to the virtual environment exposure, and facilitate immersion, respectively [92]. Then, in both real and virtual settings, the volunteers performed the three cognitive tasks (3 minutes). 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. Participants expressed also their intention to interact with the building systems presented in the scenarios (i.e., heater, fan, air condition, window).

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 [46] that can threaten the reliability and validity of the collected data.

The period of the test was limited to 25-30 minutes to reduce overall fatigue and exposure to the virtual environment, thus, avoiding the occurrence of any disturbances that could invalidate the test [108].

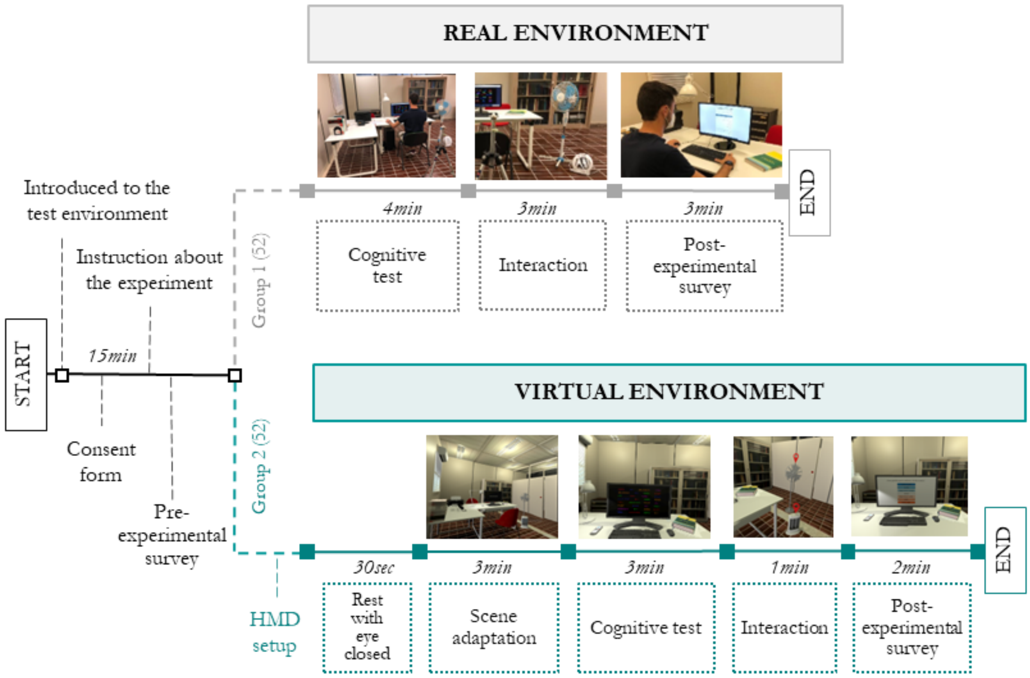

Figure IV - 5 Experimental schedule in the real and virtual environments

4.5. 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 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). In addition, the ability of TPB integrated within the IVE to predict behavioural intention was analysed looking for any eventual difference with the RE

The parametric and non-parametric statistical analysis methods for independent samples were used for the hypothesis testing. All datasets were analysed through *RStudio* software [156] setting the significance level equal to 0.05 (5%).

4.5.1. 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 [157], 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 [158] was computed: the sample size was adequate to detect significant effects with a statistical power equal to 0.80.

Figure IV - 6a 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 (Figure IV - 6b). Most of the subjects were graduates (47%), 38% were university students and 14% had a higher educational level (PhD, post-graduate school, Figure IV - 6c). None of the subjects suffered from colour blindness and 42% of the sample had typical eyesight problems (myopia, astigmatism, hyperopia, or a combination of them, as shown in Figure IV - 6d), 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 (Figure IV - 6e).

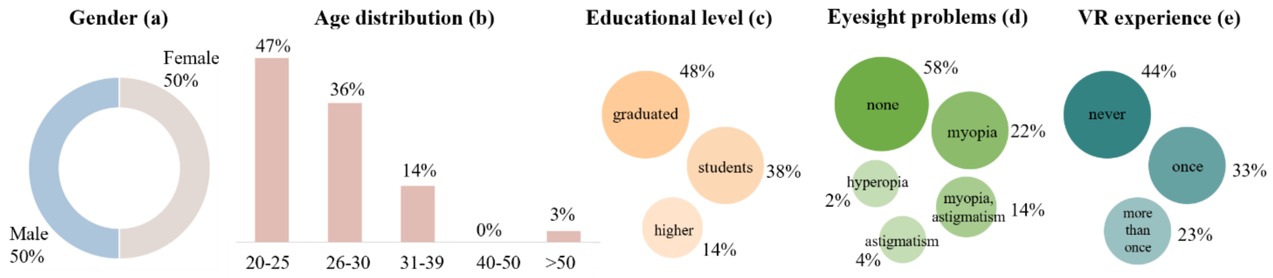

Figure IV - 6 General information about the sample: a) gender; b) age distribution; c) educational level; d) eyesight problems; e) experience with VR settings

4.5.2. Ecological validity

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 [61–63,73] 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. Figure IV - 7 summarises 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 [73] (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.

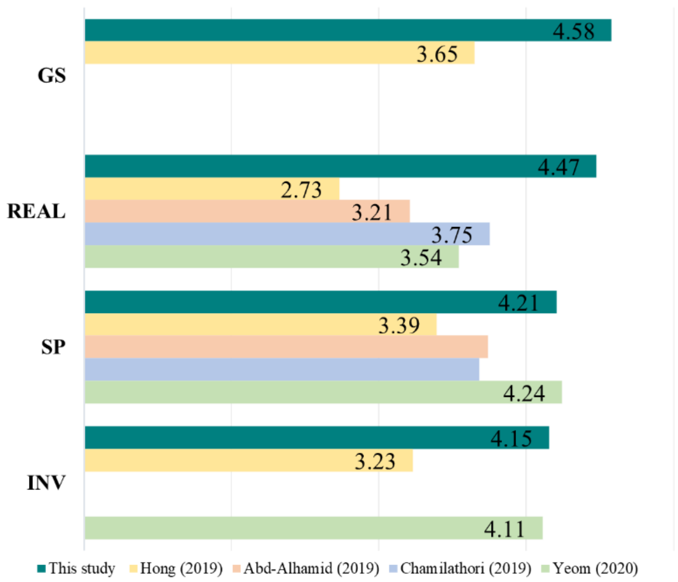

Figure IV - 7 Comparison of scores on a five-point scale of the four indicators: Graphical Satisfaction (GS), Experienced Realism (REAL), Involvement (INV), Spatial Presence (SP) [Yeom et al. [74], Chimalothori et al. [62], Abd-Alhamid et al. [63], Hong et al. [64]]

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 [159,160]. 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 [53,71]. No general discomfort is usually experienced during the virtual tests [41,62,71] even if the majority of participants have never experienced the VR tool before as in the present study (44%, Figure IV - 6e).

4.5.3. 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, intention of interaction and Theory of Planned Behaviour) 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.

4.5.3.1. Work-efficiency

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) [157]. 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 ($\pm$1.983 for df=103, α=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 of 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.

The same outcome was highlighted by looking at the execution time with about 3 seconds 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 [117]. 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 Figure IV - 7.

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

Table IV - 1 The results of the unpaired-sample t-test on the three cognitive tests

4.5.3.2. 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 the Mann-Whitney U statistic was 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 = $\pm$ 1.96 for $\alpha = 0.05$) [157]. Whether the sample data produce a Z-score that falls outside the critical region and a p-value $< \alpha$ the null hypothesis is rejected.

Figure IV - 8 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-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 $\pm$ 1.96 boundaries, Table IV - 2). 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 4000K, 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 $\pm$ 1.96 boundaries).

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 [41,52,58] and visual perception [37,62] domains.

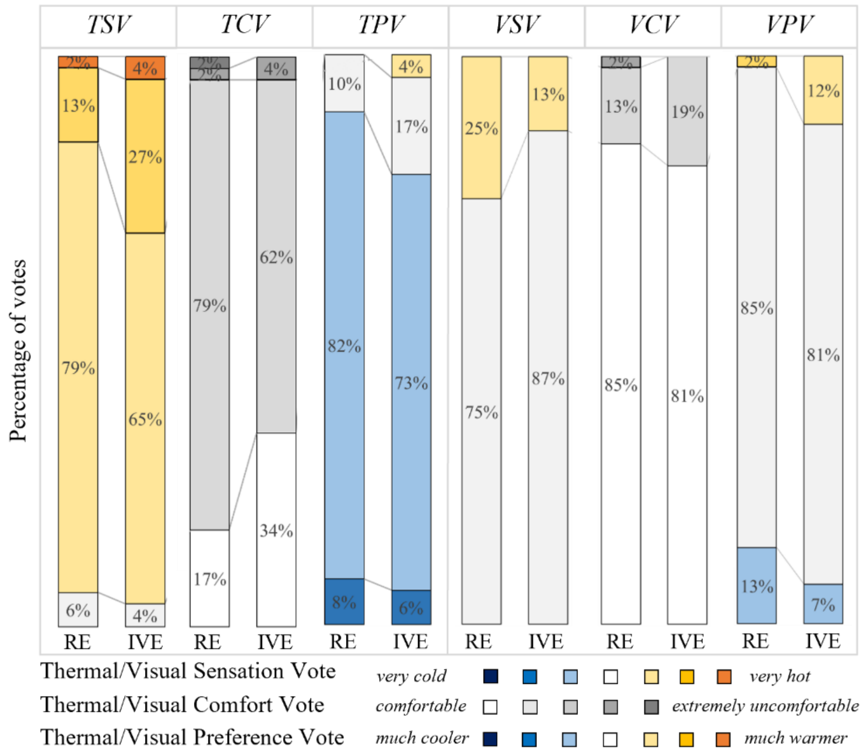

Figure IV - 8 Percentage of votes for the comfort parameters within the two tested environments (RE, IVE)

	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

Table IV - 2 The results of the Mann-Whitney test between RE and IVE on the thermal and visual comfort (Z-crit = ± 1.96)

4.5.3.3. 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 subjects 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. Figure IV - 9 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 «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 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 [52], this result confirmed the promising application of VR for human-building interaction investigations.

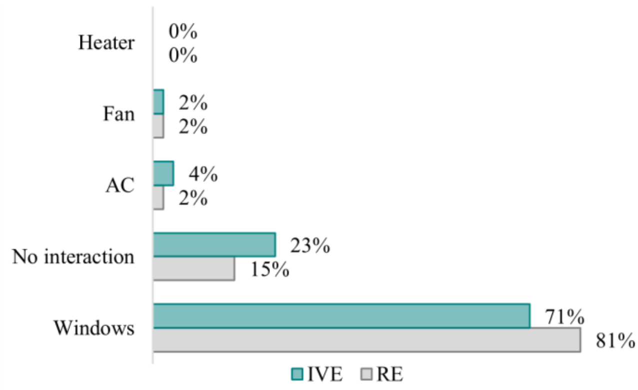

Figure IV - 9 Type of intention of interaction within the two tested environments

4.5.3.4. Theory of Planned Behaviour

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, 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 IV - 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 increases nor decreases 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	KE1	0.83					

about the energy consumption (KE)	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 [161]	≤ 3.00 [162]	≥ 0.90 [162]	≥ 0.90 [162]	≤ 0.08 [162]	≤0.08 [162]

Table IV - 3 The result of the main standardised factor loadings, reliability and convergent validity according to the cut-off values ([162,163])

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 IV - 4). Moreover, the square root value of the AVE of each construct (Table IV - 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 was established, confirming that each construct is unique and truly distinct from the others [163].
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 [163]	≥ 0.50 [163]				

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

4.6. Concluding remarks

Part IV: Validation of the experimental framework 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 research in the fields of comfort, productivity, and behaviour by ensuring reliable and effective data collection.

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 x 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. This confirmed the hypothesised suggestions proposed by the developed framework (Part III: Definition of an experimental framework for IVR applications).

In addition, the cybersickness analysis did not reveal 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 [53,71] 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 [46]. 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, intention of interaction and TPB. 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 [52,53] and visual perception [53,62,63] 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.
- Lastly, the suitability of the TPB in IVE in predicting participants' intention of interaction was confirmed with no relevant difference detected with RE. Namely, 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.

Some limitations should be addressed. 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.

Secondly, 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 (e.g., 20°C) and a more extreme colder one (i.e., 17°C, tested in Part V: Applications of the experimental framework in the fields of work-efficiency, comfort and adaptive behaviour) to establish a potential relationship between cognitive functions and indoor air temperature.
Thirdly, the TPB survey should be revised and integrated with other predictors in the model, such as personal and social norms, habits in energy-saving behaviours, and time availability. 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 a comparison between non-trained occupants and trained ones in terms of the intention of interaction and energy-saving practices.
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.

Part V: Applications of the experimental framework in the fields of work-efficiency, comfort and adaptive behaviour

The previous chapters introduced a novel experimental framework to carry out VR-based research which was later validated through the experimental comparison of a real with a virtual office scenario on individuals' comfort, work efficiency and behaviour metrics.
Building on these methodological foundations, this chapter will present the findings of three additional experimental studies that employ the developed method and the validated model to explore the core question of this thesis: «What is the most effective way to use VR as a research tool to investigate humans-buildings interaction and support the realisation of user-oriented indoor environments?»
Specifically, the purpose of the present chapter is to provide evidence about the potential of using this method for the investigation of human dimension in indoor built environments producing trustworthy data suitable to allow the researcher to make general conclusions and further support building design practises and theories.
As the fundamental question in this thesis revolves around the potential of adopting VR technology to detect the influence of indoor environmental characteristics on humans, several stimuli were explored. It was of interest not to test single-domain studies but to address the challenges of applying VR to multi-domain studies. At first, two cross-effect study types in which the variation consists of the thermal stimuli and the acoustical one were carried out (Chapter I: Investigation of users' response to varying thermal environment in a mixed-IVE, Chapter II: Identifying the effect of indoor noise through Acoustic Virtual Reality). In particular, the same-modality effect of the thermal and acoustical domains on thermal and acoustical responses was investigated. In addition, the cross-modal effects of the thermal domain on visual response and of the acoustical domain on thermal response were investigated.
Secondly, Chapter III: Exploring the impact of virtual audio-visual Biophilic Design interventions presented a combined-effect study type in which the effect of multiple stimuli in combination (i.e., visual and acoustical dimensions), was assessed on individuals' responses.
Each chapter has an introductory section which defines the research background, the experimental activity carried out with related outcomes and concluding remarks to highlight future research perspectives to complete the work.

5.1. Chapter I: Investigation of users' response to varying thermal environment in a mixed-IVE[4]

5.1.1. Background and aim

The main focus of this thesis is to demonstrate the potential of using VR to investigate the influence of indoor environment characteristics and changes on users' thermal and visual comfort, work efficiency and thermal adaptive behaviour. To illustrate the applicability of the developed framework while overcoming the aforementioned research gaps, this section presents a cross-effect case study by adopting the validated model in Part IV: Validation of the experimental framework.
The first studied stimuli consist of varying the **indoor thermal environment**.
What is the reason for selecting thermal variations? The response lies in the fact that field studies have been ongoing for decades on the thermal experience of indoor occupants. They led for example, to the development of Fanger's theory [164] and the later adaptive hypothesis [165]. Occupants' response to indoor air temperature changes was investigated in terms of comfort, behaviour, and physiological responses (e.g., Ref [16,166,167]). Such traditional thermal comfort studies showed common research methods (e.g., controlled environmental conditions in labs or climatic chambers, types of collected data) suitable to be translated into IVE experiments. Cross-modal effects of thermal conditions on visual or acoustic responses were also analysed (e.g., Ref [168–170]) with unclear outputs [171].
As highlighted in Part II: Human dimension research in buildings: Immersive Virtual Reality applications in the fields of work efficiency, comfort and adaptive behaviour, IVE-based experiments have been

[4] This section is based on A. Latini, et al. 2023 "Development and application of an experimental framework for the use of virtual reality to assess building users' productivity", Journal of Building Engineering, 70: 106280

effectively carried out to study primarily the influence of visual domain and indoor layout variations on individuals. Moreover, a limited assessment of thermal adaptive behaviour was highlighted. A possible explanation relies on the simplicity of modifying the visual dimension via virtual settings.
Nevertheless, recently, the idea to combine controlled environments for thermal state studies and virtual environments emerged and allows participants to experience the so-called mixed IVE (m-IVE) [41].
A limited number of studies (see Part II: Human dimension research in buildings: Immersive Virtual Reality applications in the fields of work efficiency, comfort and adaptive behaviour) attempted the validation of VR in the thermal domain [52–54]. In addition, a few multi-domain VR-standalone studies investigated individuals' responses by combining thermal and visual stimuli [68,69] and a few cross-modal experiments considered the effect of thermal conditions on visual comfort [69,92]. Crucial issues on experimental protocols to investigate IVE potentials were not fully addressed which led to inhomogeneous results (e.g., not fully comparable methods) [41]. To clarify the nature of the human-stimuli interaction, new research is required to provide the effectiveness of the proposed framework and develop experimental data to support these theories in this domain.

Hence, in this study, two typical indoor winter discomfort scenarios were set up: high (24°C) and low (16°C) indoor air temperatures. 52 volunteers were recruited to perform the three cognitive tests (Stroop test, OSPAN test, Magnitude-Parity test) and answer questionnaires. By using the thermal environment as a within-subject factor, the same participant was exposed to both the controlled variations while the surrounding office space was held constant.
The overall methodological approach to demonstrate the applicability of the framework in the presence of thermal variations is presented in Figure V - 1. Despite the model was already validated, since the participants' sample was different, the ecological validity was analysed. The results of cognitive tests, thermal and visual comfort ratings, and behaviour were compared between the two tested conditions and with the findings of previous literature to make general conclusions. If statistical differences in the outcomes of the independent variables and some cause-effect relationships are detected, then, the criterion validity of the virtual model in addressing the effects of thermal variation could be established.
The rest of the chapter is structured as follows: paragraph 5.1.2 summarises the research methodology, paragraph 5.1.3 covers the dataset analysis, the presentation and discussion of the results, and paragraph 0 reports the conclusions and future research perspectives.

1 Thermal stimuli and the virtual environment

▶ **Hot Virtual Environment** (H_{IVE})	Selection of a winter discomfort scenario with high indoor air temperature (24°C)
▶ **Cold Virtual Environment** (C_{IVE})	Selection of a winter discomfort scenario with low indoor air temperature (16°C)

2 Investigation on users' response to varying thermal environment in a mixed-IVE

▶ **Reported presence and immersivity**	evaluation of perceived presence in the IVE
▶ **Reported cybersickness**	evaluation of perceived sickness after using VR headset
▶ **Perceptual accuracy**	evaluation of perception in H_{IVE} and C_{IVE} (thermal comfort, visual comfort)
▶ **Behavioural accuracy**	evaluation of adaptive behavioural strategies in H_{IVE} and C_{IVE}
▶ **Task accuracy**	evaluation of accuracy in H_{IVE} and C_{IVE} across three cognitive tests

Figure V - 1 Chapter I: Illustration of the methodological approach in the study presented in Part V – Chapter I to demonstrate the potential of applying the developed framework and the validated model to a cross-modal effect experiment (thermal stimulus)

5.1.2. Experimental design

A group of volunteers were recruited to perform three productivity tests and answer questionnaires about thermal comfort, visual comfort, sense of presence and immersivity cybersickness disorders. Occupant-building system intention of interactions was also recorded.

In particular, using G*Power software [158], a minimum of 34 participants was estimated to detect a medium effect size (Cohen's d = 0.5) with a probability of 80% and confidence of 95%. To address potential data loss, 52 participants were recruited, thus, achieving 94% statistical power.
The sample was randomly divided into two balanced groups in terms of age and gender, with one group being tested at the lower temperature followed by the higher ones, and vice versa for the other group (24°C and then 16°C). Thus, there was no systematic bias in how participants were assigned to the groups, and also the groups the participants were in during experimentation were hidden. Moreover, there was one week between trials for each subject to support internal validity. As a result, any external effects on the two temperature conditions were evenly distributed.
Before the execution of the official trials, researchers carried out a pilot study with few participants to screen and overcome any problems (e.g., models, surveys, procedures), then achieved the face validity of the present study. Indeed, a newer script was added to the virtual model to go easily and sequentially back and forth between the scenes, minimising the interactions with the operators, some of the survey questions were modified, and in others, their number was reduced.
The experiments took place as presented in Figure V - 2 and followed the prescription established by the experimental framework (Part III: Definition of an experimental framework for IVR applications).
After the arrival of the volunteers, a pre-experimental phase (15 min) was carried out, to allow the adaptation to the environmental climatic conditions [172]. Meanwhile, the participants received information about the test procedure, read and signed a consent form and completed the pre-experimental questionnaire. Then, the operative phase began. After putting on the VR equipment and properly setting up the interpupillary distance, the subjects were asked to rest with their eyes closed for 30s and to adapt to the virtual scene for 3 min before the execution of the three cognitive tests (3min). Finally, subjects answered a sequence of questions (2min). The answers were given verbally and recorded by the researchers. To balance the fatigue level and IVE exposure of the subjects, each test session lasted about 25 minutes.

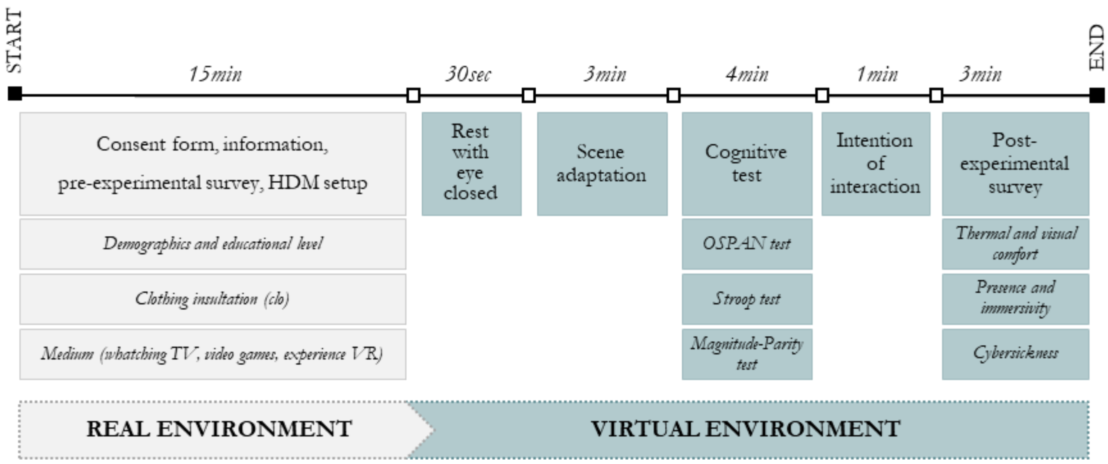

Figure V - 2 Chapter I: Experimental schedule

Each test was performed twice under different thermal stimuli (hot and cold air temperatures). Hence, the related experimental sessions were carried out by setting up two rooms with different indoor air temperatures, respectively, one inside the Building Science & Technology Laboratory (BS&T Lab) and the other inside the Department of Engineering, Civil, Construction and Architecture (DICEA) of the Università Politecnica delle Marche (Ancona, Italy). Both rooms were equipped with a computer station managed by the researcher to carry out the tests, and the equipment for the IVE visualisation.
The indoor air temperature, relative humidity and air velocity were recorded by several probes (temperature range: -40° - +125°C, accuracy ±0.3°C; relative humidity range: 0 – 100 %RH, accuracy ± 2%RH, air velocity range: 0.1 – 5 m/s, accuracy ± 0.2/0.3 m/s). The sensors were arranged on a tripod immediately behind the seated participants while performing the test (Figure V - 3) and were used to collect data at different heights corresponding to the common position of feet (0.10m), waist (0.60m) and head (1.10m). The average values during the cooler test session were 15.84°C (SD = 0.90), 50.36 % RH and 24.45°C (SD = 0.37), 32.43 %RH, in the warmer one. On average the air velocity has a constant value of 0.03 m/s in both temperature conditions.

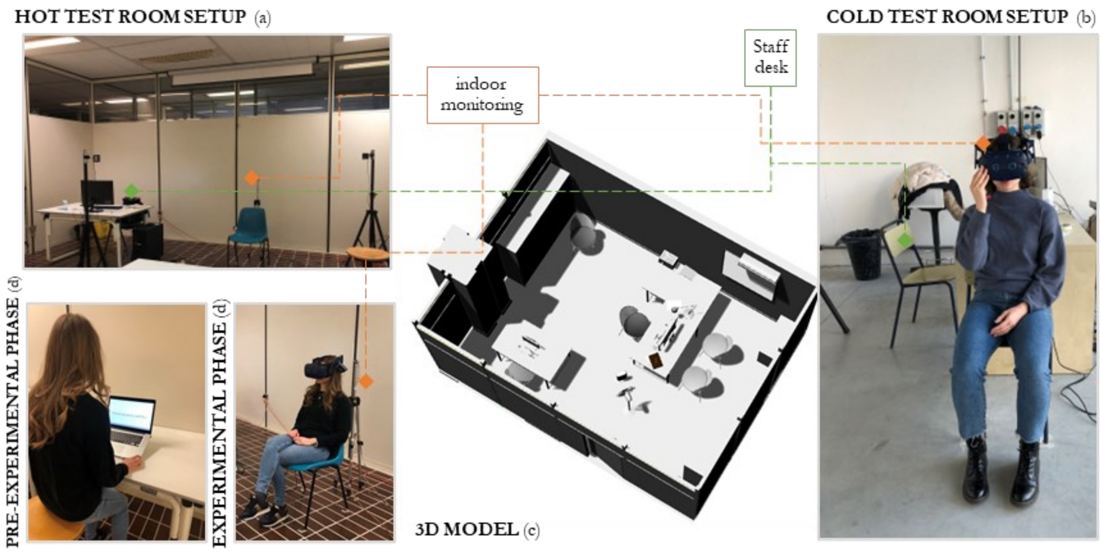

Figure V - 3 Chapter I: Chapter I: (a) Hot test room setup; (b) Cold test room setup; (c) the 3D model of the office room; (d) A subject during the experiment

5.1.3. Results and discussion

The dataset was analysed according to two objectives: the ecological validity of the model and the influence of the thermal condition on individuals' response to demonstrate that VR could adequately reflect the thermal state deriving from in situ stimuli (criterion validity).

5.1.3.1. Sample analysis

The sample consisted of 52 participants (26 male, and 26 females) and it was mostly composed of young people as follows: 29% between 20 and 25 years old (μ = 22.6; SD =4.55), 44% between 26 and 30 (μ = 27.92; SD = 7.10), 21% between 31 and 39 (μ = 33.1; SD = 2.12) and only the 6% over 50 years old (μ = 54.33; SD =2.08). Most of the subjects had already graduated from university (58%), 23% were selected among university students and 17% had a higher educational level (PhD, graduate school). In particular, the majority of them (73%) reported doing sedentary activities every working day.

52% of the participants had eyesight problems, such as myopia and astigmatism, and all of them wore corrective lenses during the tests, thus not affecting the test performance or the model visualisation.

Moreover, to understand whether participants' experience within the IVE might be affected by other variables besides the sense of presence and immersivity and cybersickness, the authors focused on the mediums. In particular, the analysis revealed that: only 58% and 19% of the subjects watch television and play video games from "often" to "every day"; 62% had at least one previous experience with virtual reality. Data were collected for two weeks in December 2021. Thus, participants wore typical winter garments with about 0.82 clo and 0.81 clo values, in the warmer and colder temperature conditions, respectively. The distributions of participants' clothing insulation values are presented in Figure V - 4: the box and the mean values highlight the correspondence between the two conditions in terms of garments worn.

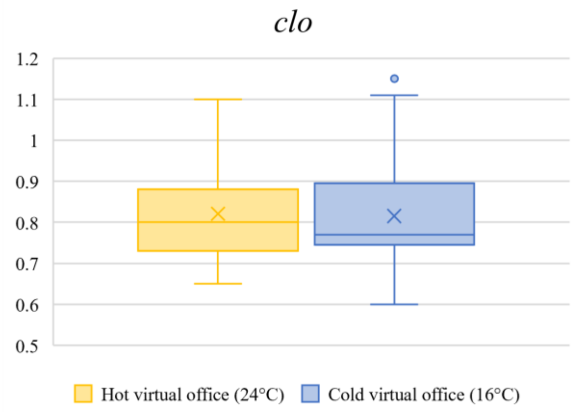

Figure V - 4 Chapter I: *clo* values within the two experimental conditions

5.1.3.2. Ecological validity

According to the first objective of this study, the self-reports from participants concerning the sense of presence and immersivity and cybersickness disorders were analysed.

Generally, the higher the values of the indicators Graphical Satisfaction (GS), Spatial Presence (SP), Involvement (INV), and Experienced Realism (REAL), the higher the sense of presence and immersivity of the participants within the IVE. The scores from the four indicators were compared with the ones from the previous studies [61–63,73]. According to Table V - 1, the scores in this study were generally higher than a moderate level (i.e. 4) on a five-point scale ranging from 1 to 5. The mean scores are reported in relevance order, as follows: graphic satisfaction (GS = 4.63), experienced realism (REAL = 4.55), spatial presence (SP = 4.23) and involvement (INV = 4.22). Moreover, the values are higher than those in the four previous studies. In particular, a very good sense of presence was obtained as the mean value for SP is 4.23 which is higher than [62] (3.74) and [61] (3.68) and almost similar to [73] (4.24). As the difference is negligible, this study developed a VE that offered an excellent sense of presence and immersivity.

		Year	*GS*	*SP*	*INV*	*REAL*
This study		2022	4.63	4.23*	4.22	4.55
Previous studies	[63]	2019	3.65	3.39	3.23	2.73
	[62]	2019	-	3.74	-	3.21
	[61]	2019	-	3.68	-	3.75
	[73]	2020	-	4.24*	4.11	3.54

Table V - 1 Chapter I: Comparison of scores on a 5-point scale of the Slater-Usoh-Steed and Igroup Presence Questionnaires for the four factors investigated: graphic appreciation (SP), spatial presence (SP), involvement (INV), realism (REAL)

Then, the authors analyse the relationship between the *mediums* and the ratings of the most significant indicators for the sense of presence and immersivity: spatial presence (SP) and realism (REAL). Somers' delta (d) was computed to analyse the association between the dependent variable (IPQ grades) and the independent variable (medium). The analysis revealed a low agreement concerning SP ($d_{\text{video games}} = 0.02$, $d_{\text{VR}} = 0.12$), and a low discordance concerning REAL ($d_{\text{video games}} = -0.001$, $d_{\text{VR}} = -0.14$). This result is in contrast with the baseline study [39] where it was found that subject gamers perceived the virtual environment as more realistic and similar to a real environment than non-gamers. However, based on the findings of the present study, the absence of a relationship between SP, REAL and the mediums seems to highlight that a high sense of presence (SP) and realism (REAL) could be achieved regardless of the level of familiarity with video games and virtual environments.

Finally, concerning VRSQ results (Figure V - 5), the qualitative analysis of the cybersickness symptoms revealed that no subject suffered from vertigo since the test was carried out in static conditions, thus, without any difference between perceived and experienced movement. Other symptoms, such as general discomfort, fatigue and headaches, were negligible since the majority of the subjects (between 96% and 100%) assigned a score of «not at all» and «slightly». Moreover, only 7% of them reported at least «moderate» eye fatigue and 23% «difficulty in focusing» due to slightly blurred images presented by the head-mounted display.

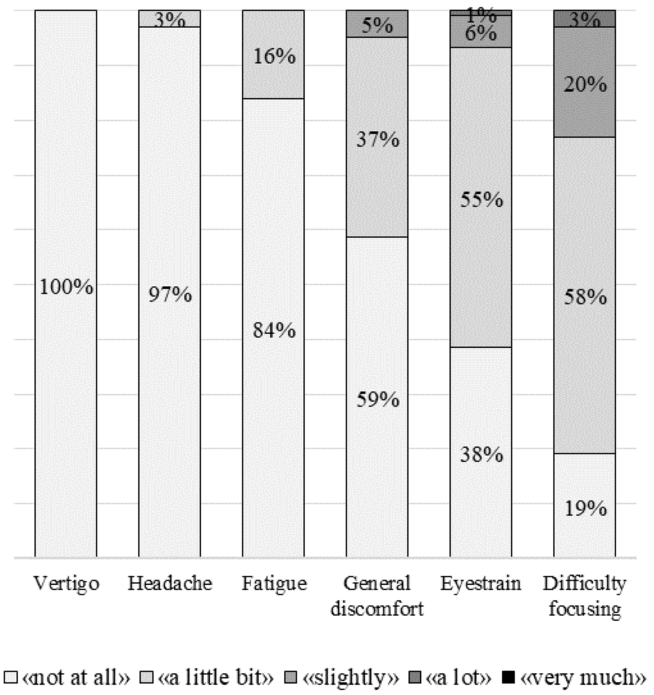

Figure V - 5 Chapter I: Cyberisickness ratings

5.1.3.3. *Temperature effect on thermal and visual comfort*

The second objective of this study (criterion validity) focused on the effect of the two temperature set-points on thermal (Thermal Sensation Vote, Thermal Comfort Vote, Thermal Preference Vote) and visual comfort (Visual Sensation Vote, Visual Comfort Vote, Visual Preference Vote). Thus, this study evaluated both a same-modality effect (thermal domain – thermal response) and a cross-modal effect (thermal domain and visual response).

Figure V - 6 shows the subjective ratings on the left-hand side for the thermal votes and on the right-hand side for the visual votes. Within each temperature level, the plots represent participants' percentage of votes.

As expected, the temperature has a significant influence on TSV: at 16°C, 84% of the subjects felt at least «slightly cold» and «cold», while at 24°C, 90% felt «slightly warm» and «warm». As a consequence, both thermal conditions were evaluated as not fully comfortable (from «slightly uncomfortable» to «uncomfortable»), by 52%-60% of the subjects. Thus, according to the TPV, at 16°C the majority (87%) of the subjects would have wanted to feel at least «slightly warmer» in the cooler conditions, while 77% would have preferred a «slightly cooler» within the warmer environmental condition. To support the previous assumptions, a statistical analysis was carried out on the ordinal data using the non-parametric Wilcoxon signed-rank test. The null hypothesis stated that there was no difference in terms of thermal comfort votes ($\mu_\Delta = 0$). Because the sample data produced T values lower than the critical values in two out (TSV, TPV) of the three cases, the authors concluded that there was a significant difference (p-value < 0.00001). On the other side, there was no significant difference in TCV (p-value > 0.05). These results are not surprising. Indeed, the qualitative analysis suggested that the tested thermal conditions were discovered to be almost equally uncomfortable because both temperatures were ±4°C away from the winter thermal comfort temperature (20°C).

Then, the same methodological approach was used to analyse visual comfort. The qualitative analysis reveals a congruence in VSV for both temperature set points. Indeed, between 60 and 79% of the subjects evaluated the correlated colour temperature of the lighting between «neutral» and «slightly cool». Interestingly, the researchers noted that, while filling out the surveys in the IVE, the participants focused on the virtual ambient light by a quick check looking away from the computer monitor. They focused more on the light colour of the work lamp (4000K, cool white light) than on the colour of the LED

ceiling lighting (warm white light). This supports the effectiveness and suitability of administrating questionnaires integrated into the virtual model. The same agreement was discovered also for the VCV parameter: most of the subjects (75%-81%) felt comfortable.
As a result, between 58% and 69% of them would have not changed their visual condition. Therefore, the qualitative analysis does not reveal a significant influence of temperature on visual comfort, thus, supporting previous literature studies in both IVEs [53,69] and real settings [170]. This hypothesis is supported by the statistical analysis (Wilcoxon signed-rank test) for all three visual parameters (p-value > 0.05) (see Table V - 2).

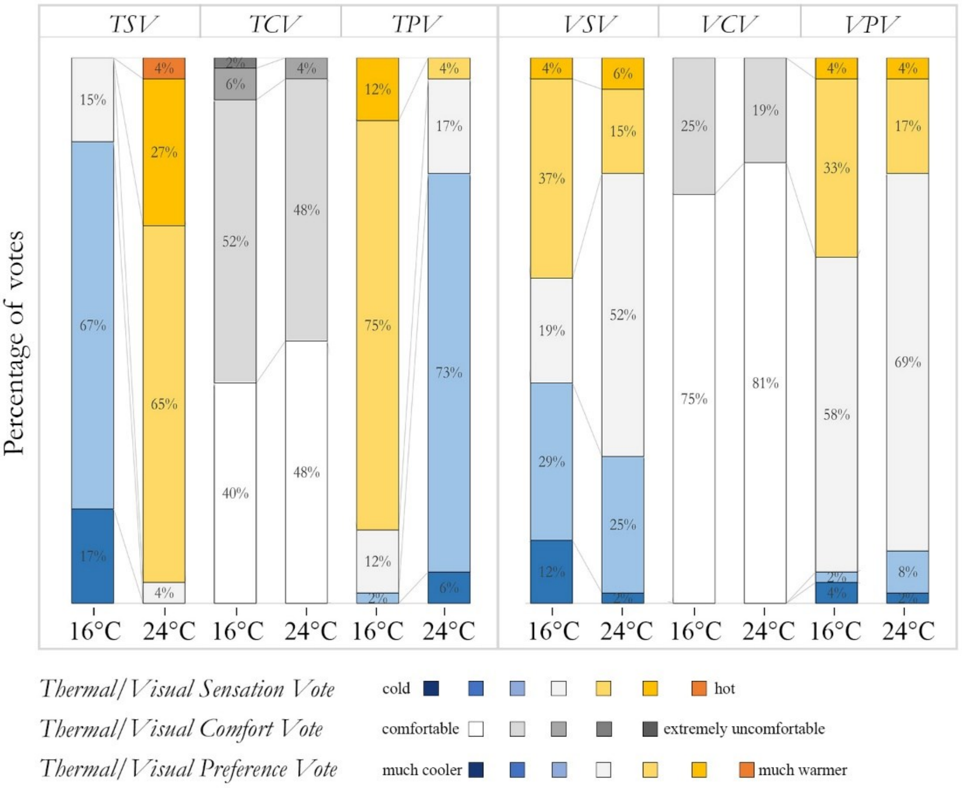

Figure V - 6 Chapter I: Thermal and visual comfort percentage of votes vote within the two experimental conditions (16 - 24°C)

	Parameter	T-value	T-critic	p-value	$\Delta\mu$ 16-24
Thermal comfort	TSV	0	434	<0.00001	-2.29
	TCV	130	116	0.97	0.23
	TPV	43	361	<0.00001	0.05
Visual comfort	VSV	271.5	170	0.87	-0.05
	VCV	78.5	10	0.42	0.05
	VPV	110	46	0.70	0.17

Table V - 2 Chapter I: The results of the Wilcoxon signed-ranks test on the thermal and visual comfort

5.1.3.4. Temperature effect on adaptive behaviour

To investigate adaptive strategies for improving well-being within the indoor environment, the authors analysed participants' intention of interaction with typical thermal environment control systems (heater, fan, window, air conditioning). The analysis evaluated the number, order and type of interaction intentionality within both temperature set points. Generally, a maximum of one intention per participant was recorded in both thermal conditions: at least 77% of participants would have modified their thermal condition by interacting with one of the highlighted components. This result agrees with the TPV scores.

The Wilcoxon test also confirmed that there was no significant difference in the number of interactions for both temperature set-points (p-value$_{16\text{-}24}$ = 0.68, T-value = 76, T-critic (18) = 40). Since only one interaction intention per subject was detected, it was not possible to study their order.
Moreover, the authors compared the types of interactions. The qualitative analysis in Figure V - 7 showed a difference between the two thermal conditions: opening the window (65%) and turning on the heater (58%) were found to be the best strategies that the subjects would use to improve their thermal sensation in the higher temperature environment, to decrease the indoor temperature and enhance air change, and in the lower temperature environment, respectively. The significant differences across the type of interaction were also confirmed by the Wilcoxon signed-rank test, which generated a p-value< 0.00001 (T-value = 181, T-critic (49) = 416).

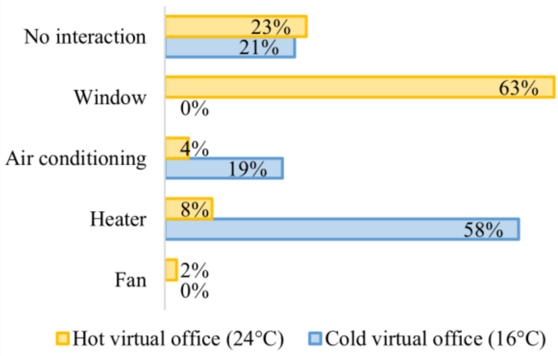

Figure V - 7 Chapter I: Comparison of the intention of interaction within the two temperature conditions

5.1.3.5. Temperature effect on work-efficiency

The data from the three cognitive tests are assumed to be normal because they belong to a ratio scale distribution and the sample size is greater than 30 (n=52), thus, the qualitative hypotheses were tested with parametric statistical analysis on a dependent-measure research design.
The Magnitude-Parity test results were analysed by calculating the number of times the subject wrongly classified the digits even/odd and greater/lower than “5”. The analysis of the mean and standard deviations revealed no difference between the errors between the two thermal conditions: mean$_{16°C}$ = 0.58 (dev.st = 1.02), mean$_{24°C}$ = 0.40 (dev.st = 0.60). The outcomes of the t-test allowed not to reject the null hypothesis (no difference in terms of productivity, $\mu_\Delta = 0$): the t-value falls within the critical region (±2.011 for df=51, α=0.05), therefore the task-switching of the subjects was not influenced by the thermal conditions.
According to the automated OSPAN test the working memory was evaluated as follows: the number of errors in the true/false combination (mean$_{24°C}$ = 0.29, dev.st = 0.64; mean$_{16°C}$ = 0.35, dev.st$_{16°C}$ = 0.84), the correct order of the letters recalled (mean$_{24°C}$ = 4.48, dev.st = 0.98; mean$_{16°C}$ = 4.60, dev.st$_{16°C}$ = 0.91), and the OSPAN score, i.e. the sum of the number of the right true/false and the letters correctly reported (mean$_{24°C}$ = 9.33, dev.st = 1.08; mean$_{16°C}$ = 9.33, dev.st$_{16°C}$ = 1.40). The mean and standard deviation values, following the statistical analysis, revealed the absence of statically significant difference (p-value > 0.05) also for the OSPAN test.
For the Stroop test, the number of errors in the colour recall, and the time in seconds participants took to pronounce all 32 colours (speed of execution) were measured. The qualitative analysis revealed approximately double the error in the warmer thermal condition (mean$_{24°C}$ = 0.31, dev.st$_{24°C}$ = 0.94), compared to the cooler one (mean$_{16°C}$ = 0.15, dev.st$_{16°C}$ = 0.46). Despite this, the t-test did not reveal any statistically significant differences in the inhibition function between them. The same result was found in the speed of execution (mean$_{24°C}$ = 28.85, dev.st = 5.49; mean$_{16°C}$ = 29.71, dev.st$_{16°C}$ = 6.98), as confirmed by the t-test.
In conclusion, based on the outcome of the qualitative and statistical analyses (see Table V - 3), no influence of temperate on the subjects’ executive functions was detected.

Cognitive function test	Parameter	t-value	p-value	$\Delta\mu_{16\text{-}24}$
Magnitude-Parity	number of errors in the classification of the digits even/odd and greater/lower than “5”	+1.46	0.15	0.17

OSPAN	the number of errors in the true/false string	0.28	0.78	0.02
	the correct order of the letters recalled	0.09	0.93	0.02
	OSPAN score (the sum of the number of the right true/false and the letters correctly reported)	0	1	0
Stroop	number of errors in the colour recall	-1.01	0.31	-0.15
	speed of execution	0.99	0.33	0.86

Table V - 3 Chapter I: The results of the paired-sample t-test on productivity within the three cognitive tests

5.1.4. Concluding remarks

In this experimental study, the developed framework was applied in a step-by-step procedure as a first attempt to demonstrate the potential of using VR to investigate the influence of indoor environment characteristics on users.

In particular, the effect of two indoor air temperatures (hot - 24°C and cold - 16°C) on users' comfort, work efficiency and adaptive behaviour was evaluated. The data were analysed according to two objectives: the external-ecological validity of the model created and the evaluation of the effect of the independent variable (temperature set-point) on the dependent variables (interactions, thermal and visual comfort, productivity). The main results of the case study are:

- The analysis and the comparison of the four indicators (graphical satisfaction, experienced realism, involvement, and spatial presence), with similar past studies, revealed that the virtual environment created an excellent level of presence and immersivity. The cybersickness analysis showed that most subjects did not report high disorder levels, except 23% who presented at least moderate «difficulty focusing» due to slightly blurred images. Moreover, the absence of a correlation with the mediums showed that, regardless of the level of familiarity with video games and other virtual environments, users can experience a high level of sense of presence and realism. As a result, these outcomes allowed the authors to support ecological validity.
- The independent variable (temperature set-point) did not influence the subjects' executive functions (task-switching, inhibition, working memory) and visual comfort. As expected it had a significant impact on thermal comfort (TSV) and the interactions with the building system. In particular, participants rated both the thermal conditions to be equally «uncomfortable» (TCV), because the set points were about ±4°C far from the winter thermal comfort temperature (20°C). Indeed, at least 77% of them would have to interact with opening the window (65%) and turning on the heater (60%), in warmer and cooler environments, respectively, thus, identified as the best feasible strategies. The reliability of these results confirms the criterion validity of the IVE.

The application of the framework and the validated model to this experimental activity demonstrated the potential of IVE in replicating the thermal state of participants. This was the initial step in demonstrating that the proposed framework enables the development of an effective and efficient testing procedure to apply VR in further analysis and deliver valid and generalisable results. This result enhances the possibility of strengthening and facilitating research about human comfort through multi-domain and cross-effect analyses carried out in virtual environments by varying other stimuli.

5.2. Chapter II: Identifying the effect of indoor noise through Acoustic Virtual Reality[5]

5.2.1 Background and aim

The second studied stimuli to illustrate the applicability of the developed framework and the validated model while overcoming the literature gaps, consist of varying the **indoor acoustical environment** in a VR crossed-effect study.

Office environments are becoming smarter in terms of lighting dimmer tools, and mainly indoor thermal devices, such as air conditioners, fans, heaters, and ventilation systems, which are the most commonly used ones and significantly account for noise. However, light and thermal conditions can be adjusted and adapted to users, while noise is not under control and then more difficult to change and modulate according to subjective preferences. Recently, increased indoor noise levels have become a relevant issue since noise pollution harms users' productivity causing unwanted distractions, stress and dissatisfaction within the office environment [20,25,168,173]. Indeed, a 66% drop in performance is accounted for when employees are exposed to distracting noise from internal or external sources [25] and 99% of people reported that office sound damages concentration [25]. As a result, there is widespread interest in studying how the office acoustic environment influences work efficiency, mainly focusing on sound source type, sound pressure level, and reverberation time [174]. In recent years, many researchers investigated this topic. Findings show that noise from internal sound sources, such as background speech, ventilation and air conditioning equipment, unanswered phones, typewriters, keyboards, computers, and other office machinery [20,95,173,174], can significantly disrupt employees' cognitive performance [20,25,173–176]. As a consequence, sound and acoustic strategies should have a vital priority in office design to achieve a high degree of occupant comfort and work efficiency.
In addition, the cross-relationship between individuals and acoustical factors should be refined to clarify not only the individual influence of each factor alone but also their interaction. A recent literature review [177], highlighted few attempts in traditional studies to study the crossed-effect between sound level upon thermal or visual perception. In particular, the outcomes highlighted a strong cross-relationship between sound level and thermal perception even if the number of studies was limited (9/29).

In this research context, the use of IVEs is limited to designing a space «visually» optimising the sight sense. To reach a high level of realism and immersivity it is necessary to improve also the sense of hearing with valid and proper acoustics. Several sets of indoor spaces can be modelled and experienced via audio and video using the head-mounted display [95]. Thus, a growing interest in generating immersive sound simulations to study the effect of building acoustics on individuals has recently been enhanced. However, to the authors' knowledge, a few limited studies investigated the influence of the noise factor using virtual environments, by considering only a single cognitive function at a time in combined-effect studies of visual and acoustical domains on individuals' perception [93,95–97]. Hence, research focusing on the evaluation of the cross-effect of acoustic virtual reality on multiple visual cognitive functions and cross-modal comfort is lacking, and it is a new topic in virtual reality research.

By these findings, in the present experimental study (summary in Figure V - 8), the impact of virtual sounds on thermal comfort is tested within a temperature-controlled IVE. The aim was to evaluate the effectiveness of the modelled Acoustic Virtual Reality (AVR) in terms of sense presence and immersivity, and cybersickness ratings (ecological validity), and to detect the influence of the acoustic environment on users' cognitive performance, and thermal comfort (criterion validity). In particular, a no-ambient-noise condition, or «quiet environment», was chosen as the reference for acoustic comparison with the noise condition, or «noisy environment». Five representative sound sources (phone rings, machine noise, mechanical systems, human-based sounds and acoustical effects) were selected as the sound samples of typical office noises to generate a binaural soundtrack. A multitask cognition experiment (working memory, inhibition, task switching (ASHRAE Standard, 2019) and surveys were carried out in a virtual office environment to measure the work efficiency and comfort of 104 participants under different acoustic conditions.

[5] This section is based on A. Latini, et al. 2023 "Crossed Effect of Acoustics on Thermal Comfort and Productivity in Workplaces: A Case Study in Virtual Reality", Journal of Architectural Engineering 29(2): 04023009

1 Acoustical stimuli in the virtual environment

▶ **Noise Virtual Environment** (N_{IVE}) — selection, recording and measurement of five disrupting sound sources (phone rings, machine noise, mechanical systems, human-based sounds)

▶ **Quite Virtual Environment** (Q_{IVE}) — selection, recording and measurement of non disrupting sound sources (mechanical systems)

2 Identifying the effect of indoor noise through Acoustic Virtual Reality

▶ **Reported presence and immersivity** — evaluation of perceived presence in the IVE

▶ **Reported cybersickness** — evaluation of perceived sickness after using VR headset

▶ **Task accuracy** — evaluation of accuracy in Q_{IVE} and N_{IVE} across three cognitive tests

▶ **Perceptual accuracy** — evaluation of perception in Q_{IVE} and N_{IVE} (sound distinction, acoustical comfort)

Figure V - 8 Chapter II: Illustration of the methodological approach in the study presented in Part V – Chapter II to demonstrate the potential of applying the developed framework and the validated model to a cross-modal effect experiment (acoustical stimulus)

5.2.2 Experimental design

In this study, the experiments were conducted in the test room described in section 4.2. The study took place from December 2021 to April 2022. Experiments were not performed continuously due to the subjects' availability.

104 participants performed the three productivity tests (section 3.3.1) and answered questionnaires. An independent measure experimental design was employed, thus, the subjects were randomly divided into 2 groups composed of 52 subjects each and were immersed in the same virtual office environment described in section 4.3. The indoor temperature was constant at 24.45 °C ± 0.48 and it was collected continuously at 1-s intervals (temperature range: from -40° to +125°C and accuracy ±0.3°C).

Participants took part in one test session experiencing the same thermal condition, but they were randomly assigned to a no-ambient-noise condition, or «quiet environment» (group 1) or a noise condition, or «noisy environment» (group 2) session.

The sound stimulus for the «noisy environment» was generated based on field measurement. In particular, five representative sound sources were selected as sound samples due to the disrupting effect on employees' cognitive performance [20,95,173,174]: phone rings, machine noise of a laptop and a copier, mechanical systems, human-based sounds and acoustical effects of the closing door, paper and pens.

At first, the reverberation time of the virtual room was calculated (Figure V - 9) according to UNI EN 12354-6:2006 [179] considering the characteristics of the real environment (localisation, background noise, geometry) and its materials (acoustic absorption). The room does not have acoustic treatment: the walls are plastered, the floor is tiled, the ceiling is flat, and there is wooden and plastic furniture inside. The room is located in a suburban area of the city, away from traffic lines and at the back of the building with an external ambient noise level between 40 and 50 dB(A) during the daytime period. The room geometry was described in section 4.2.

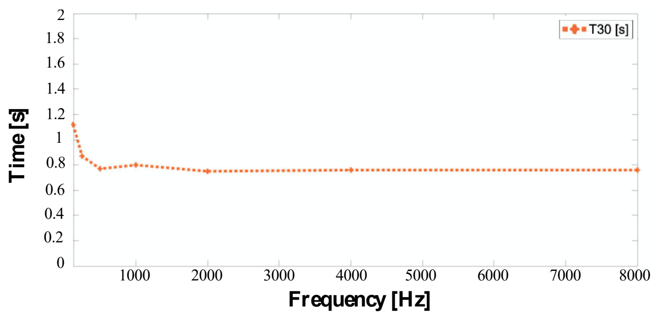

Figure V - 9 Chapter II: Calculated reverberation time value in the octave bands 125-8000 Hz

Secondly, a portable recorder (Zoom Hn4) and binaural microphone and headphones (CS 10-EM Roland, 24-bit/96 kHz recordings high-resolution audio) were used to collect audio recordings and

perform measurement of the surrounding acoustics in any directions. The recordings and measurements took place in an office room located inside the university (in the absence of high reverberation), similar to the virtual office room modelled for this study. The noise recordings (Figure V - 10a) were then used to obtain the information needed for the generation of the virtual audio stimulus through Adobe Audition (Adobe, 2022) and MATLAB (MathWorks, 2022).
Secondly, the noise samples recorded were mixed into a single stereo soundtrack with a sample rate of 44100 at 16 bit/s, an average LAeq equal to 55.6 dB. The binaural soundtrack (Figure V - 10b) was provided in stereophonic WAVE format.

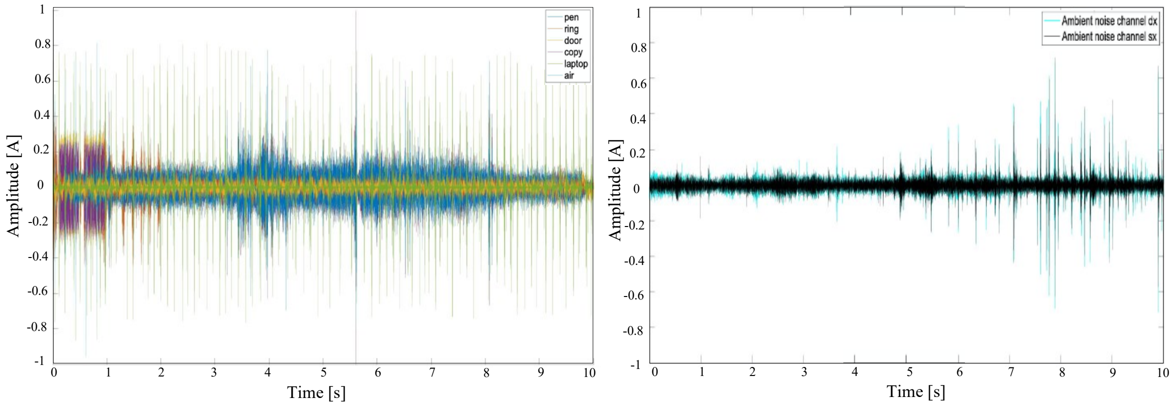

Figure V - 10 Chapter II: TimeVarying signal of the six sound sources (a), and of the binaural soundtrack (b)

Then, the psychoacoustic characteristics of the sound source were analysed in terms of loudness, sharpness, and fluctuation strength according to ISO 532-1:2017 [182], as shown in Figure V - 11, and Table V - 4 which reported the mean values. For the calculation of the psychoacoustic parameters Brüel & Kjær head and torso simulator and related software were used (BK CONNECT Type 8405-G, sound quality metrics) [183].

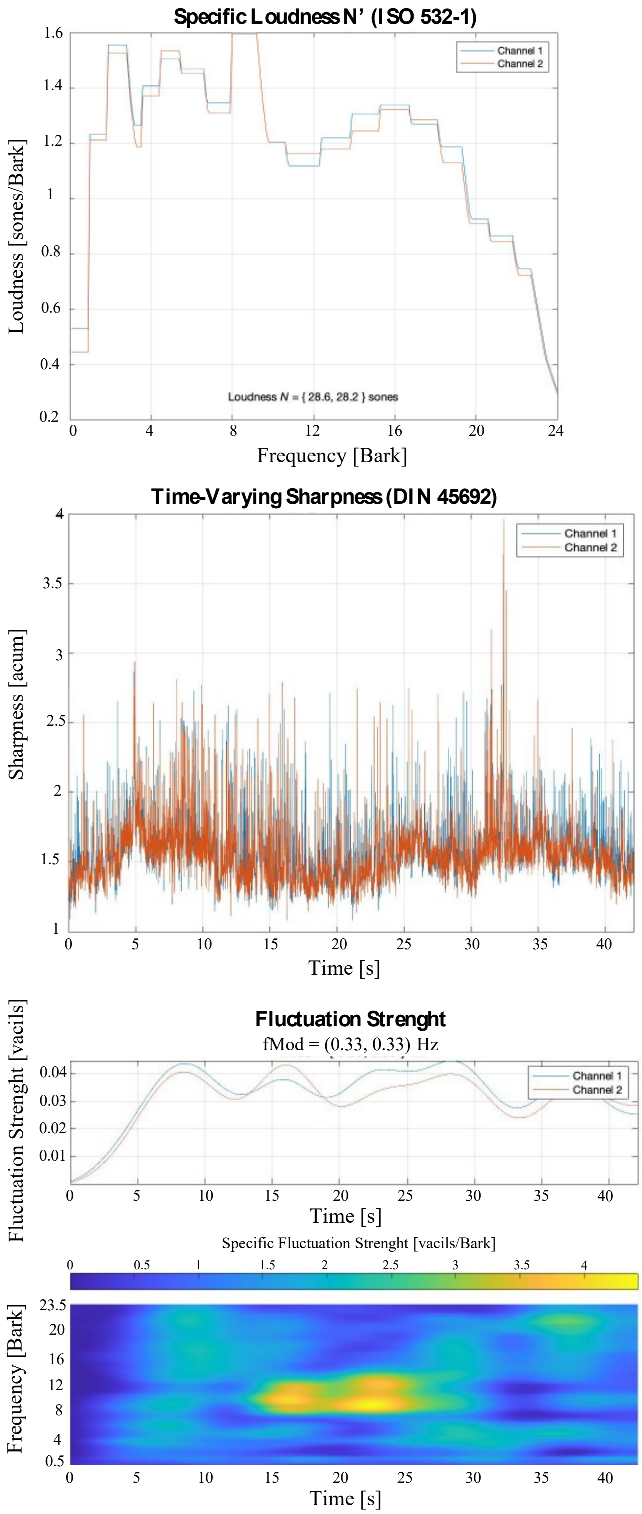

Figure V - 11 Chapter II: Results of the psychoacoustic parameters of the binaural soundtrack for each channel (Channel 1 = dx, Channel 2 = sx)

Acoustic and Psychoacoustic parameters	Channel dx	Channel sx
Sound pressure level [dBA]	54.5	54.3
Loudness [phone]	88.3	88.1
Sharpness [acum]	1.76	1.75
Fluctuation strength [vacil]	0.034	0.031

Table V - 4 Chapter II: Acoustic and Psychoacoustic mean values of the parameters calculated from the binaural recording in the office environment

One participant at a time was invited to take part in the experiment. Each experimental session lasted approximately 25 minutes (Figure V - 12) to follow the same protocol of the developed framework.
To avoid any bias in participants' responses, the specific objectives of the study were blinded: they were told that the experiment was focused on studying the effect of different indoor environmental conditions on people's work performance and comfort, without specifying which conditions. Once the pre-experimental phase ended, subjects wore and adjusted the head-mounted display and the headphones in the noisy environment. During a visual and acoustical adaptation phase, subjects were asked to rate how much they could distinguish the five sound sources and the overall quality of the virtual sound environment (pleasant, relaxing, peaceful, boring, chaotic) on a seven-point Likert scale. After that, they performed the three cognitive tests (3 minutes) and completed the post-experimental survey (2 minutes) about the sense of presence and immersivity, cybersickness and their thermal and acoustical comfort as suggested by the standards ISO 12913-2: 2018 [103] and ITU-R BS 1116-3: 2015 [104]. The specific questions are reported in section 3.3.2.

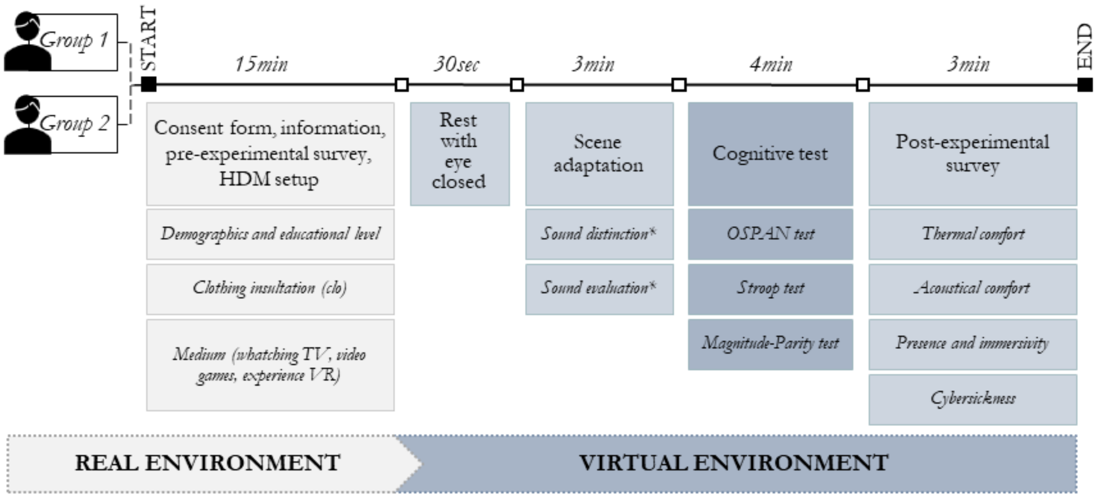

Figure V - 12 Chapter II: Experimental schedule

5.2.3 Results and discussion

The following paragraphs present the sample's data analyses and the results according to two objectives: the ecological validity of the modelled IVE, and the criterion validity by evaluating the effect of the sound stimulus on thermal comfort (crossed-effect) and work efficiency to ensure the tool provides an accurate representation of the outcomes. All datasets were analysed qualitatively, and, then, the assumptions were tested with parametric and non-parametric statistical tests for an independent-measure research design through RStudio software [156]. The significance level α was set equal to 0.05.

5.2.3.1. Participants

A total of 104 participants took part in the experiment on a voluntary base, of which 52 were male and 52 females, with a perfect gender balance. The sample size has a relevant effect on the results. Indeed, according to a power analysis carried out with the G*Power software [158], it was adequate to detect significant effects of statistical power of 0.81 and medium effect size of 0.50. The group was mostly composed of young people as follows: 48% between 20 and 25 years, 35% between 26 and 30, 21% between 31 and 39 and only 6% over 50 years old. The pre-selection process was based on the following criteria: generally healthy, full-colour vision. All of the participants had normal hearing, a normal or correct-to-normal vision not to influence the model visualisation and then the test performance: 42% of the participants reported eyesight problems (myopia and astigmatism), but all of them wore corrective lenses. Moreover, 58% experienced VR tools at least once.

5.2.3.2. Ecological validity

First, the analysis of the presence questionnaire was carried out.
Figure V - 13 shows the comparison of the four indicators average scores from the presence and immersivity survey with the ones from the previous VR-related studies [61–63,73]. All four attributes in this study (i.e. GS: 4.65; REAL: 4.51; INV: 4.29; SP: 4.18) were generally higher than a moderate level

score (i.e. 4 on a five-point scale). Thus, a relatively higher sense of presence and immersivity was detected. In particular, the mean score of the graphical satisfaction (GS), which represents how much the subject appreciated the visual model, is the highest among the four indicators, followed by experienced realism (REAL), the involvement within the IVE (INV) and the spatial presence (SP), which represents the sense of presence within a physical space. Moreover, the mean scores were generally higher than those in the four previous studies, except for the SP (4.18) which is almost similar to [73] (4.24) but the difference (0.06) was negligible. To sum up, the analysis revealed that the model offered a good sense of presence and immersivity to participants for the research objectives.
Secondly, the cybersickness ratings were analysed.
As presented in Figure V - 14, no participants reported vertigo (100%) due to the static condition of the test where participants sat in front of the virtual monitor. Other disorders, such as general discomfort, fatigue and headaches, were not significant due to 94-100% of ratings assigned to «not at all» and «slightly». However, of all the subjects, 27% claimed difficulty in focusing due to slightly blurred images presented by the head-mounted display which caused moderate eyestrain for 12% of the 104 participants.

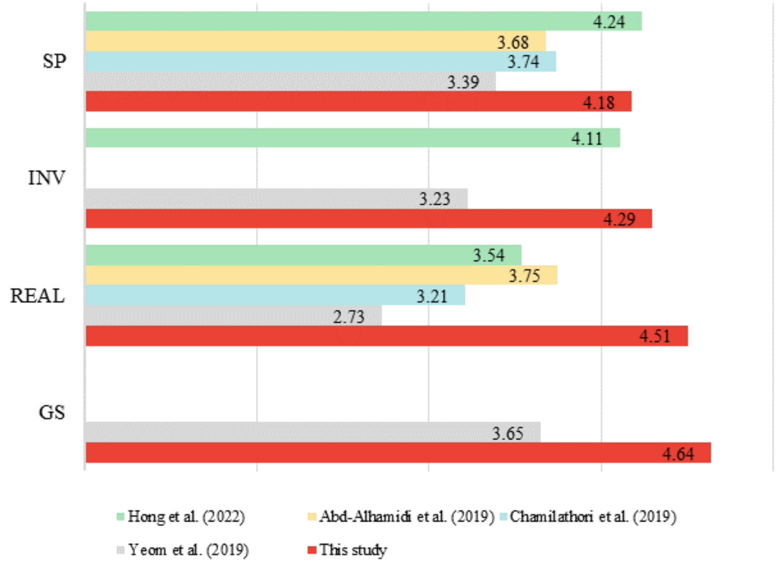

Figure V - 13 Chapter II: Comparison of scores on a five-point scale of the four indicators with previous literature (Abd-Alhamid et al., 2019; Chamilothori et al., 2019; Hong et al., 2019; Yeom et al., 2020

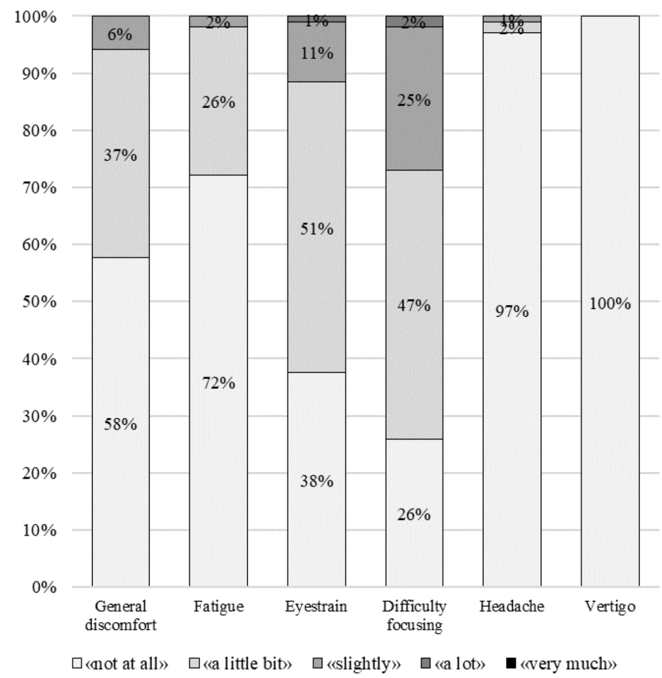

Figure V - 14 Chapter II: Results of the cybersickness disorders

5.2.3.3. Acoustical effect on work-efficiency

Concerning the Magnitude-Parity test, to examine the effects of the acoustic conditions on individuals' task-switching ability, the authors computed the digits even/odd and greater/lower than "5" were wrongly classified. Approximately, the comparison of the mean and standard deviation of the two conditions revealed double errors in the noisy environment. Then, a parametric statistical analysis was carried out, because the data constitute a ratio scale supposed to be normally distributed, due to the number of participants exceeding 30 (n=104). The result of the t-test (p-value = 0.002) confirmed the assumption: the t-value (-3.17) falls outside the critical region (±1.983 for df=103, α=0.05). Thus, a significant main effect of the virtual sound environment on subjects' task-switching was detected, with a 59% decrease in performance from the quiet to the noisy condition.

The authors calculated the number of errors and speed of execution (in seconds) in recalling the 32 colours while performing the Stroop test. A non-significant effect of acoustic on inhibition load was revealed in terms of errors, as confirmed by the t-test (t-value = 1.00, p-value = 0.00). Despite that, a 10% decrease in the velocity of pronouncing the nouns was discovered from the quiet to the noisy environment, as statistically confirmed (t-value = -2.96, p-value = 0.004).

Concerning the OSPAN test, the number of errors in the true/false strings, the correct order of the letters recalled, and the OSPAN score, which is the sum of the right true/false and letter correctly reported were calculated. A significant difference in the mean and standard deviations was detected only in the letter recalling (t-value = 7.76, p-value = 9.785e-12), and in the overall OSPAN score (t-value = 7.50, p-value = 3.867e-11). Indeed, the results indicated that the noisy condition reduced subjects' performance by 53% and 65%, respectively.

The overall results for each cognitive task and the comparison between the quiet and noisy conditions are presented in Table V - 5.

Statistics	Magnitude-Parity test		Stroop test				OSPAN test					
	Q	N	Q	N	Q	N	Q	N	Q	N	Q	N
	errors (-)		*errors (-)*		*velocity (sec)*		*errors T/F*		*order letter*		*OSPAN score*	
mean	0.40	0.98	0.31	0.31	28.85	31.97	0.15	0.33	4.48	2.71	9.33	7.38
(SD)	(0.60)	(1.16)	(0.94)	(0.78)	(5.49)	(5.24)	(0.36)	(0.62)	(0.98)	(1.32)	(1.08)	(1.52)
t-value	-3.17		0.00		-2.96		-1.74		7.77		7.50	
p-value	0.002*		1.00		0.004*		0.085		9.79e-12*		3.87e-11*	

Table V - 5 Chapter II: Results of the mean (standard deviation) and statistical analysis (*p < 0.05) of each cognitive task

Finally, the ratings of the sound distinction, the assessment of the virtual acoustical environment and the acoustic comfort were analysed. According to the participants, the most distinguishable sound sources (score «a lot» and «extremely») were, in relevant order: phone rings (96%), machine noise (58%), mechanical systems noise (17%), human-based sound sources (13%), and acoustical effects (4%) (Figure V - 15a). The majority of the participants (98%) reported the sound environment to be at least «uncomfortable», due to being mostly chaotic (96%) and boring (27%) and not at all «pleasant», «relaxing» or «calm», as expected (Figure V - 15b). All the participants expressed that personal productivity could be influenced by the acoustical environment (score «a lot» and «extremely»). Thus, the authors discovered a strong correspondence between the results of the three cognitive tasks and the self-reports about the acoustical environment assessment and the awareness of its effect on work efficiency.

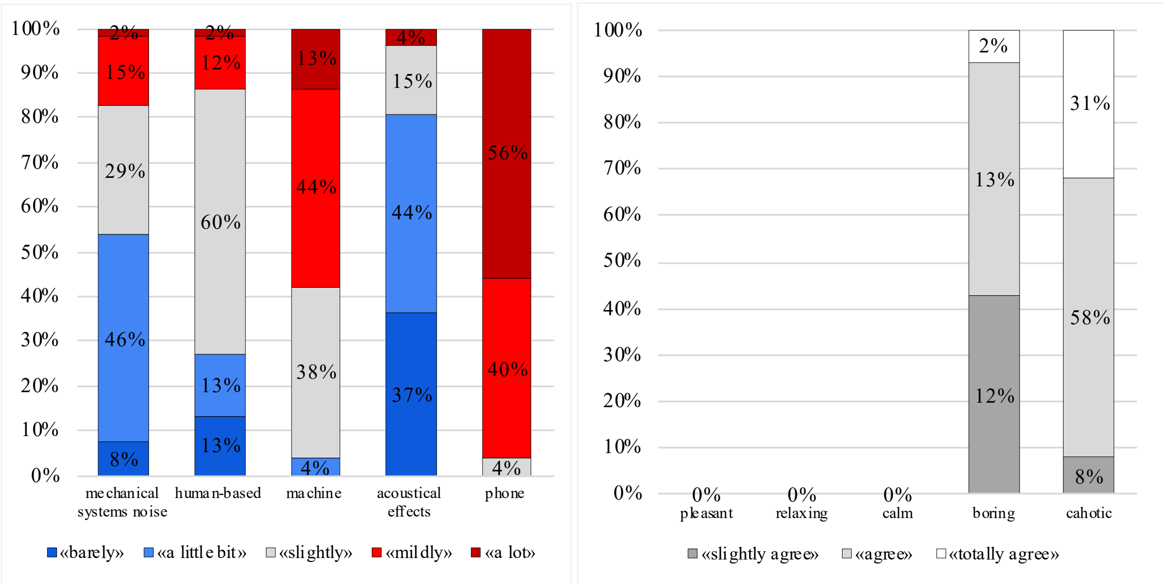

Figure V - 15 Chapter II: (a) Sound distinction and (b) sound evaluation ratings

5.2.3.4. Acoustical effect on thermal comfort

Figure V - 16 depicts the percentage of thermal sensation (TSV), comfort (TCV) and preference votes (TPV) across the different experimental conditions (quiet and noisy environments).

As a general trend, the sound condition did not affect thermal sensation and thermal preference votes. Indeed, 94% of the subjects felt from «slightly warm» to «very warm» (TSV). Thus, the majority (between 81% and 90%) would prefer to feel at least «slightly cooler» within both environments (TPV). As expected, the qualitative analysis suggested that the overall thermal environment was uncomfortable in both conditions because the temperature set-point was 4°C higher than the winter thermal comfort temperature (20°C). Surprisingly, the thermal environment was evaluated to be 44% more uncomfortable in the noisy condition compared with the quiet environment, thus, suggesting a potential cross-modal effect of the sound environment.

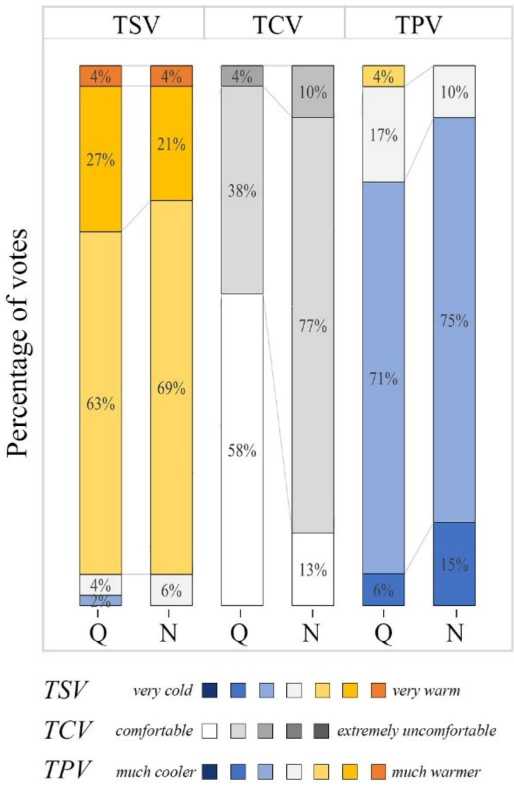

Figure V - 16 Chapter II: Thermal comfort percentage of votes within the two experimental conditions (Q: quiet, N: noise)

To support these hypotheses, the non-parametric Wilcoxon signed-rank test for two independent samples was computed on the ordinal data (Table V - 6). The null hypothesis stated that there was no difference in terms of thermal scores between the quiet and noise conditions ($\mu_{\Delta} = 0$). The sample data produced T values higher than the critical values in two out (TSV, TPV) of the three cases. Thus, the results of the preliminary qualitative analysis were confirmed: the authors concluded that there was no significant difference (p-value > 0.05) between the quiet and noise environments in terms of thermal sensation and preference. Meanwhile, it was confirmed that thermal comfort was significantly affected by the acoustical conditions (p-value < 0.05). Thus, the authors discovered an inconsistency between thermal sensation and thermal comfort, which are usually strongly linked. Indeed, it was expected to have the same correspondence between the tested conditions in TCV as for the TSV. A possible explanation could be found in the widely widespread definition of thermal comfort which states «..is that condition of mind that expresses satisfaction with the thermal environment» [184]. According to ASHRAE Handbook Fundamentals, this definition emphasises the cognitive process behind thermal comfort which involves many well-known primary factors, such as temperature, air speed, humidity, individuals' metabolism and clothing insulation, and other inputs influenced by physical, physiological, and psychological processes. As a result, the authors may expect that the disturbing noise within an environment enhances thermal discomfort. This finding supported the previous theory that changes in thermal comfort are affected by physiological aspects more than physical ones [185].

Parameter	Thermal comfort		
	TSV	TCV	TPV
T-value	148	82.5	203
T-critic (n)	89 (25)	182 (34)	65 (22)
p-value	0.69	0.00024	0.13
$\Delta\mu_{16\text{-}24}$	-0.04	0.5	-0.34

Table V - 6 Chapter II: The results of the Wilcoxon signed-ranks test on the thermal comfort: n is the sample size from the number of non-null ranks

5.2.4 Concluding remarks

A fundamental challenge in adopting VR to support human-dimension research lies in enhancing the overall realistic perception within the virtual environment integrating the "visual space" with the acoustical one. The application of the developed framework and validated model allowed the study of the effect of building acoustics on individuals since the analysis of the influence of the acoustic environment on cognitive performance and comfort via VE is still in its infancy.

The present study provides a binaural soundtrack generation integrated within an immersive virtual environment of an office room. The aim was to evaluate the effectiveness of the modelled VE (ecological validity), also in detecting the effects of the acoustics on cognitive performance, and thermal comfort (criterion validity).

In particular, five-sound sources (phone rings, machine noise, mechanical systems, human-based sounds and acoustical effects) were selected among the literature review as the most disrupting to generate the soundtrack. A total of 104 participants, divided into two balanced groups, were recruited to perform three productivity tests (working memory, inhibition, task switching) and to answer questionnaires before and after the experiment session. Each group randomly performed one test session within the virtual environment: a no-ambient-noise condition or «quiet environment» was compared to a noise condition, or «noisy environment».

The data were analysed according to two objectives: the ecological validity of the virtual model and the evaluation of the effect of the independent variable (acoustical scenario) on the dependent variables (work efficiency, thermal and acoustical comfort). The main results are:

- the VE of the present study offered an excellent level of presence and immersivity to the participants and no high disorder levels were detected. An exception is the 27% of subjects who claimed «difficulty focusing» due to slightly blurred images presented by the head-mounted display which caused moderate eyestrain (12%). However, all the subjects completed the test and the authors established the ecological validity.
- Participants' work efficiency was negatively affected by the ambient noise: a 59% decrease in performance was discovered for the task-switching, 53% for the working memory in the recalled letters task as in [20,25,93,95,96,173–176]), and an increase of the 10% in speed of execution was detected for the inhibition task. The disrupting effect of sound on performance was confirmed also by the self-reports. Indeed, participants evaluated the virtual sound environment to be chaotic, boring, and uncomfortable as a result. Moreover, the overall sample expressed that the acoustical environment could influence productivity.
- The sound condition had no impact on thermal sensation (TSV) and preference (TPV): thermal votes were the same under the quiet and noise conditions. However, a statistically significant difference was discovered concerning thermal comfort. Indeed, participants rated the thermal conditions to be 44% more «uncomfortable» (TCV) than the noise condition may be due to the psychological effect of the disturbing noise. Thus, the tool reflects the theoretical expectation about the effect of acoustics on work efficiency and comfort supporting the criterion validity of the virtual environment [115,186].

These findings highlighted the effectiveness of the proposed acoustic virtual reality to study comfort and various cognitive skills, to deliver effective user-centred design analysis and strategies. There are a lot of potentialities in this method because it provides multi-sensory 3D environments, and the audio-visual rendering is carried out within the technology itself which enhances the users' immersion.

However, future research should analyse the effect of different characteristics of the sound stimuli on the dependent variables (comfort, work efficiency). Further research activities should also integrate physiological devices to measure, for example, heart rate, blood pressure, EEG or electrodermal activity to take into account any objective deleterious effects of noise on workers' well-being and productivity and allow the development of a proper attenuation design strategy. Moreover, this study was limited to auditory senses and the combined effect with other drivers should be tested, such as other workplaces (e.g., open-plan offices) with different layouts (e.g. walls and light colours, window-to-wall ratio, view) and environmental stimuli (e.g. thermal, visual crossed with the acoustics) to further create a multi-domain study. Lastly, VR should be adopted to support a shift in perspective of workplace evaluation towards a more salutogenic and user-centred approach [2]. The aim should be to look at the positive influence of the indoor environmental conditions against the analysis of more disrupting ones (i.e., the effect of noise condition), suitable to promote users' health and well-being in buildings.

5.3 Chapter III: Exploring the impact of virtual audio-visual Biophilic Design interventions[6]

5.3.1. Background and aim

The third experimental activity to illustrate the applicability of the developed framework and the validated model consists of varying the **indoor visual and acoustical connection with nature** in a VR combined-effect study. Namely, the trigger for the stimuli choices depended on the concept that individuals' well-being and work-efficiency depend not only on the absence of environmental problems or diseases but also on the presence of attributes that can evoke positive effects on task performance and perception.

In this context, Nature-Based Solutions (NBS) are innovative and powerful approaches central to achieving the challenge of the EU strategies for 2030 aiming for sustainability, climate resilience, and increased biodiversity-rich ecosystems [187]. However, the term "Nature Based System" has been recognized as an "umbrella concept" that does not deal only with technical aspects related to climate change adaptation, which is currently the main topic of a large body of literature [188]. NBSs are key to improving individual health and well-being and address the demands for the co-existence between nature and humans within the same space. Introducing greeneries in buildings addresses the issue of less land available to build urban green infrastructure initiatives [189]. In addition, the implementation of NBSs in indoor human environments could be considered a tool capable of sustaining human life and activities over time through a commonly well-known Biophilic Design (BD) approach. As a new design paradigm, BD aspires to progress in building development in the beneficial human contact with nature to design more liveable and comfortable spaces [190].

Numerous studies have demonstrated that exposure to natural environments is associated with positive outcomes, in particular: enhanced health and well-being (e.g., anxiety and stress reduction), improved thermal comfort, positive physiological responses (e.g., decrement in skin temperature conductance, deceleration of heart rate in response to a more relaxed status), increased positive emotions and cognition (e.g., attention, memory, problem-solving, creativity) [87,191–201].

That is why, World GBC framework [202] for healthy and green offices and Green Building Rating Standards increasingly supported BD intervention in a sensorial design approach [203]. Indeed, nature's potential can be triggered by several nature-related sensory stimuli (e.g., visual, acoustical, olfactory).

Traditionally, the main attention has been directed towards the visual connection with nature (e.g., nature elements in space, natural view from windows) since vision is the primary sense that building occupants use to recognize and process environments and has a relevant influence on the perception of other senses [204].

Beyond vision, supportive office environments might be evaluated and designed considering other sensory modalities, such as acoustical stimuli. Among these factors, noise and poor acoustics are the most prominent issues in contemporary office designs [205] influencing work efficiency and overall satisfaction and representing a common dissatisfaction source. Several studies and post-occupancy evaluations dealing with the evaluation of occupants' experience of a building and the analysis of the effects of noise annoyance (e.g., Ref [205–207]) identified irrelevant speech, people on their phones, and speech privacy as the biggest challenges in workplaces. Indeed, in office design most office-related tasks require a degree of noise control to enable work efficiency and workers who are exposed to excessive

[6] This section is based on:

A. Latini, et al. 2023 "Effects of Biophilic Design intervention on university students' cognitive performance: An audio-visual experimental study in an Immersive Virtual office Environment", Building and Environment, doi: 10.1016/j.buildenv.2024.111196

A. Latini, et al. 2023 "Virtual Reality application to explore indoor soundscape and physiological responses to audio-visual Biophilic Design interventions: An experimental study in an office environment" Journal of Building Engineering

A. Latini, et al. 2023 "Using Virtual Reality to investigate the impact of greenery elements in office environments: an eye-tracking pilot-study on cognitive tasks, visual attention and distraction, Applied Ergonomics

noise or excessively low background noise levels are more likely to be unsatisfied with the environment [207].
A growing body of literature has highlighted the potential of nature sound sources, like bird songs or flowing water, on individuals' perception, stress recovery and emotional responses (e.g., Ref [208–211]). Several solutions have been suggested such as soundscape augmentation through natural sounds (which can be combined with biophilic design) to provide useful masking, improved privacy and positive affective outcomes [205,207].
The soundscape framework, as defined by the ISO 12913 series of standards and technical specifications [212], aligns perfectly with the current research trend aiming to create comfortable and healthy environments by investigating human perception of their acoustic surroundings in context. Soundscape research is focused on understanding the potential of the sound environment to generate positive impacts on people through acoustic design [213] by integrating engineering approaches with physical, social, and psychological ones [214]. The primary goal of soundscape research and practice is to leverage acoustic stimuli as a design tool, enhancing pleasant sounds while reducing or masking unpleasant ones based on how they are perceived [215]. Originally stemming from urban design and the study of outdoor environments [216,217], this approach has more recently been extended to indoor built environments, referred to as the "indoor soundscape" [218,219]. These studies encompassed various types of buildings and purposes, with a particular focus on residential spaces [213] but also including libraries [220], schools [221] and offices [93,222], among others. To comprehensively characterize people's emotional responses to their acoustic surroundings, moving beyond just assessing disturbances, perception models were developed for both outdoor [124] and indoor residential acoustic environments [123].
Despite the growing interest in the literature regarding the promotion of a connection with nature, there is a noticeable scarcity of scientific evidence substantiating the potential of such a connection through soundscapes [223].

Recent studies showed how sound and visual interaction affect perception and demonstrated that auditory perception improves when accompanied by visual cues, and vice versa sounds can improve attention to related visual elements [224,225]. Thus, a holistic approach to study the multisensory nature of human perception in indoor built environments should be adopted with increasing attention to understanding the combined visual and acoustical components and their interactions [226]. Ignoring the possible connections between sight and hearing senses could lead to ineffective design resulting in building performance issues, occupant discomfort or decreased performance [204].

The first studies on NBS implemented indoors were carried out in real physical contexts, such as test rooms or lab settings integrated with real green elements (e.g., [227,228]), resulting in time and cost-consuming research activities, depending on the complexity and scale of experiments.
That is why, the advent of technological improvements, the development of more efficient devices for human-computer interactions have led to the diffusion of Virtual Reality to study the effects of changes in environmental conditions creating realistic experiences with visual and acoustical reproduction.
BD-based studies in indoor VR environments are still limited, mainly focused on stress and anxiety levels reduction [81–83,87], self-emotion assessment [57,79,84], thermal state [87], single [57] or multiple cognitive tests [56,85], thus, rarely including a comprehensive evaluation of work efficiency potentials.
According to the "14 Patterns of Biophilic Design" [229], BD can be organized into three categories: Nature in the Space, Natural Analogues, and Nature of the Space. A significant body of studies carried out in VR has shown the benefits mainly deriving from «Visual Connection with Nature» occurring indoors (e.g., nature elements in space) [56,57,81–87,230], «Prospect» (e.g., natural view from windows) [79,81,82,86] and «Material Connection with Nature» [81,86]. Few studies carried out a combination of the above-mentioned patterns [81,82,86].
Some recent investigations have already used VR techniques on the perceptual evaluation of greenery to detect the potential of combined sound and visual connection with nature. However, they are mainly focused on urban environments (e.g., Ref [224,231,232]).

In addition, during the evaluation of users' comfort and work efficiency, should be of interest to understand if the integration of natural elements could foster changes in physiological responses (e.g., pulse rate, skin temperature), attention and potentially damage concentration during task execution. In this context, traditional psychophysiological measures, and eye movements, can provide an objective and unbiased understanding of individual physiology, mental workload and visual engagement/disengagement to complement data from traditional approaches (i.e., surveys). The benefits of NBS on physiological responses have already been demonstrated in VR-based studies [56,83,84,86,87,230]. Despite that, to the authors' knowledge, only a few studies adopted eye-tracking technology during the assessment of cognitive functions [81,85] in immersive environments integrated with indoor greenery. A lack of literature on users' emotional attachment and distraction induced by specific virtual green elements, and a comparison with other greenery interventions (i.e., natural view) emerged, even if these are crucial points to understand the effectiveness of design strategies.

Hence, underdeveloped is the application of VR to support researchers in understanding the potential effects of visual and non-visual (acoustical) connection with nature on human work efficiency and comfort through a multi-domain approach.
Given the above-mentioned knowledge gaps, it is imperative to focus on the audio-visual interaction of BD intervention in office environments demonstrating the suitability of the new methodological approach based on VR and IVEs.

To extend the existing body of literature, the goals of the study (summary in Figure V - 17) were to i) examine the experience of participants in a combined audio-visual IVE to confirm its ecological validity; ii) understand the potential of Biophilic Design interventions in shaping more supportive and comfortable office environments. In particular, the fundamental goal is to understand the effect of different audio-visual connections with nature on cognitive performance, soundscape assessment and physiological parameters (i.e., Electro-Dermal Activity, Pulse Rate, Skin Temperature, Eye-tracking metrics) to determine how overall perception varies depending on BD intervention indoors.
To achieve these goals and demonstrate the suitability of the developed framework in such a research domain, a comparative assessment between three office layouts (Indoor Green, Outdoor Green and Non-Biophilic) combined with three acoustic scenarios (Office, Office+Traffic and Office+Nature) was carried out on 198 participants. These topics were addressed by subjectively and objectively assessing the difference between the nine scenarios.
The overall methodology is presented in Section 5.3.2. The outcomes of the experiments will be analysed in Section 5.3.3 and related subparagraphs.
The experiment was approved by the Research Ethics Committee of the Università Politecnica delle Marche (No. 0216363, 01/12/2022).

Visual Factor Selection and creation of three visual scenarios for the IVEs: Non-Biophilic, Indoor Green, Outdoor Green

Acoustical Factor Selection, recording and measurement of three acoustical scenarios: Office, Office + Traffic, Office + Nature

1 Experimental Phase 1: Effectiveness of VR to investigate Biophilic Design research interventions

▶ **Reported presence and immersivity** evaluation of perceived presence in the IVE

▶ **Reported cybersickness** evaluation of perceived sickness after using VR headset

2 Experimental Phase 2: Effect of audio-visual connection with nature on cognitive performance

▶ **Task accuracy** evaluation of accuracy in the three cognitive tests across combination of Visual Factor * Acoustic Factor

3 Experimental Phase 3: Effect of audio-visual connection with nature on soundscape assessment

▶ **Perceptual accuracy** evaluation of perceived affective quality of soundscape in office environments across combination of Visual Factor * Acoustic Factor

4 Experimental Phase 4: Effect of audio-visual connection with nature on physiological response

▶ **Physiological response** evaluation of physiological responses (EDA, PR, ST) across combination of Visual Factor * Acoustic Factor

evaluation of the relationship between physiological responses (EDA, PR, ST) and the subjective assessment of the sound environment across combination of Visual Factor * Acoustic Factor

5 Experimental Phase 5: Effect of audio-visual connection with nature on visual attention and distraction

▶ **Visual attention** * evaluation of the visual attention (eye-tracking metrics) to greenery across the levels of Visual Factor during the adaptation phase

▶ **Visual distraction** * evaluation of the visual distraction (eye-tracking metrics) induced by the presence of greenery during the task execution

▶ **Task accuracy** * evaluation of the relationship between eye-tracking responses and the task accuracy across the levels of Visual Factor during the task execution

evaluation of accuracy in the three cognitive tests across the levels of Visual Factor

* Pilot study on a limited part ($n = 63$) of the overall sample ($n_{tot} = 198$)

Figure V - 17 Chapter III: Illustration of the methodological approach in the study presented in Part V – Chapter III to demonstrate the potential of applying the developed framework and the validated model to a multi-domain combined stimuli experiment (visual + acoustical stimuli)

5.3.2. Experimental design

In this study, a 3x3 factorial design was employed with three between-participants levels of Visual Factor office layout (Factor V: Indoor Green, Outdoor Green and Non-Biophilic) and three within-participants levels of Acoustic Factor (Factor A: Office, Office + Traffic and Office + Nature sounds). The experimental sessions were designed to counterbalance the presentation order of acoustic stimulus, and subjects were randomly assigned to a visual scenario (66 participants per Factor V level) to avoid the introduction of confounding variables. In this section, the research equipment, the development of the virtual model and soundtracks, followed by the experimental schedule and the data processing and analysis are described.

The testing room (section 4.2) was equipped with air and operative temperature, humidity and air velocity sensors of HD32.1 Thermal Microclimate Station by DeltaOHM [233] to monitor the environmental conditions. The probes were installed at the height of 1.1 m, to ensure that the height of the sensors was similar to the participants' height when they were in the sitting position during experiments. Data were transmitted in 1-minute intervals. DeltaLog10 software [234] provides a real-time data monitoring, acquisition and analysis system over the testing room conditions. The indoor climate condition depends on the HVAC system of the office space. Indoor temperature condition was kept constant in this study. During the experimental session, the mean of the zone temperature and standard deviation were

23.30±0.43, 23.29±0.44, and 23.38±0.47 for the Indoor Green (IG), Outdoor Green (OG) and Non-Biophilic (NB) conditions, respectively. The mean radiant temperature was 23.14±0.38, 23.19±0.36, and 23.31±0.40, respectively, and air velocity was always below 0.06m/s.
To provide additional physiological signals, an Empatica EmbracePlus wristband [126], worn on the left hand of the participant, was used for continuous monitoring of Electro-Dermal Activity (EDA, Skin Conductance Levels), Heart Rate (HR) and Skin Temperature (ST) responses.
The specifications of the sensor equipment are shown in Table V - 7.

Sensor	Model	Measure Range	Accuracy
Air Temperature	DeltaOHM - HP3217R	-40 to +100°C	±1.5 + 1.5% of the measurement
Radiant Temperature	DeltaOHM - TP3275	-10 to +100°C	Class 1/3 DIN (±0.13/0.17 from 15 to 40°C)
Air velocity	DeltaOHM - AP3203	0.1 to 5m/s	± 0.2 m/s (0.1-1 m/s) / ± 0.3 m/s (1- 5 m/s)
SCL sensor	Embrace Plus - Empatica	0.01 to 100 μS	-
HR sensor	Embrace Plus - Empatica	24 to 240 bpm	3 bpm (no motion) / 5 bpm (motion)
ST sensor	Embrace Plus - Empatica	0 to +50 °C	± 0.1°C (from 30°C to 45°C)

Table V - 7 Chapter III: Sensors specifications

5.3.2.1. Sound material

During the tests, participants were exposed to three sound scenarios (Office, Office + Traffic and Office + Nature sounds) via headphones (integrated into the HMD). The sound material was recorded in a real office environment of similar floor plan, door and window sizes to the simulated one, located on the 3rd floor of an office building, using a First Order Ambisonics (FOA) tetrahedral microphone (Sennheiser AMBEO VR Mic) with accompanying portable multi-channel audio recorder (Sound Devices MixPre-10T), with microphone capsules placed 1.2 m above the floor and microphone's orientation matching the orientation of the worker, with the window on the side. In this way, the room acoustics properties, such as reverberation time, that would be characteristic of a room presented to the participants, were considered to be realistically captured. The office condition was recorded in the presence of four people performing office-type activities (i.e., quietly talking on the phone, tapping on the keyboard, and moving around the office). The sound material for the traffic condition was recorded in the same environment, unoccupied, and with windows open to outside traffic. The office and traffic recordings were made together with a sound level meter (NTi Audio XL2) placed as closely as possible to the microphone capsules. Natural sounds were recorded via a binaural head-mounted microphone kit (Head Acoustics BHSII connected to Squadriga III) inside a room, close to the open windows, so the additional sound level meter was not needed. Those recordings consisted mainly of birdsong. All the recordings were edited to obtain 1-minute excerpts representative of the targeted scenario (office-type activities, outside traffic, birdsong). The FOA recordings were transformed to an AmbiX B-format using the appropriate plugin (Sennheiser AMBEO A-B format converter). The B-format audio files were then decoded to a pair of headphones using the Oculus Spatializer package in Unity. The playback level was set through binaural head measurements (HMS II.3 LN by Head Acoustics) with the exact headphones and the virtual reality head-mounted display (VR HMD) used in the experiment, with the simulation running from Unity and at the listener in the centre of the simulated sound field, so the loudest playback level would match sound levels similar to those experienced in the real environment (L_{Office} = 45 dB(A), $L_{Office+traffic}$ = $L_{Office+Nature}$ = 54 dB(A), higher value of left and right ear).
Figure V - 18 presents the relevant steps for the generation of the sound material, its integration within the virtual model and the set up of the test room with the adopted devices.

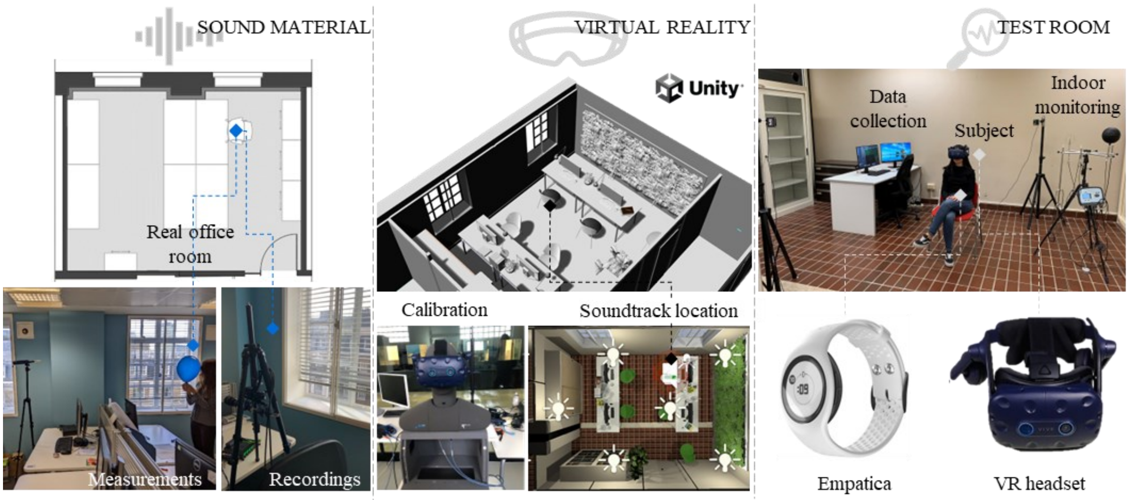

Figure V - 18 Chapter III: Sound material (a), virtual environment (b) and test room (c) set-ups

5.3.2.2. Virtual Environment

The validated model (Part IV: Validation of the experimental framework) was the starting point in this experiment. It was slightly modified to better fit the room where the sound material was generated (e.g., ceiling height, higher number of windows and workstations).

Thus, a 3D four-occupancy office room with two windows (Figure V - 18b) represented the basic scenario (Non-Biophilic, NB) of the presented study. Based on the Nature in the Space patterns of biophilic design proposed by Terrapin Bright Green LLC [229] two additional visual scenarios were generated considering the «Visual Connection with Nature» occurring indoors (e.g., nature elements in space) and «Prospect» (e.g., natural view from windows). Specifically, in the Indoor Green condition (IG) a living wall and potted plants were added within the office room, which is frequently used in indoor biophilic design practices; the Outdoor Green (OG) condition represents the natural view of trees to the windows. From a quantitative point of view, the greenery was added exceeding the minimum requirement of the WELL Standard [235] to support occupant well-being and restorative spaces by providing a connection to nature. Thus, the plant wall covered a wall area equal to 60% of the floor area (greater than 2%) while potted plants covered 4% of the floor area (min 1% of the floor area). To ensure the participants the greatest views of outdoor greenery, the sitting position within the virtual model was chosen in such a way as to have a View Factor (total view rating from the desk) equal to 5, corresponding to a lateral view angle of 53° and vertical view angle of 73° (threshold 50-90°) [236]. Except for the integration of the biophilic pattern, all three office scenarios were identical (see Figure V - 19).

Unity game engine [154] (Version 2018.4.14f1) was adopted to virtualise the 3D model. In addition, to gauge participants' visual attention, it was integrated with iMotion [237] (Version 9.3) to record participants' eye tracking. Finally, the IVE model was visualized through the HTC Corporation VIVE PRO Eye head-mounted display (1440 x 1600 resolution image per eye, a pixel density of 615 PPI, a field of view of 110° per eye, an adjustable interpupillary distance from 60.7 to 73.5 mm) using the SteamVR plugin [155].

The immersive soundscape experience was provided to participants through the Unity audio system which allows for a head-tracking binaural rendering of the acoustic environment via the Oculus Spatializer package (tempo-spatial congruency between the audio clip and participant's movement). The soundtracks were implemented within the virtual environment in the position of the first player control, in agreement with the position from which measurement and recording were carried out in the real office room where the recordings took place (see section 5.3.2.1) so that the traffic and natural sounds seemed to come from the open window (as confirmed by the participants, see section 5.3.3.2).

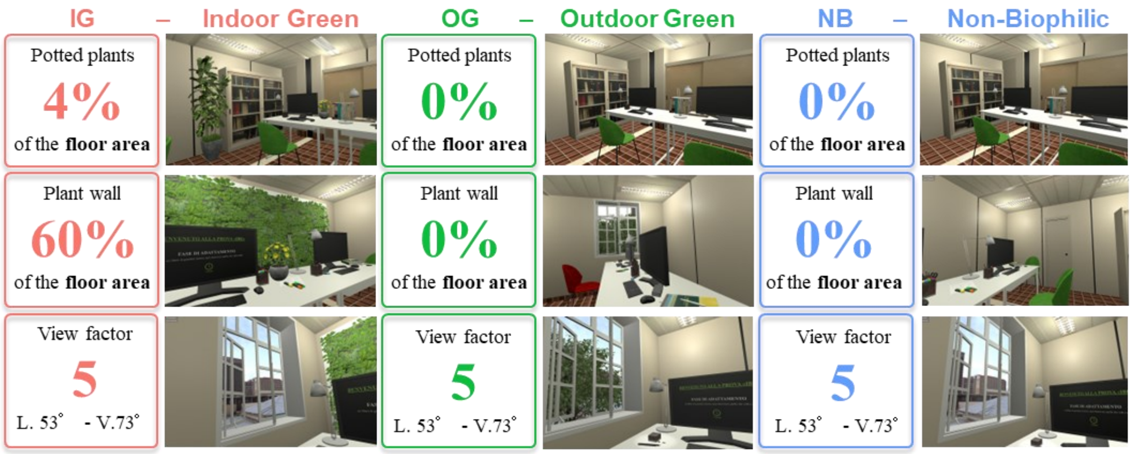

Figure V - 19 Chapter III: The Visual Factor Levels: Indoor Green, Outdoor Green and Non-Biophilic scenarios with greenery percentages related to the virtual room floor area and the View Factor from the participants position during the test

5.3.2.3. Experimental procedure

The overall experimental procedure is presented in Figure V - 20 and, as the previous experimental activity, it followed the developed framework.

The test had an overall duration of about 35 minutes. Each participant was recruited for a one-day test and was randomly assigned to experience the Indoor Green, the Outdoor Green or the Non-Biophilic Factor V levels (between-subjects independent variables).

After their arrival, participants experienced a pre-experimental phase (15 min) to allow the adaptation to the environmental climatic conditions (about 23-24°C), read and signed a consent form, received information about the test procedure, and completed the pre-experimental questionnaire.

Then, they were invited to wear the Empatica wristband and the head-mounted display, properly calibrate the eye-tracking and rest with their eyes closed for 30s. The researchers asked the volunteers to adapt to the virtual scene for 3 min to reduce the physical and psychological fluctuation related to exposure to the virtual environment, and to improve the immersivity within the scenario from a visual and an acoustic point of view [92]. During the adaptation phase, participants were asked to verbally describe the indoor office environment they were experiencing, considering both the visual and the acoustic domains.

During the operative phase, participants performed the three cognitive tests and the soundscape assessment (section 3.3). This procedure was repeated three times, one for each Factor A level (O+N, O, O+T, within-subjects independent variables), with 30 seconds of rest with eyes closed between each. The presentation order of the acoustic scenarios and cognitive tests was randomized across each participant to reduce the learning effect and time-related factors. Finally, subjects answered questions about the sense of presence and immersivity and the cybersickness disorders (1min). Answers to cognitive tests and surveys were given verbally and recorded by the researchers.

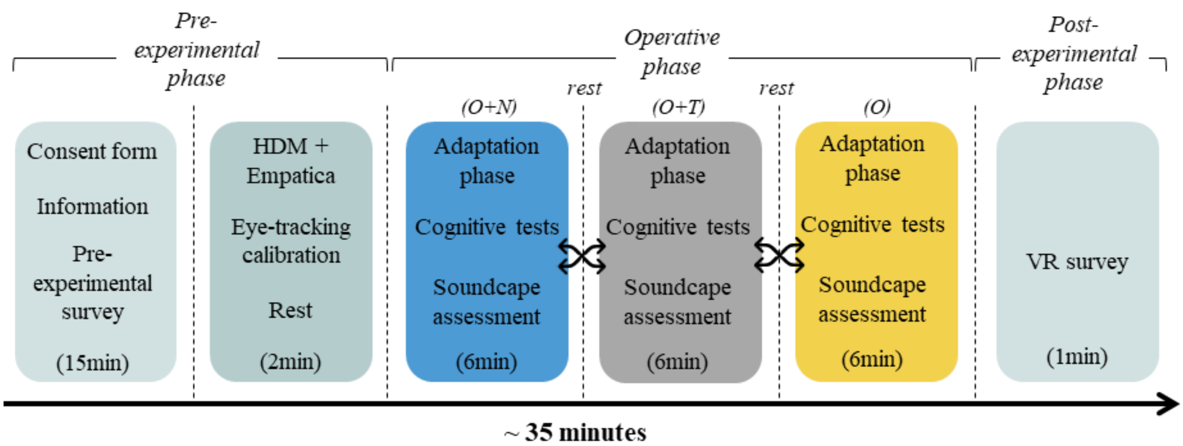

Figure V - 20 Chapter III: Experimental procedure

5.3.2.4. Data processing and analysis

Cognitive test - soundscape assessment - physiological measures

The experimental activity employed two independent factors with three levels each: Factor A (O, O+N, O+T levels) as a within-subject factor, with repeated-measure for each subject, and Factor V (NB, IG, OG levels) as a between-subject factor. Specifically, the authors investigated the effect of visual and acoustic scenarios on the participants' responses. Moreover, the possible interaction between visual and acoustic factors was inspected.

Considering this mixed experimental design, the Authors adopted Generalized Linear Mixed-Effects Models (GLMM) which combine the properties of linear mixed models incorporating random effects and generalized linear models which handle the non-normality and the non-homogeneity of residual data distributions [238–240]. The basic theory of the GLMM is that subjects' responses are the sum of fixed factors, which are the variables of interest controlled during the study, and random factors that can influence the covariance of the data. The GLMM analyses were carried out using the statistical software R [156] and the R packages g*lme4*, considering a separate GLMM for each dependent variable. A Poisson distribution was used to analyse cognitive function scores (performance accuracy), whereas the speed of processing, physiological data and soundscape results were analysed by a Gaussian and a Gamma (log-ink function) distribution, respectively.

In particular, the visual layout and acoustic scenarios were used as fixed effects. Participants were treated as a random factor, as they were not controlled but randomly chosen from a larger population. By-subject random intercept and by-subjects random slope for the effect of acoustics [241] were included in each model to estimate the variance in the outcomes related to the different individuals and to account for the possible correlation between responses of the same subject concerning the repeated measures. Whenever the order term in which the participants were randomly assigned to an acoustic condition did not meet significance effects, it was excluded from the final model. The specification of the final model with interaction was as follows:

DependentVariable ~ AcousticFactor * VisualFactor + (1 | VisualFactor) + (0+ AcousticFactor | ParticipantID)

$$Y_{si} = \beta_0 + I_{0i} + (\beta_1 + S_{1s}) X_i + e_{si}$$

The statistical significance of the effect of each term was calculated using Analysis of Variance (ANOVA, Type II, Wald χ^2 tests) using the *Anova* function in the R package *car* by considering a 95% level of significance.

For the null hypothesis evaluation, the authors considered the critical values of χ^2 distribution equal to 5.99 and 9.49 for 2 and 4 degrees of freedom, respectively. In the case of a significant effect of the main factors or the interactions, post-hoc pairwise comparisons of estimated marginal means were undertaken to investigate the difference between groups using the R package *emmeans* and applying the Bonferroni correction to account for planned multiple comparisons. Interaction plots were also printed to interpret any possible interaction effects between Factor V and Factor A.

The Akaike Information Criterion (AIC) was used to compare the quality of the hypothesised models. In addition, to compare the accuracy of the tested models and represent the proportion of the total variance explained by the fixed effects and by both fixed and random effects, the marginal (R_m^2) and conditional (R_c^2) coefficients of determination were generated for each model. AIC, R^2_m and R^2_c are reported in Table V - 8 for each GLMM. Indexes were estimated using the function *r.squaredGLMM* from the *MuMIn package* to be interpreted using the recommended thresholds for a minimum (0.20), moderate (0.50), and strong (0.80) effect size [242].

Concerning the data processing of soundscape assessment, the 8 perceptual attributes (pleasant, exciting, eventful, chaotic, unpleasant, monotonous, uneventful, and calm) conceptually create a 2D circumplex space defined by *Pleasantness* and *Eventfulness* components on the x- and y-axis [243]. According to Part 3 of ISO 12913 [122], the eight attribute values were transformed by a trigonometric transformation into a pair of coordinates suitable to be plotted in the Pleasant-Eventful diagram. A 45° relationship between the diagonal axes and the pleasant and eventful axes was adopted to compute the ISOPLeasant (x coordinate) and ISOEventful (y coordinate) values across all respondents.

Group variable	Dependent variable	AIC	$R^2_{marginal}$	$R^2_{conditional}$
Cognitive test	MP number errors	1322.3	0.19	0.29

	Stroop number errors	845.8	0.09	0.19
	Stroop speed of processing	3684.7	0.19	0.33
	OSPAN errors T/F	869.6	0.07	0.11
	OSPAN errors in letters	2100.9	0.21	0.29
	OSPAN score	2507.9	0.10	0.10
Physiological parameters	Electro-Dermal Activity	1534.3	0.02	0.57
	Heart Rate	3650.1	0.08	0.47
	Skin Temperature	1786.0	0.04	0.57
Subjective rating	ISO Pleasant	156.1	0.39	0.73
	ISO Eventful	206.2	0.42	0.46

Table V - 8 Chapter III: AIC, marginal and conditional R2 of the LMM for each dependent variable

Eye-tracking metrics

The eye-tracking metrics were processed and analysed for a smaller part of the sample consisting of 63 participants (21 for each Visual Factor). Due to the huge computation efforts needed to carry out such analysis and research gaps, this experimental phase was considered a first attempt - a pilot study - to understand the metrics that need to be considered and how to interpret and generalise the results.

Firstly, the authors selected the visual stimuli on which to define the Areas of Interest (AOI): the plant wall and the potted plants for the IG configuration, and the trees for the OG scenario. In addition, the computer monitor was identified as a stimulus considering the slide that showed the letters to be recalled on the OSPAN test, the whole screen during the instruction presentation, and the Stroop and Magitude-Parity tests. Gaze outside those boundary areas were considered «eyes-off-task».
All the participants' videos of the experiment were exhaustively scanned to identify ranges where the selected visual stimuli (landmarks) were in the field of view. The gaze mapping algorithm allowed to mapping eye-tracking data recorded in the dynamic environments (e.g., adaptation phase, task executions), onto a static reference image of the environment.
In this manner, iMotion software could derive within the selected static AOIs the stimuli-related gaze behaviour based on fixations which were defined as a point-of-gaze that remained on a location for a minimum of 60 ms and classified using the I-VT Fixation filter [244]. The velocity value is computed for every eye position sample and is then compared to the threshold of 30 degrees/sec. If the sampled velocity is less than the threshold, the corresponding eye-position sample is marked as part of a fixation, otherwise, it is marked as a part of a saccade. Thus, the extracted metrics were: fixation count (number of fixations detected inside the AOI), fixation duration (sum of all fixation durations inside the AOI expressed in ms), saccade count (number of saccades with start and end points detected inside the AOI), gaze time (amount of time that respondents have spent looking at a particular AOI). These raw metrics were adopted for the eye-tracking analysis of cognitive performance and were post-processed for the adaptation phase assessment. Indeed, participants' attention to greenery was calculated in percentage terms using the approach suggested by Bernardini et al. [245]. In particular, gaze time and fixation count were adopted to compute A(o,t) and A(o,f), respectively. In addition, Time to First Fixation (TTFF) and First Fixation Duration (FFD) were calculated due to their relevance in visual interest assessment. TTFF indicates the amount of time that it takes a respondent to look at a specific AOI, while FFD provides data about how long that first fixation lasted. Thus, they give information about how AOIs were prioritized and how much they initially attracted attention: if a participant has a short TTFF and a long FFD, the area is in all likelihood very eye-catching.
In the meanwhile, the ranges where the landmarks were in the participants' field of view during cognitive task execution and instructions reading, were adopted to compute the blink rate and pupil dilatation. The latter was calculated also during the adaptation phase for the green elements.
The blink rate was operationally defined as the blink rate per minute. In particular, blinks were detected as eye closures lasting a minimum of 20 ms and a maximum of 500 ms. If the eyes were closed for a time outside this range, it was considered a technical issue of the eye tracker. The minimal duration needed between two blinks to be considered as separated was 70 ms. According to the iMotion guide, the threshold values allowed the most optimal results since a 90Hz eye tracker records one data sample every 11,1 ms.
Data related to pupil dilation was provided as raw data and a continuous stream of left and right pupil size estimates, with the corresponding indication of timestamp relative to task duration. Pupil peak

dilation was computed as the maximum percentage of pupil diameter change. The percentage change in pupil diameter was assessed for each data point by using the equation provided by Lemercier et al. [246]. Cognitive tests were presented on screens of variable luminance (i.e., black background for Stroop test, white background for MP and Ospan test). Hence, the baseline was defined as the pupil size at the start of each task to allow light to not significantly affect pupil size variations.
Figure V - 21 suggested a workflow for interpreting each eye-tracking metric depending on the correlation with cognitive load and emotional arousal.

Eye-tracking metrics		Correlation with COGNITIVE LOAD
Fixation count [-]	+	The higher the fixation counts the more the cognitive load in extracting information.
Fixation duration [s]	+	The higher the fixation duration the more the cognitive load in extracting information.
Saccade counts [-]	+	The higher the saccade counts the more the cognitive load in extracting information.
Blinks rate [-]	-	High mental demand causes blinks inhibition to reduce the risk of missing incoming information.
Peak pupil dilation [%]	+	Greater pupil dilatation represents higher cognitive load.

Eye-tracking metrics		Correlation with EMOTIONAL AROUSAL
Time to First Fixation (TTFF) [s]	-	A longer TTFF to look at a specific AOI from stimuli onset means that the area is not likely very eye-catching.
First Fixation Duration (FFD) [s]	+	A longer FFD duration means that the area is likely very eye-catching.
Gaze duration (Ao.t) [%]	+	The higher the fixation duration the more engaging is the AOI.
Number of fixations (Ao.f) [%]	+	The higher the fixation counts the more engaging is the AOI.
Pupil diameter [mm]	+	Greater pupil dilatation represents higher emotional arousal.

Figure V - 21 Chapter III: Workflow for interpreting the correlation between eye-tracking metrics and cognitive load / emotional arousal. Positive correlation is marked in green colour, and negative correlation in orange.

To evaluate how the eye-tracking metrics and cognitive functions differed between the virtual experimental conditions, several statistical methods were applied to the collected sample data using the statistical software R [156].
Data were first tested for normality with the Shapiro-Wilk test and then analysed with parametric and non-parametric tests according to the normality of the distribution. Since data are found not to be normally distributed, the Kruskal-Wallis test was used as a non-parametric alternative to the independent-measures ANOVA, to investigate the presence of differences in cognitive task results (e.g., time to completion, the number of errors) and eye tracking features (e.g., blink rate, peak pupil diameter, fixations count, fixation duration and saccades count) between the three visual conditions (NB, IG, OG). The null hypothesis states that there is no effect, no change, or no difference between the indoor layouts: if the computed H-value falls within the critical region (chi-square = ±5.99 for df=2, α=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. In case statistically significant differences were found between conditions, a post-hoc Dunn Kruskal-Wallis test was performed to compare all the pairs. Lastly, Kendall Tau correlation analysis was adopted to investigate the relationship between eye-tracking metrics and cognitive task results.
The significance level was set as equal to 0.05 (5%) for all tests. In addition, descriptive statistics (mean, standard deviation) were computed for the eye-tracking metrics and cognitive test results.

5.3.3. Results and discussion

The results of the present chapter were analysed according to several objectives: the ecological validity of the developed IVE, the evaluations of the audio-visual connection with nature on working memory, inhibition, and task-switching performance, the soundscape assessment and the physiological responses. Considering the latter, it was of interest to look at a relationship between the physiological parameters and the perceived affective quality of soundscape. Moreover, eye-tracking metrics and cognitive performance relationship were also assessed together with the effect of visual connection with nature on visual attention and distraction from task execution.

5.3.3.1. Sample analysis

Word of mouth and flyers were adopted to recruit participants. 198 healthy adults participated in the study from January to March 2023 randomly divided into three groups composed of sixty-six participants each. The sample size was determined via *a-priori* ANOVA power analysis through the G*Power software [158] considering not only main effects but also interactions ones, with an effect size f = 0.25, α = 0.05. The sample size was adequate to detect significant effects with a statistical Power equal to 80% for the interaction effect (Factor A * Factor V) and 88% for the main effect of Factor A and Factor V.

An overview of the characteristics of the 198 participants and features within the three conditions (IG, OG, NB) are presented in Table V - 9. In general, participants had an average age of 23 ± 3.85 years, distributed as follows: 79% between 20 and 25 years old (μ = 21.5), 17% between 26 and 30 (μ = 27.37), 4% between 31 and 39 (μ = 34.38). It was mainly composed of university students (60%), 34% graduated, and only 5% had a higher educational level (PhD, post-graduate school).

None of the subjects suffered from hearing problems, colour blindness and strabismus. 56% of the sample had common eyesight problems, such as astigmatism, myopia, and hyperopia, but all of them wore corrective lenses during the tests, not to invalidate the test execution and the visualisation of the model. In addition, 54% of participants had never had previous experience with VR technology and 26% frequently played video games.

	Overall	IG	OG	NB
Gender				
Female	36%	44%	35%	29%
Male	64%	57%	65%	71%
Age				
20-25	79%	68%	79%	92%
26-30	17%	25%	17%	8%
31-39	4%	8%	3%	-
40-45	-	-	2%	-
50-60	-	-	-	-
Educational level				
Non-graduated	34%	43%	35%	26%
Graduated	60%	49%	59%	74%
PhD, post-graduate school	5%	8%	6%	
Eyesight problems				
None	44%	44%	52%	38%
Myopia	33%	29%	26%	44%
Myopia + Astigmatism	15%	17%	18%	9%
Astigmatism	7%	9%	5%	8%
Hyperopia	1%	1%	-	2%
Previous experience with VR				
Never	54%	53%	55%	53%
Once	26%	25%	27%	27%
More than once	20%	22%	18%	20%
Videogames usage				
Never	32%	42%	33%	20%
Rarely	42%	49%	39%	36%
Frequently	19%	8%	20%	30%
Everyday	7%	1%	8%	14%

Table V - 9 Chapter III: Characteristics of study participants (n = 198) in general and across the three experimental visual scenarios

According to the second part of the pre-experimental survey, only 26% of participants were satisfied with the visual design and acoustic characteristics of their work/study places. In general, 83% reported having access to natural light and natural ventilation. Indoor green plants and natural landscape outdoor views were equally the most desired workplace elements (53%). More than half of their work and study places had no plants at all (85%) and 64% reported mainly enjoying urban landscapes, resulting in relevant anthropic sounds (40%, e.g. traffic) and lower natural ones (32%, e.g., leaves, birds). In addition, 63% of subjects experienced co-working environments. A quieter workplace from indoor and outdoor noises were the second and third most desired elements (50%, 41%).

In Figure V - 22 are reported, in order of relevance, desirable features that subjects would like to introduce into their work or study environment to improve it.

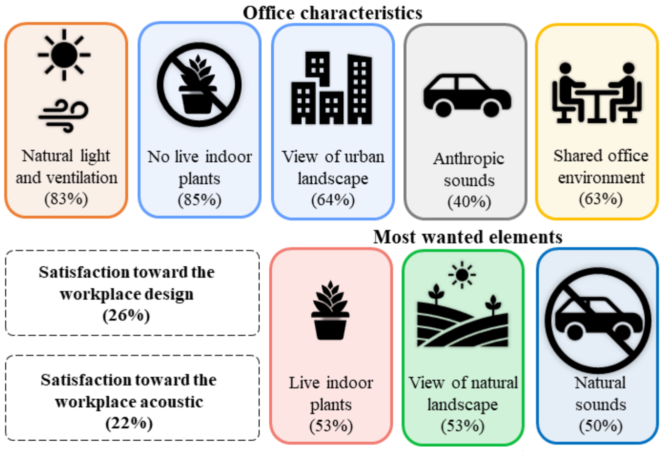

Figure V - 22 Chapter III: Characteristics of participants' work environments and most wanted elements

5.3.3.2. Ecological validity

Data about the sense of presence and immersivity, the cybersickness ratings and the sensory congruency were analysed to evaluate the ecological validity of the model. As previously done, the average values of each indicator of the visual sense of presence and immersivity were compared to other literature studies, namely, Latini et al. [15,59], Tawil et al. [247], Yeom et al. [73], Hong et al. [63], Chamilatori et al. [61], Abd-Alhamid et al. [62]. As reported in Table V - 10 the mean scores exceed a moderate level (i.e. 4) for all four indicators (REAL = 4.45; SP = 4.29; INV = 4.05; GS = 4.40). Thus, the virtual model offered the participants a very good experienced realism, presence and involvement within the virtual environment and graphics satisfaction. In addition, all mean values are higher than the references and almost similar to [15,59], concerning GS, INV and REAL and [73] concerning INV. However, the differences between the mentioned indicators and the reference study are not relevant (between 0.02 and 0.18).

Indicator	This study	[59]	[15]	[247]	[73]	[63]	[61]	[62]
GS	4.40	4.58*	4.64*	3.93	-	3.65	-	-
SP	4.29	4.21	4.18	3.44	4.24	3.39	3.68	3.74
INV	4.05	4.15*	4.29*	3.27	4.11*	3.23	-	-
REAL	4.45	4.47*	4.51*	2.68	3.54	2.73	3.75	3.21

Table V - 10 Chapter III: Comparison of scores on a five-point scale of the four indicators (* highlight the indicators higher than the present study)

Secondly, the authors qualitatively evaluated the sensory congruency of the acoustic environment with the verbal description supplied by participants during the adaptation phase. In particular, the open-ended answers were analysed considering some keywords for each acoustic scenario, as follows:

1. Office: 70% of participants reported having heard some typical workplace noises such as, «keyboard», «laptop», «mouse», «typing activity» (69%), and «telephone alert» (13%), while 30% described the indoor environment as characterized by general «office» noise. In addition, sounds generated by «people» like unintelligible «speech» (31%) and «steps» (6%) were also identified. In general, 82% of participants describe the sounds as coming from the inner side of the virtual room.
2. Office + Nature: the whole sample (100%) identified the «natural sounds» of «birds» coming from the open «window» on the left-hand side of the office. In addition, 61% of participants reported having heard also indoor office sounds.
3. Office + Traffic: 100% of participants described the acoustic environment as including «traffic», «road», «cars», «buses», and «horn» noises coming from the open «window» on the left-hand side of the office. In this acoustic scenario, only 50% of the sample clearly described the presence of indoor office sounds, as traffic sounds seemed more predominant.

The methods of generating and integrating acoustic scenarios into VR provide an immersive acoustic experience. Indeed, according to the description provided by participants during the adaptation phase, an excellent sensory congruency was highlighted between the elements of each soundtrack and the perception within the virtual model in terms of the location and direction of the noise. The sensory congruency feedback is a crucial point for the researchers to understand the user experience within an IVE that will ensure the highest degree of ecological validity and then the reliability of participants' responses.

According to the results of the VRSQ, no subject during the pilot study reported «vertigo» (100% scores assigned to «not at all»). Other symptoms, such as «headaches», «fatigue», and «general discomfort» were negligible since between 89% and 98% of the subjects gave a score of «not at all» and «slightly». However, slight «eyestrain», and «difficulty in focusing» were reported, 77% and 63% respectively. According to [59], these results are consistent with the sickness symptoms analysis from previous studies. This result was possible thanks to the application of the previously developed experimental protocol (Part III: Definition of an experimental framework for IVR applications), which considers the need to limit the VE exposure time below 25/30 min. This experimental strategy allowed participants not to suffer from relevant cybersickness disorders even if short-term exposure to the acoustic scenarios was set up.

Finally, the authors confirmed the ecological validity of the model which allowed to consider that the created IVE offers a valuable tool to investigate the potential of Nature-Based Solutions and Biophilic Design interventions.

5.3.3.3. Effect of audio-visual connection with nature on cognitive performance

Magnitude - Parity test (task-switching executive function)

Considering the errors in the classification of the digits even/odd and greater/lower than "5" in the Magnitude - Parity test, the results of the statistical analysis revealed a significant main effect for Acoustic ($\chi^2(2) = 51.50$, $p < 0.05$, $\eta^2 = 0.96$). In particular, a higher number of errors occurred in the Traffic sound condition (1.30±1.19) than in Natural (0.38±0.59) and Office (0.55±0.85) ones. Post-hoc test confirmed the difference between the three acoustic scenarios. In particular, the paired comparison (Figure V - 23 b) showed in all three visual levels (IG, OG, NB), that the number of errors was significantly higher under the traffic sounds than with nature and traffic. Notably, Traffic sounds had the same detrimental effect on the number of errors while performing the task-switching activity in all the visual scenarios, as highlighted by the means and standard deviation values reported in Table V - 12. The result indicated the absence of a significant effect for the Visual Factor ($\chi^2(2) = 1.60$, $p = 0.43$), and the interaction with Factor A (χ^2 (4) = 2.08, $p = 0.72$).

Participants scored on average 71% lower in the traffic sound environment compared to the natural one, and 58% lower compared to the office sound environment, as in [15]. In addition, 31% greater accuracy was detected between the office and natural sound scenarios. These results are coherent in all three visual scenarios. Although participants scored higher when in indoor green (12%) and outdoor green environments (13%) in comparison with non-biophilic settings, those improvements were not statistically significant. Even if the increased accuracy seemed relevant in the presence of a visual connection with nature, this result is in line with the trend highlighted in the (indoor) VR-based BD literature on cognitive assessments [56,85].

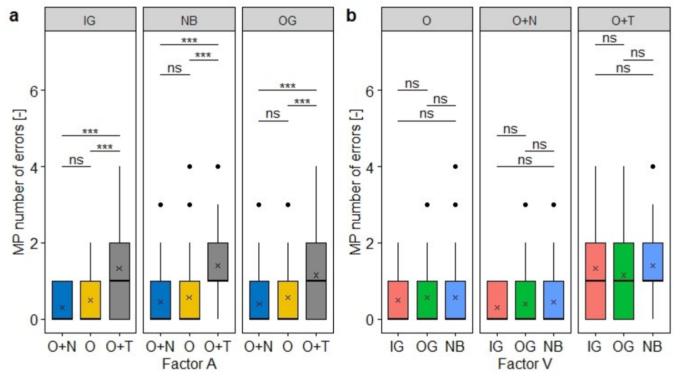

Figure V - 23 Chapter III: Boxplot of the number of errors within the MP test. Data are grouped by Factor V and pairwise comparisons are shown. Inside the boxplots, the cross is the mean value, and the line is the median value. ns.: non significative, * p≤ 0.05, ** p≤ 0.01, *** p≤ 0.001

Stroop test (inhibition executive function)

Considering the Stroop test, a significant main effect for the Acoustic Factor, ($\chi2$ (2) = 30.51, $p < 0.05$, $\eta^2 = 0.77$), was detected for the number of errors. As for the MP task, results indicated a lower number of errors in the Natural sound condition (0.18±0.45) than in the Office (0.22±0.69) and Traffic (0.55±0.94).

Post-hoc test confirmed the difference between the three acoustic scenarios. Indeed, the paired comparisons (Figure V - 24a) show a significant increase in the number of errors with Traffic sounds in both the Indoor Green and Outdoor View conditions compared with Nature and Office conditions ($p < 0.05$).

There were no main effects of Visual Factor (H = 4.10, p = 0.13), as also shown in Figure V - 24b, but comparing the mean values of the number of errors (Table V - 12), participants scored fewer errors with Natural sounds in the IG condition (0.13 ± 0.35) in comparison with OG (0.17 ± 0.48) and NB (0.24 ± 0.53).

In addition, the interaction effect was significant (χ^2 (4) = 9.53, $p < 0.05$). The plot in Figure V - 26a shows that the lines for IG, NB and OG are not parallel, which indicates that the relationship between Factor A and the number of errors depends on the Factor V scenario. For example, Indoor Green resulted in a good accuracy from the Stroop test when participants experienced Nature Sounds but quite lower accuracy when exposed to Traffic sound.

Also, for the speed of processing the analysis revealed a significant main effect of Acoustic Factor (χ^2 (2) = 9.31, $p < 0.05$, $\eta^2 = 0.17$), with lower time in Natural sounds (31.02 ± 6.39s) than in Office (31.71 ± 6.87s) and Traffic (33.99 ± 6.50s) conditions, but no effect of visual layouts (χ^2 (2) = 145.62, $p > 0.05$). Figure V - 24c, d shows the pairwise comparison. In accordance with post-hoc results, the speed of processing was significantly lower with Natural sounds than Traffic ($p < 0.05$) and not significantly different from the Office sounds ($p > 0.05$) in all IG, OG and NB conditions. The same result is highlighted for all three V-Levels. In the analysis of Stroop speed of execution also a significant effect of Visual factor (χ^2 (2) = 145.62, $p < 0.05$, $\eta^2 = 0.81$) was found, with lower time with indoor greenery (28.27 ± 5.25s) than in outdoor greenery (34.21 ± 6.89s) and no-greenery at all (33.24 ± 6.67s) conditions. As presented in Figure V - 24d, the speed of processing was significantly lower with Indoor Green than Non-Biophilic ($p < 0.05$) and Office sounds ($p < 0.05$) in all IG, OG and NB conditions. Comparing the mean values (cf. Table V - 12), participants rapidly completed the test with Natural sounds in the IG condition (26.98s ± 5.28s) in comparison with OG (34.02 ± 7.10) and NB (32.05 ± 6.79) within the same A-Level.

No interaction effect was found (χ^2 (2) = 2.14, p = 0.47).

The results highlighted that participants were more accurate in the natural sound environment than in the office and traffic sound environment (18% and 67%, respectively), and performed faster (speed of processing 9% lower) than in the traffic. In addition, participants performed faster in comparison with non-biophilic and outdoor natural environments (15% and 21%, respectively). This finding is consistent with existing literature which reported a positive correlation between greenery and cognitive function (e.g. [56,85]). The best visual*acoustic condition in terms of increased accuracy and speed of processing for the inhibition task occurred with Natural sounds in the Indoor Green condition, while the worst performance was detected within the Traffic sound in the Non-Biophilic condition.

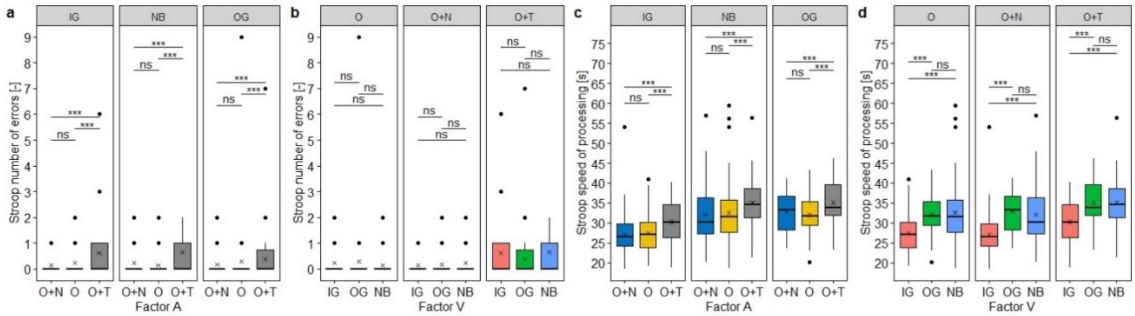

Figure V - 24 Chapter III: Boxplot of the number of errors (a,b) and speed of processing (c,d) within the Stroop test. Data are grouped by Factor V (a,c) and Factor A (b,d), and pairwise comparisons are shown. Inside the boxplots, the cross is the mean value, and the line is the median value. ns.: non significative, * p≤ 0.05, ** p≤ 0.01, *** p≤ 0.001

OSPAN test (working memory cognitive function)

Regarding the OSPAN test, a significant effect of the Visual Factor (χ^2 (2) = 6.03, $p < 0.05$, $\eta^2 = 0.10$) was found for the errors in the true-false string. Participants were more accurate in Indoor Green (0.28 ± 0.52) than in Non-Biophilic (0.41 ± 0.61) and Outdoor Green (0.33 ± 0.52). A main effect was also detected for the Acoustic Factor (χ^2 (2) = 23.51, $p < 0.05$, $\eta^2 = 0.90$) with higher accuracy scores in Natural (0.21 ± 0.43) than in Office (0.25 ± 0.49) and Traffic (0.56 ± 0.72) conditions. The magnitude of the effect highlighted (cf. Table V - 11) that acoustic factors had a higher effect on OSPAN score compared to that of visual factors.

According to the post-hoc for the pairwise comparison (Figure V - 25a), the number of errors in the true-false string was significantly higher with Traffic than Natural and Office sounds ($p < 0.05$) in all IG, OG and NB conditions. The higher mean scores (cf. Table V - 12) occurred with Indoor Green in the O+N condition (0.20 ± 0.40) in comparison with O (0.24 ± 0.53) and O+T (0.41 ± 0.63). The same trend occurred also within the non-biophilic and outdoor greenery conditions. As presented in Figure V - 25b, with the Office sounds, NB resulted in a significantly lower accuracy (0.27 ± 0.48) compared to IG (0.24 ± 0.53, $p < 0.05$) and OG (0.23 ± 0.46, $p < 0.05$). The same result can be highlighted in the condition of Traffic sounds but not for the Natural conditions where the effect of the visual layout was not significant.

Moreover, the interaction effect was significant (χ^2 (4) = 10.54, $p < 0.05$, $\eta^2 = 0.03$). The plot in Figure V - 26b shows that the lines for the indoor green condition, non-biophilic and outdoor greenery intersect, thus, indicating that the relationship between Factor A and the number of errors in the true-false string depends on the Factor V scenario. For example, if participants experienced Natural sounds, Non-Biophilic and Indoor Green were associated with the highest accuracy in comparison with the Traffic sound which was the most detrimental one.

The number of errors in the letters memorised revealed a significant main effect of Visual Factor (χ^2 (2) = 48.81, $p < 0.05$) with higher accuracy in Indoor Green (1.59 ± 1.36) than in Outdoor Green (2.22 ± 1.57) and Non-Biophilic (2.62 ± 1.34) conditions. Also, the main effect of acoustic scenarios (χ^2 (2) = 68.41, $p < 0.05$) was significant with fewer errors in Natural sounds (1.62 ± 1.50) than in Office (1.94 ± 1.48) and Traffic (2.87 ± 1.29) conditions. The magnitude (cf. Table V - 11) of the impact acoustic factors ($\eta^2 = 0.54$) was larger compared to that of indoor layouts ($\eta^2 = 0.36$). Post-hoc test confirmed the difference between the three acoustic and visual scenarios.

Indeed, the pairwise comparison presented in Figure V - 25c, shows that the number of letters correctly memorised was significantly higher with Natural sounds than Traffic ($p < 0.05$) and in Office compared to Traffic ($p < 0.05$) in all IG, OG and NB conditions. Comparing the mean values (cf. Table V - 12), the higher accuracy occurred with Indoor Green in the N condition (1.09 ± 1.25) in comparison with O (1.36 ± 1.57) and T (2.32±1.28), for all three V-Levels. Considering the results presented in Figure V - 25d, with the Natural sounds, IG (1.09 ± 1.25) resulted in a higher accuracy compared to NB (1.92 ± 1.52, $p < 0.05$) and OG (1.83 ± 1.73, $p < 0.05$). The same result can be highlighted in the other two acoustic conditions.

The mean values lines on the graph in Figure V - 26c show an interaction effect, confirmed by GLMM results(χ^2 (4) = 13.22p < 0.05). The plot shows lower accuracy for Outdoor Green compared to Non-Biophilic scenario within the Office scenario and slightly better accuracy within Natural sound conditions.

The same result was highlighted from the OSPAN score, computed as the sum of the number of the right true/false and the letters correctly memorised, with a maximum obtainable OSPAN score equal to 10.
A significant main effect of Visual Factor (χ^2 (2) = 15.74, p < 0.05, η^2 = 0.05) was detected with higher scores in Indoor Green (8.11 ± 1.57) than in Non-Biophilic (7.16 ± 1.31) and Outdoor Green (7.46 ± 1.68) conditions.
There was also a main effect of Acoustic Factor (χ^2 (2) = 33.21, p < 0.05, η^2 = 0.11) with higher OSPAN scores in Natural (8.15 ± 1.65) than in Office (7.79 ± 1.59) and Traffic (6.79 ± 1.33) conditions. The magnitude of the effect highlighted (cf. Table V - 11) that acoustic factors had a higher effect on OSPAN score compared to that of visual factors.
According to the pairwise comparison (Figure V - 25e), the OSPAN score was significantly lower with Traffic sounds than the other two acoustic scenarios (p < 0.05) in all IG, OG and NB conditions. The lower mean scores (cf. Table V - 12), occurred with Indoor Green in the O+T condition (7.18±1.58) in comparison with O (8.39 ± 1.80) and O+N (8.76 ± 1.35). The statistically significant results highlighted the same trend for all three V-levels. As presented in Figure V - 25f, with the Natural sounds, IG (8.76 ± 1.35) resulted in a higher OSPAN score compared to NB (7.89 ± 1.51, p < 0.05) and OG (7.79 ± 2.09, p < 0.05). The same result can be highlighted in the condition of Office and Traffic sounds.
The interaction effect was also significant (χ^2 (4) = 10.54, p < 0.05, η^2 = 0.03). Figure V - 26d shows similar scores between Non-Biophilic and Outdoor Green scenarios if participants experienced Natural sounds, while lower OSPAN scores were obtained in NB within the Traffic sound condition.

In general, the results highlighted that the visual and acoustic factor levels and their interaction influenced all three parameters. In particular, participants were more accurate in the true-false string tasks in Indoor Green than in Non-Biophilic and Outdoor View (31% and 16% respectively). Moreover, the exposure to the indoor traffic environment reduced the accuracy by 56% and 62% in comparison with the office sound and the natural condition. In addition, participants memorised a higher number of letters (39%) when in the indoor natural environment than in the non-biophilic and outdoor natural environments. Moreover, they scored 15% higher in the outdoor natural environments in comparison with the non-biophilic scenario. The same trend was detected considering the acoustic factor. As expected, the traffic sound scenario was the most disruptive environment with a 32% decrease in accuracy in comparison with a traditional office sound environment, thus supporting previous findings in VR-based studies (e.g. Ref [15]) and 44% compared to the natural sound environment. 17% higher errors in letters recalled were also detected in the office environment compared to the natural one. The same detrimental trend of traffic noise was highlighted regarding the OSPAN score. Indeed, 17% and 23% lower OSPAN scores occurred compared to office and natural environments, respectively. Regarding the visual factor, a positive influence of the presence of natural elements was highlighted. Participants scored higher when in the indoor green scenario than in the non-biophilic and outdoor natural environments (16% and 8%, respectively), and 7% higher in the outdoor natural environments in comparison with the non-biophilic scenario. The percentages of improvement linked to natural visual and acoustic factors for the OSPAN score were a little lower in comparison with the number of letters memorised. This was caused by the fact that the OSPAN score was computed as the sum of the number of the right true/false and the letters correctly memorised. In particular, the acoustic factors had a higher impact on the number of correct letters memorised in comparison with that of indoor layouts. However, the improvement in working memory due to visual biophilic elements is in line with previous studies [56,57]. Considering the significant interaction effect, the best visual*acoustic condition in terms of letters memorised and OSPAN score for the working-memory task occurred with Natural sounds in the Indoor Green condition, while the lower score was detected within the Traffic sound in the Non-Biophilic condition.

To sum up, the results indicated that the improvement in task-switching, inhibition and working memory performance seemed to be dependent upon the acoustic and visual presence of nature within the working environment. This is in agreement with existing literature even if previous VR-based studies evaluated the impact of nature-based solutions exposure only concerning the visual dimension and a limited assessment of cognitive responses.

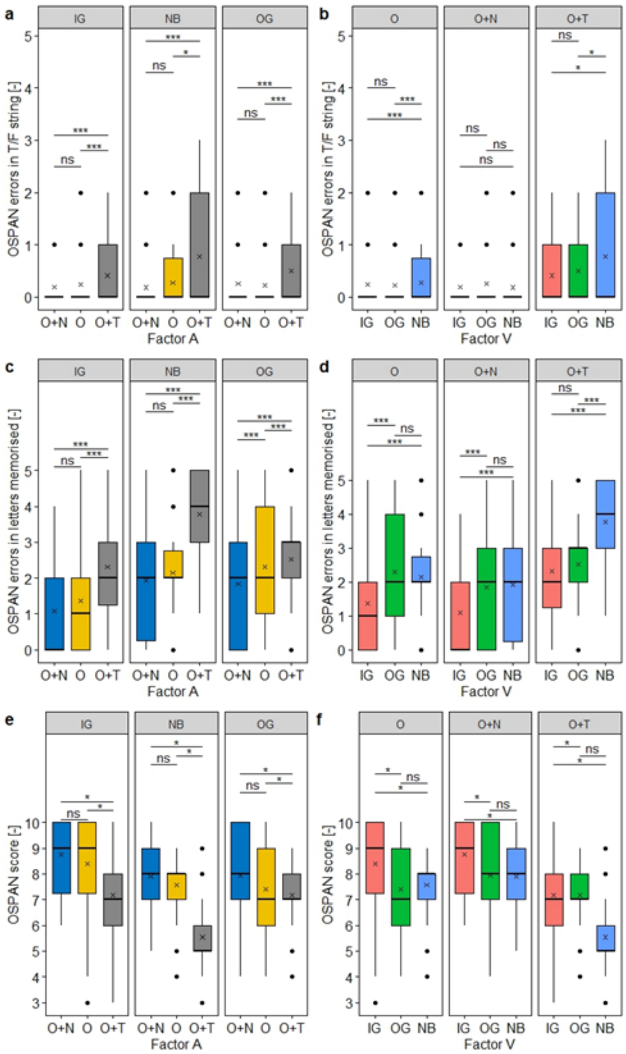

Figure V - 25 Chapter III: Boxplot of the errors in T-F string (a,b), errors in letters memorised (c,d) and OSPAN score (e,f) within the OSPAN test. Data are grouped by Factor V (a,c,e) and Factor A (b,d,f), and pairwise comparisons are shown. Inside the boxplots, the cross is the mean value, and the line is the median value. ns.: non significative, * p≤ 0.05, ** p≤ 0.01, *** p≤ 0.001

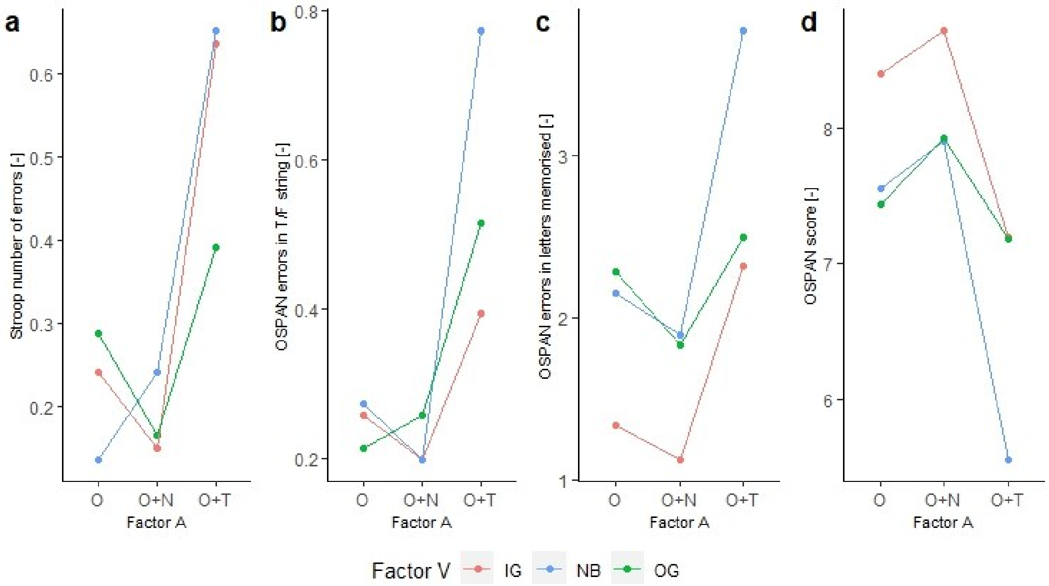

Figure V - 26 Chapter III: Interaction plot for the Stroop test (a) and OSPAN test considering the errors in T/F string (b), errors in letters memorised (c) and OSPAN score (d)

Cognitive function parameter	Factor	Level	Mean(sd)	Anova, type "III" (GLMM)	η^2	Pairwise comparison	Pairwise comparison result
MP number errors	V	NB	0.81(0.97)	$\chi^2(2) = 1.60$, $p = 0.43$			
		IG	0.71(0.79)				
		OG	0.70(0.87)				
	A	O	0.55(0.85)	$\chi^2(2) = 51.50$, **$p < 0.05$**	0.96	O – O+N	$p_{adj} = 0.97$
		O+N	0.38(0.59)			O+N – O+ T	**$p_{adj} < 0.05$**
		O+T	1.30(1.19)			O+T – O	**$p_{adj} < 0.05$**
	VxA			χ^2 (4) = 2.08, $p = 0.72$			
Stroop number errors	V	NB	0.34(0.60)	$\chi^2(2) = 1.48$, $p = 0.47$			
		IG	0.33(0.61)				
		OG	0.28(0.87)				
	A	O	0.22(0.69)	χ^2 (2) = 30.51, **$p < 0.05$**	0.77	O – O+N	$p_{adj} = 0.99$
		O+N	0.18(0.45)			O+N – O+ T	**$p_{adj} < 0.05$**
		O+T	0.55(0.94)			O+T – O	**$p_{adj} < 0.05$**
	VxA			χ^2 (4) = 9.53, **$p < 0.05$**			
Stroop speed of execution	V	NB	33.24(6.67)	χ^2 (2) = 145.62, **$p < 0.05$**	0.81	NB – IG	**$p_{adj} < 0.05$**
		IG	28.47(6.19)			IG – OG	**$p_{adj} < 0.05$**
		OG	34.21(6.89)			OG – NB	$p_{adj} = 0.99$
	A	O	31.71(5.93)	χ^2 (2) = 21.85, **$p < 0.05$**	0.17	O – O+N	$p_{adj} = 1.00$
		O+N	31.02(6.39)			O+N – O+ T	**$p_{adj} < 0.05$**
		O+T	33.99(6.50)			O+T – O	**$p_{adj} < 0.05$**
	VxA			χ^2 (4) = 2.14, $p = 0.47$			
OSPAN errors T/F	V	NB	0.41(0.61)	χ^2 (2) = 6.03, **$p < 0.05$**	0.10	NB – IG	**$p_{adj} < 0.05$**
		IG	0.28(0.52)			IG – OG	$p_{adj} = 1.00$
		OG	0.33(0.52)			OG – NB	**$p_{adj} < 0.05$**
	A	O	0.25(0.49)	χ^2 (2) = 23.51, **$p < 0.05$**	0.90	O – O+N	$p_{adj} = 1.00$
		O+N	0.21(0.43)			O+N – O+ T	**$p_{adj} < 0.05$**
		O+T	0.56(0.72)			O+T – O	**$p_{adj} < 0.05$**
	VxA			χ^2 (4) = 9.85, **$p < 0.05$**			

OSPAN errors in letters	V	NB	2.62(1.34)	χ^2 (2) = 48.81, **p < 0.05**	0.36	NB – IG	**p_{adj} < 0.05**
		IG	1.59(1.36)			IG – OG	**p_{adj} < 0.05**
		OG	2.22(1.57)			OG – NB	p_{adj} = 0.16
	A	O	1.94(1.48)	χ^2 (2) = 68.41, **p < 0.05**	0.54	O – O+N	p_{adj} = 0.06
		O+N	1.62(1.50)			O+N – O+ T	**p_{adj} < 0.05**
		O+T	2.87(1.29)			O+T – O	**p_{adj} < 0.05**
	VxA			χ^2 (4) = 13.22, **p < 0.05**			
OSPAN score	V	NB	7.00(1.35)	χ^2 (2) = 15.74, **p < 0.05**	0.25	NB – IG	**p_{adj} < 0.05**
		IG	8.11(1.57)			IG – OG	**p_{adj} < 0.05**
		OG	7.51(1.60)			OG – NB	p_{adj} = 0.09
	A	O	7.79(1.59)	χ^2 (2) = 33.21, **p < 0.05**	0.57	O – O+N	p_{adj} = 0.46
		O+N	8.19(1.57)			O+N – O+ T	**p_{adj} < 0.05**
		O+T	6.64(1.37)			O+T – O	**p_{adj} < 0.05**
	VxA			χ^2 (4) = 10.54, **p < 0.05**			

Table V - 11 Chapter III: Summary of the main and interaction effects of the type of visual scenario (independent variable 1) and the type of acoustic scenario (independent variable 2) on the parameter of the three cognitive tests from the GLMM Anova test. The table presents the Chi-squared statistic, the p-values, the generalized eta squared values (η^2) and the post-hoc comparison results. V = Visual scenario; A = Acoustic scenario; VxA = Interaction.

		MP test	Stroop test		OSPAN test		
Factor V	Factor A	number of errors	number of errors in the colour recall	speed of execution	number of errors in the T/F	number of errors in letters recalled	OSPAN score
		[-]	[-]	[s]	[-]	[-]	[-]
IG	O+N	0.30±0.46	0.14±0.35	26.98±5.28	0.20±0.40	1.09±1.25	8.76±1.35
IG	O	0.50±0.64	0.24±0.50	27.55±5.13	0.24±0.53	1.36±1.57	8.39±1.80
IG	O+T	1.33±1.28	0.62±0.99	30.28±5.34	0.41±0.63	2.32±1.28	7.18±1.58
OG	O+N	0.39±0.68	0.17±0.48	34.02±7.09	0.26±0.47	1.83±1.72	7.92±1.85
OG	O	0.56±0.79	0.29±1.15	32.01±4.92	0.23±0.46	2.30±1.68	7.41±1.72
OG	O+T	1.15±1.14	0.38±0.97	36.60±8.67	0.50±0.61	2.52±1.29	7.18±1.23
NB	O+N	0.44±0.64	0.24±0.53	32.05±6.80	0.18±0.43	1.92±1.52	7.89±1.51
NB	O	0.58±1.12	0.14±0.43	32.57±7.74	0.27±0.48	2.15±1.19	7.56±1.24
NB	O+T	1.41±1.16	0.65±0.85	35.09±5.48	0.77±0.92	3.77±1.30	5.55±1.30

Table V - 12 Chapter III: Data mean and standard deviation of the cognitive tasks across Factor V and Factor A scenarios

5.3.3.4. Effect of audio-visual connection with nature on soundscape assessment

The results of the GLMM model highlighted a primary effect of acoustic stimuli on the perceptual dimensions of pleasantness and eventfulness. Considering the ISOPleasant score, the results of the statistical analysis revealed a significant main effect for Acoustic ($\chi^2(2)$ = 605.98, $p < 0.05$, η^2 = 0.96) and for Visual Factor even if the effect size was negligible ($\chi^2(2)$ = 7.7, $p < 0.05$, η^2 = 0.02). The same result occurs for the ISOEventful scores with a significant main effect for Factor A ($\chi^2(2)$ = 415.49, $p < 0.05$, η^2 = 0.92) and a significant but negligible effect for Factor V ($\chi^2(2)$ = 28.40, $p < 0.05$, η^2 = 0.06). Post-hoc test confirmed the difference between the three acoustical scenarios but not between the three visual office layouts for both ISOPleasant and ISOEventful (see Table V - 13).

In addition, the interaction effect between Factor A and Factor V was significant (χ^2 (4) = 15.68, $p < 0.05$) for the ISOPleasant scores. Figure V - 27 shows that the effects of sound conditions on pleasantness depend on the visual factor. Notably, the IG condition is the most effective visual condition in the O+N, while it is associated with lower pleasantness when exposed to Traffic sounds compared to

Non-Biophilic and Outdoor Green scenarios. Similarly, the OG condition is most effective in the O+T acoustic scenario, and the least effective in the O+N condition. However, differences in median scores seemed negligible.

Parameters	Factor	Level	Mean(sd)	Anova, type "III" (GLMM)	η^2	Pairwise comparison	Pairwise comparison result
ISOPleasant	V	NB	0.09(0.23)	$\chi^2(2) = 7.77$, $\mathbf{p < 0.05}$	0.02	NB – IG	$p_{adj} = 0.99$
		IG	0.14(0.20)			IG – OG	$p_{adj} = 0.99$
		OG	0.07(0.24)			OG – NB	$p_{adj} = 0.99$
	A	O	0.14(0.24)	$\chi^2(2) = 605.98$, $\mathbf{p < 0.05}$	0.96	O < O+N	$\mathbf{p_{adj} < 0.05}$
		O+N	0.41(0.19)			O+N > O+T	$\mathbf{p_{adj} < 0.05}$
		O+T	-0.25(0.25)			O+T < O	$\mathbf{p_{adj} < 0.05}$
	VxA			$\chi^2(4) = 15.68$, $\mathbf{p < 0.05}$			
ISOEventful	V	NB	-0.08(0.25)	$\chi^2(2) = 28.40$, $\mathbf{p < 0.05}$	0.06	NB – IG	$p_{adj} = 0.99$
		IG	0.05(0.24)			IG – OG	$p_{adj} = 0.99$
		OG	-0.06(0.27)			OG – NB	$p_{adj} = 0.99$
	A	O	-0.27(0.27)	$\chi^2(2) = 415.49$ $\mathbf{p < 0.05}$	0.92	O< O+N	$\mathbf{p_{adj} < 0.05}$
		O+N	-0.04(0.23)			O+N < O+T	$\mathbf{p_{adj} < 0.05}$
		O+T	0.23(0.26)			O+T > O	$\mathbf{p_{adj} < 0.05}$
	VxA			$\chi^2(4) = 8.11$, $p = 0.08$			

Table V - 13 Chapter III: Summary of the main and interaction effects of the type of visual scenario (independent variable 1) and the type of acoustical scenario (independent variable 2) on the ISOPLeasant and ISOEventful coordinates from the GLMM Anova test. The table presents the Chi-squared statistic, the p-values, the generalized eta-squared values (η^2) and the post-hoc comparison results. V = Visual scenario; A = Acoustical scenario; VxA = Interaction.

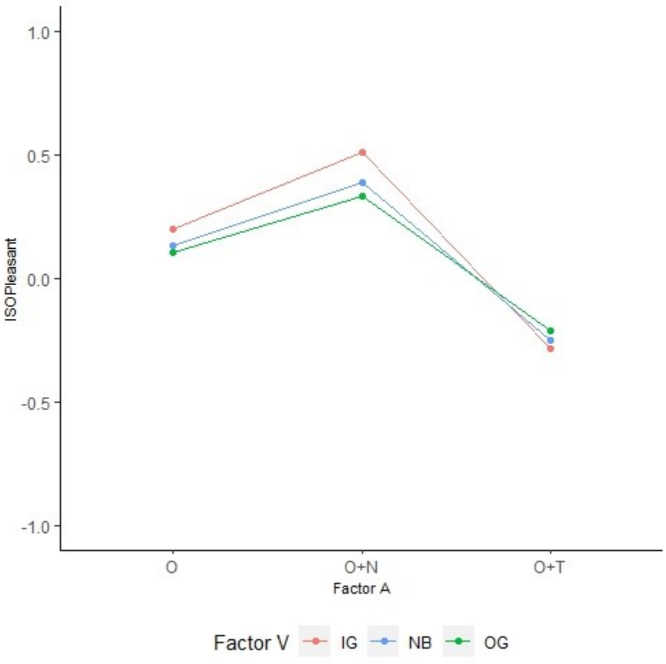

Figure V - 27 Chapter III: Interaction plot for the ISOPleasant scores

Figure V - 28 presents a visualisation of the soundscape assessment of the three visual (IG, NB, OG) and acoustical conditions (O, O+N, O+T), together with their combination. In the figure, the three contours represent the 50th percentile contours, i.e. the areas including 50% of responses [243].
Considering Factor V (Figure V - 28a), it can be noticed that the visual factor is not effective in determining the affective response to the indoor soundscape. It can be observed how the three visual conditions range across positive and negative pleasantness evaluations, depending on the associated acoustic conditions. This is substantiated by the results of the GLMM model.
Concerning Factor A levels, Figure V - 28b reveals that the Traffic scenario with vehicle noise was perceived as chaotic and unpleasant by at least 81% of users (scores assigned to «agree», and «totally agree»). Nature+Office and Office scenarios were perceived as similarly calm (85% and 77%, respectively), but it can be noticed how natural sounds could improve the pleasantness of the office

environment (86% vs 42%, respectively). Looking at the indoor soundscape contours that characterise each perceptual attribute for Factor A, it can be noticed that the office scenario, characterized by the presence of people quietly chattering and phone rings, was rated as rather uneventful (76%), or even monotonous. The superimposition of natural sounds makes the O+N scenario perceived as more pleasant and eventful, thus resulting overall vibrant (58%).
Figure V - 28c shows the relative change in the soundscape perception of the mean ISO coordinates for each combined Factor A * Factor V scenario.

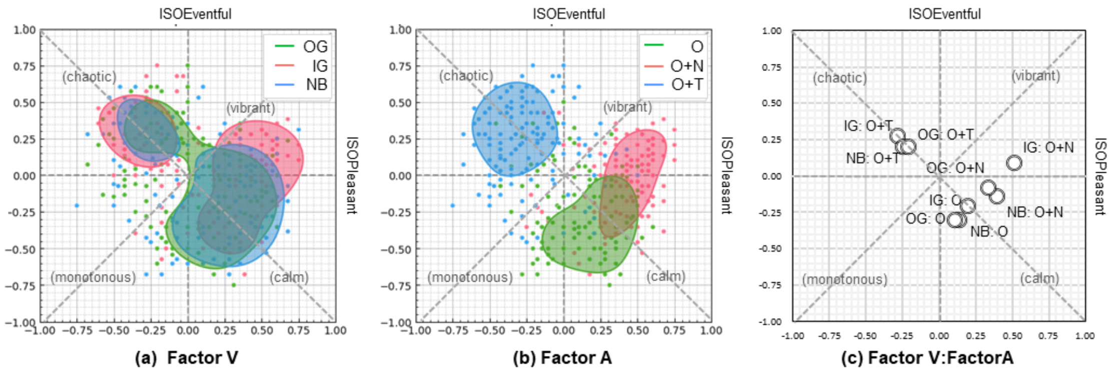

Figure V - 28 Chapter III: Comparison of the soundscape of the three Visual scenarios (a) and of the three Acoustical scenarios (b); the dots representing the median ISOPleasant and ISOEventful responses for each Factor V: Factor A scenarios (c)

These results can be discussed as follows.
While the reference acoustic condition (office noise) was assessed as uneventful, and slightly pleasant but also somewhat monotonous, the addition of traffic sounds led to an increase in eventfulness and a decrease in pleasantness, resulting in a chaotic soundscape. This aligns with previous literature indicating that the sound of traffic negatively affects pleasantness [231,248,249] in such a way to be considered as a negative component [124,250].
Interestingly, the introduction of natural sounds increased the eventfulness ratings, saturating the acoustic environment with additional sounds, and enhanced pleasantness, thus resulting in a vibrant soundscape. The improvement in pleasantness attributed to natural sounds can be explained, on one hand, by an energetic masking effect of office noise and, on the other hand, by an affective effect related to the meaning associated with natural sounds. Whereas traffic noise and other mechanical/technological sounds are often perceived negatively, this study supported literature [124,232] indicating that people tend to perceive natural sounds as positive components of soundscapes. Natural sounds (e.g., consisting of bird songs) can facilitate restorative outcomes [223,251,252], and provide masking opportunities over traffic noise [253]. Literature has demonstrated that the sounds of nature are often the most desirable and beneficial to promote positive indoor soundscapes, enhance mood and cognitive performance, and reduce stress [123,124,254–256]. Those findings supported restorative potentials consistently with the Attention Restoration Theory [257]. This study adds to the present literature by showing the benefits of natural sounds in the specific context of office environments, in terms of increased pleasantness but also eventfulness, thus increasing soundscape vibrancy.
Although the visual factor is not significant, there are interesting audio-visual interaction effects on the perception of soundscape pleasantness. Despite the rather small effect size, it can be observed that the impact of natural sounds on pleasantness is amplified in the presence of an indoor green condition, while it is reduced when the green element is observed through the window. This result aligns with previous studies on the connection between visual and auditory pathways demonstrating, for example, that bird songs were perceived as more positive if coupled with congruent natural visual stimuli [258]. This may indicate that the positive effect of natural sounds on pleasantness might be overperformed when people are in a «Visual Connection With Nature» [229] indoors. Thus, outcomes demonstrated that visual and acoustical connection with nature was effective for increasing pleasantness. On the other hand, a view of greenery through the window can improve pleasantness in the presence of traffic noise, although the effect is relatively small. This outcome accords with the one presented by Sanchez [231] who showed that visual elements including greenery can positively influence soundscape pleasantness in the presence of light traffic noise (but not with heavy traffic noise). The moderating effect of green views on pleasantness (or annoyance) associated with traffic noise is consistently reported in the literature (see

e.g., [259–261]). This might indicate that green scenarios are more likely to draw attention for a longer period, which in turn decreases the attention given to environmental noise [261]. Indeed, Jo [232] proposed to increase natural elements as an effective way to improve both acoustic and visual satisfaction.
If the benefits of Biophilic Design interventions on individuals have been mainly studied so far from an urban planning perspective, this study contributes with considerations on the potential benefits from combined visual and acoustic exposure to nature-related stimuli in indoor environments. This evidence prompts consideration of the importance of urban green corridors that can be accessed (also auditorily) indoors, for example, through urban ventilation strategies. However, depending on the specific building environment site and location, natural contexts might be not always available. Thus, the outcomes of the present study suggest that in these contexts artificial natural sounds and indoor greenery might be beneficial to the (perceived) soundscape. However, building designers should carefully take into consideration occupants' needs and preferences, the specific building use (e.g., working environment, residential, commercial) and related tasks to be performed. In order to design indoor environments to be perceptually more supportive and comfortable via audio-visual connection with nature, a participative approach involving end-users should be considered during the design stage [218], accompanied by VR scenarios that have been recognized as useful soundscape evaluating tools [262].

5.3.3.5. Effect of audio-visual connection with nature on physiological response

Electro-Dermal Activity

Considering the participants' Electro-Dermal Activity, the results of the statistical analysis revealed a significant main effect of Visual Factor ($\chi^2(2)$ = = 9.07, $p < 0.05$, $\eta^2 = 0.78$) with lower values in Indoor Green (0.40 ± 0.77) than in Non-Biophilic (0.73 ± 1.24) and Outdoor Green (0.75 ± 1.50) conditions. There was also a main effect of Acoustic Factor ($\chi^2(2)$ = = 9.07, $p < 0.05$, $\eta^2 = 0.91$) with lower values of EDA in Natural (0.44 ± 0.91) than in Office (0.64 ± 1.21) and Traffic (0.81 ± 1.39) conditions. The magnitude of the effect highlighted that acoustical factors had a similar influence on EDA values compared to visual factors (cf. Table V - 14).
According to the post-hoc test results and the pairwise comparison presented in Figure V - 29a, the values of EDA were significantly lower with Natural sounds than Traffic ($p_{adj} < 0.05$) in all IG, OG and NB conditions. The lower mean scores (cf. Table V - 15), occurred with IG in the O+N condition (0.27±0.52) in comparison with O (0.41±0.79) and O+T (0.53±0.99) for all the other three visual scenarios. Notably, Traffic sounds had a significant detrimental effect on EDA values in all the visual scenarios. In addition, considering Factor V (Figure V - 29b), a significant difference occurred only in IG compared to both NB and OG ($p_{adj} < 0.05$): IG resulted in lower EDA values within the three acoustical scenarios. However, the results in outdoor greenery conditions were not significantly different from those in IG and NB. Moreover, the absence of a significant effect for the interaction between Factor V and Factor A was detected ($\chi^2(4) = 0.43$, $p = 0.98$).

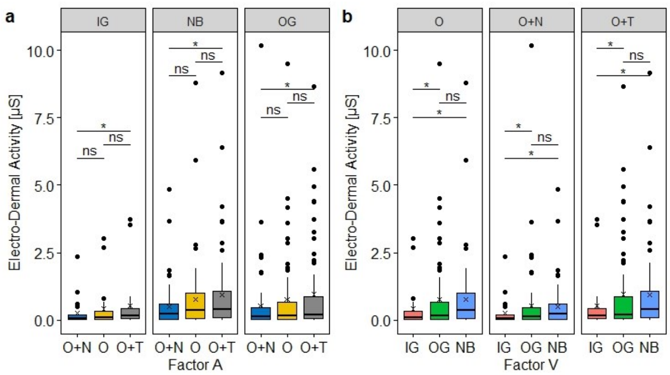

Figure V - 29 Chapter III: Boxplot of the participants' Electro-Dermal Activity expressed in µS. Data are grouped by Factor V (a) and Factor A (b) and pairwise comparisons are shown. Inside the boxplots, the cross is the mean value and the line is the median value. ns.: non significative, * p≤ 0.05, ** p≤ 0.01, *** p≤ 0.001

Pulse Rate

A significant main effect for the Acoustic Factor, ($\chi^2(2) = 58.48$ $p < 0.05$, $\eta^2 = 0.94$), was detected for the Pulse Rate. Results indicated lower bpm in the Natural sound condition (74.84±11.52) than in the

Office (79.32±12.14) and Traffic (84.48±12.37). Post-hoc test confirmed the difference between the three acoustical scenarios ($p_{adj} < 0.05$). Indeed, the paired comparisons (Figure V - 30a) showed the highest decrease in the bpm with Natural sounds in the IG, OG, and NB conditions compared with Office and Traffic sounds. The same result occurs with Office compared with Traffic sounds. An ameliorative effect of natural sound above traditional working soundscape was highlighted and a detrimental effect of traffic conditions.

There were no main effects of Visual Factor ($\chi^2(4) = 2.79$, $p = 0.59$), and the interaction effect was not significant ($\chi^2(2) = 0.18$, $p = 0.91$). Indeed, comparing the distributions (Figure V - 30b) and mean values reported in Table V - 15, participants had about the same average bpm values with natural sounds in the IG condition (75.97±9.91) in comparison with OG (74.84±12.57) and NB (74.61±12.08).

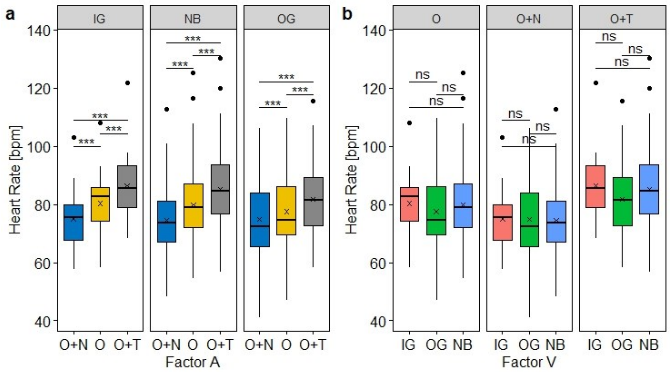

Figure V - 30 Chapter III: Boxplot of the participants' Pulse Rate expressed in beats per minute. Data are grouped by Factor V (a) and Factor A (b) and pairwise comparisons are shown. Inside the boxplots, the cross is the mean value and the line is the median value. ns.: non significative, * p≤ 0.05, ** p≤ 0.01, *** p≤ 0.001

Skin Temperature

Lastly, regarding the Skin Temperature (cf. Table V - 14 and Figure V - 31), the statistical analysis revealed the absence of significant effects of Visual Factor ($\chi^2(2) = 0.18$, $p = 0.91$), Acoustical Factor ($\chi^2(2) = 4.51$, $p = 0.11$) and their interaction ($\chi^2(4) = 2.59$, $p = 0.63$).

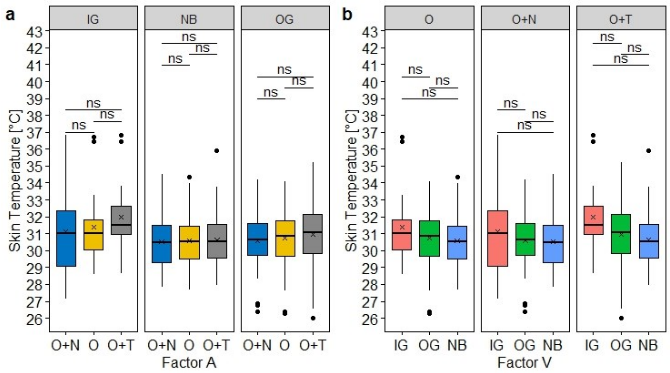

Figure V - 31 Chapter III: Boxplot of the participants' Skin Temperature expressed in beats per minute. Data are grouped by Factor V (a) and Factor A (b) and pairwise comparisons are shown. Inside the boxplots, the cross is the mean value and the line is the median value. ns.: non significative, * p≤ 0.05, ** p≤ 0.01, *** p≤ 0.001

These results can be interpreted as follows. First, the authors confirmed that the selected physiological parameters (except for ST) were stress responses attributed to the pleasantness of acoustical scenarios and that parasympathetic activation might be affected by acoustical dimensions during task execution. Indeed, stress caused by traffic noise exposure stimulated sympathetic nerves and increased EDA and PR. On the contrary, the lower activation of the sympathetic nerves occurred in the presence of natural elements and decreased EDA and PR. Second, considering the perceptual assessment of soundscape, highly pleasant natural excerpts resulted in lower EDA and PR than unpleasant traffic excerpts. Indeed, results from sound exposure showed that the soundscapes rated as the least pleasant (O+T) were linked to higher EDA values compared to the most pleasant one (O+N) Outcomes are consistent with the expectation that exposure to pleasant soundscapes will be associated with lower physiology, compared to unpleasant sounds. In addition, these results support previous literature showing the relationship

between pleasantness soundscape and lower EDA values (e.g., Ref [210,248,263,264]) and pulse rate in both VR [263] and real settings studies[264]. However, this did not agree with other works [248,256], which found an opposite relationship between unpleasantness and deceleration in bpm, while Irwin et al. [249] found no significant alteration of pulse rate as a function of pleasantness.
Concerning the visual dimension of the office room, the same decrease in EDA associated with natural-element presence was highlighted in other studies focusing on virtual indoor environment (e.g., Ref [56,81,83]), and urban context (e.g., Ref [230,265]). Considering PR, the findings are not consistent with previous empirical studies [230,265] which demonstrated that the presence of indoor greenery reduced stress levels and individual bpm values due to the activation of the parasympathetic nerve. However, similar inconclusive results were highlighted by [87], because PR showed no effect of visual factor, this null finding suggests that the parasympathetic activation may be less affected by visual dimensions during task execution.
In general, the absence of relevant influence of visual and acoustical factors on ST agrees with previous literature [87]. However, this is inconsistent with the expectation that visual connection with nature and natural sound exposure will be associated with positive changes in ST.
In an indoor built environment, it is important to couple equal concerns on IEQ levels, perceptual implications and the need to support building occupants in returning to baseline psychophysiological conditions after experiencing a stressor [23], particularly in office space. For example, several studies provided evidence from correspondence between physiological variables (e.g., skin conductance, heart rate, brain activity) and the perceptual dimension of sound (e.g., Ref [210,230,248,249,256,263,264,266,267]. In the BD context, several studies have measured and analysed the physiological responses of people to natural elements with time, cost, and labour constraints since experimental environments with controlled factors are difficult to realize without VR advantages (e.g., Ref [192,200,201]). Moreover, most studies examining the potential of natural features on stress recovery [268] analysed one sensory stimulus at a time, even if human perception of the environment is highly multisensory. Thus, the measure of objective physiological responses in association with the subjective perceptual dimension in VR could support the development of meaningful patterns of response as the starting point for a more comprehensive assessment of the indoor built environment since the early design stages.

Physiological parameters	Factor	Level	Mean(sd)	Anova, type "III" (GLMM)	η^2	Pairwise comparison	Pairwise comparison result
Electro-Dermal Activity	V	NB	0.73(1.24)	$\chi^2(2) = 6.12$, $\mathbf{p < 0.05}$	0.78	NB – IG	$\mathbf{p_{adj} < 0.05}$
(EDA)		IG	0.40(0.77)			IG – OG	$\mathbf{p_{adj} < 0.05}$
[μS]		OG	0.75(1.50)			OG – NB	$p_{adj} = 0.57$
	A	O	0.64(1.21)	$\chi^2(2) = 9.07$, $\mathbf{p < 0.05}$	0.91	O – O+N	$p_{adj} = 0.51$
		O+N	0.44(0.91)			O+N – O+T	$\mathbf{p_{adj} < 0.05}$
		O+T	0.81(1.39)			O+T – O	$p_{adj} = 0.82$
	VxA			$\chi^2(4) = 0.43$, $p = 0.98$			
Heart Rate	V	NB	79.95(13.10)	$\chi^2(2) = 0.18$, $p = 0.91$			
(HR)		IG	80.63(10.45)				
[bpm]		OG	78.05(12.48)				
	A	O	79.32(12.14)	$\chi^2(2) = 58.48$ $\mathbf{p < 0.05}$	0.94	O – O+N	$\mathbf{p_{adj} < 0.05}$
		O+N	74.84(11.52)			O+N – O+T	$\mathbf{p_{adj} < 0.05}$
		O+T	84.48(12.37)			O+T – O	$\mathbf{p_{adj} < 0.05}$
	VxA			$\chi^2(4) = 2.79$, $p = 0.59$			
Skin Temperature	V	NB	30.58(1.53)	$\chi^2(2) = 0.34$, $p = 0.84$			
(ST)		IG	31.48(2.09)				
[°C]		OG	30.76(1.65)				
	A	O	30.90(1.71)	$\chi^2(2) = 4.51$, $p = 0.11$			
		O+N	30.74(1.79)				
		O+T	31.19(1.77)				

VxA	$\chi^2(4) = 2.59$, $p = 0.63$

Table V - 14 Chapter III: Summary of the main and interaction effects of the type of visual scenario (independent variable 1) and the type of acoustical scenario (independent variable 2) on the physiological parameter from the GLMM Anova test. The table presents the Chi-squared statistic, the p-values, the generalized eta squared values (η^2) and the post-hoc comparison results. V = Visual scenario; A = Acoustical scenario; VxA = Interaction.

Factor V	Factor A	EDA [μS]	HR [bpm]	ST [°C]
IG	O+N	0.27±0.52	75.97±9.91	31.11±2.35
IG	O	0.41±0.79	80.39±10.27	31.37±2.00
IG	O+T	0.53±0.99	86.44±11.16	31.96±1.91
OG	O+N	0.54±1.38	74.84±12.57	30.58±1.52
OG	O	0.75±1.49	77.53±12.53	30.74±1.61
OG	O+T	0.95±1.63	81.78±12.34	30.97±1.81
NB	O+N	0.50±0.82	74.61±12.08	30.52±1.48
NB	O	0.76±1.36	80.03±13.61	30.59±1.51
NB	O+T	0.94±1.55	85.23±13.61	30.64±1.60

Table V - 15 Chapter III: Data mean and standard deviation of the physiological parameters across Factor V and Factor A scenarios

5.3.3.6. Physiological parameters and soundscape assessment relationship

In the following analysis, associations between ISOPleasant and ISOEventful scores and physiological parameters were considered.

The graphs and the calculation of Spearman's rho coefficient (Figure V - 32) show a statistically moderate-to-strong negative correlation between ST and ISOPleasant, in the case of natural sound within the indoor green scenario (rho=−0.61, $p < 0.05$). The negative correlation between ST and ISOPleasant showed a faster decline in skin temperature in response to more pleasant and less eventful acoustical conditions (nature). If the authors consider a specific environmental condition with indoor greenery, the expectation that a visual connection with nature and natural sound exposure will be associated with positive changes in ST seems satisfied. However, this result can be generalized only to a site-specific condition.

No statistically significant correlation was found with the electro-dermal activity and the pulse rate in all visual and acoustical scenarios (all p-values > 0.05).

The analysis for ISOEventful values showed no statistically significant correlation with the three physiological parameters (all p-values > 0.05) as in [248,249]. An exception occurred for a small-to-moderate positive correlation with PR in the case of traffic sound within the NB scenario (rho=0.35, $p < 0.05$) which suggested the more unpleasantly and eventfully scored sound (traffic) gave the largest bpm increase. This result is consistent with the previously mentioned result and literature showing that higher bpm is significantly related to the least pleasant and most eventful sound due to higher activation in the sympathetic nerve related to a stressful situation (e.g., Ref [263,264]). However, it is generalisable in case of the absence of nature-related elements indoors.

It is important to note that these limited outcomes might be related to the experimental design of the research activity. Firstly, the sample size of this study was limited to young university students, and groups such as middle-aged and elderly people need to be recruited to enhance the generalizability of the results. Secondly, due to the use of a VR headset and the within-subject design of the experiment, participants were exposed to each acoustical condition for a short time (6 minutes) which restricted the generalizability of the physiological parameters correlation results. Future research activities should carry out long-term experiments and further explore the benefits of a more prologued exposure to non-visual connection with nature, above all on physiological parameters. The importance of studying longer soundscape exposure times [248], could lead to an increase in the external–ecological validity of the study and could support further assessments of sound habituation underpinning physiological processes. In addition, the research investigation on the physiology of soundscape is still in its infancy and inconclusive [266]. Indeed, as previously stated by Erfanian et al. [266] «physiological expressions of the soundscape are not always aligned with the perceptual attributes and may remain inconclusive».

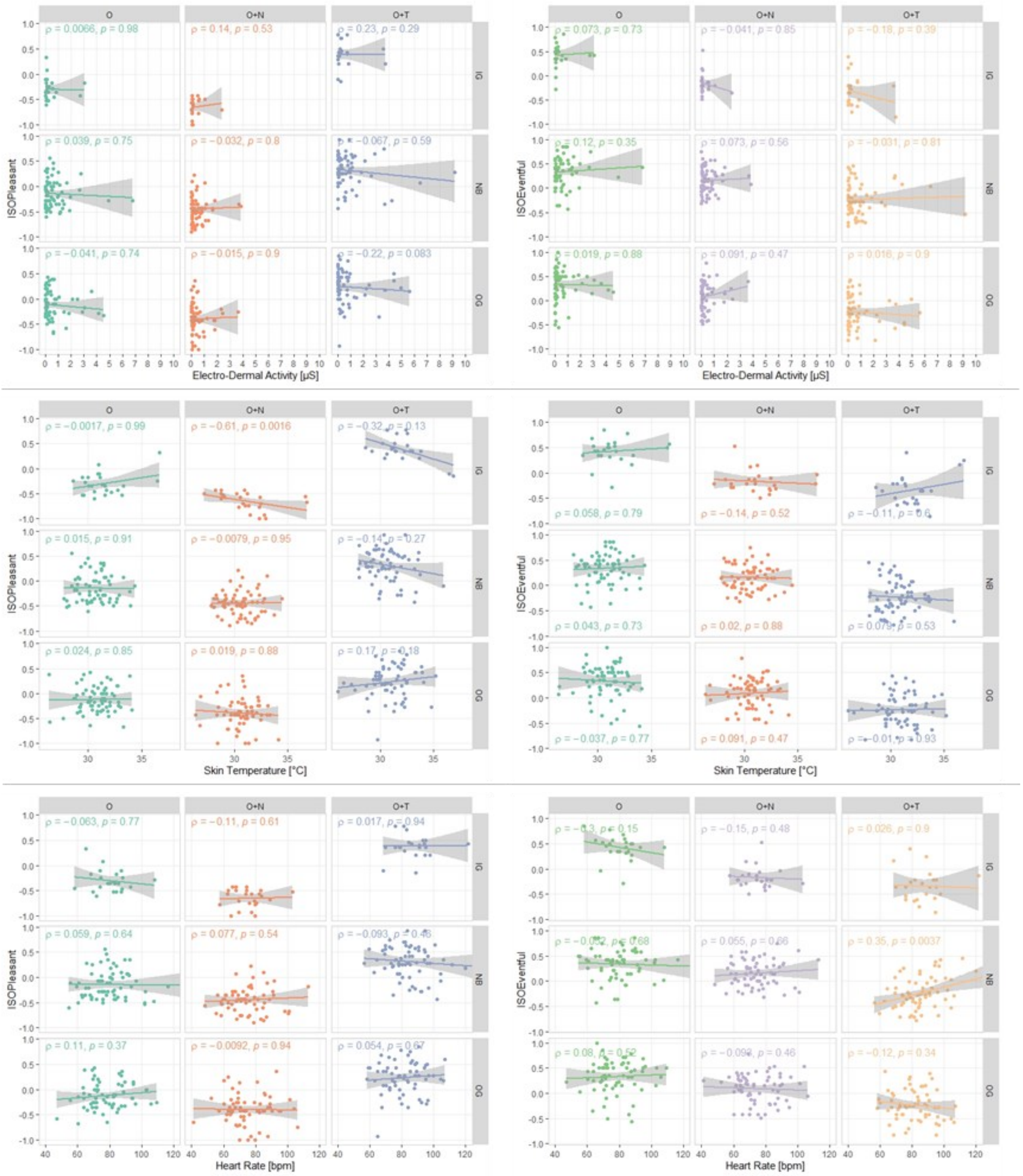

Figure V - 32 Chapter III: Correlation plot of the physiological parameters and the ISO coordinates

5.3.3.7. Effect of visual connection with nature on visual attention (adaptation phase)

Participants' visual attention and interest in the presence of indoor and outdoor greenery (IG: potted plant with flower, potted plant on the floor, green wall; OG: tree) were analysed during the adaptation phase.

Figure V - 33 shows the participants' attention to each of the considered natural elements in terms of A(o,t) and A(o,f). Results (Figure V - 33) showed that the flowered plant on the desk had the highest gaze time (A(o,t) = 100%), followed by the tree (A(o,t) = 68%), which means that it was observed for a longer time with respect to the other greeneries. On the contrary, the outdoor tree reported the highest number of fixations (A(o,f) = 100%), followed by the flowered plant (A(o,f) = 60%), indicating that it was the most engaging green element. Indeed, both the flowered plant and the outdoor tree were the nearest greenery to the participants with a higher visual interaction potential. During the adaptation phase participants could freely get closer to the flowered plant and turn to the left to look at the tree out of the window, while they were not given the possibility to get up to explore the green wall or the plant on the floor that was located farther away.

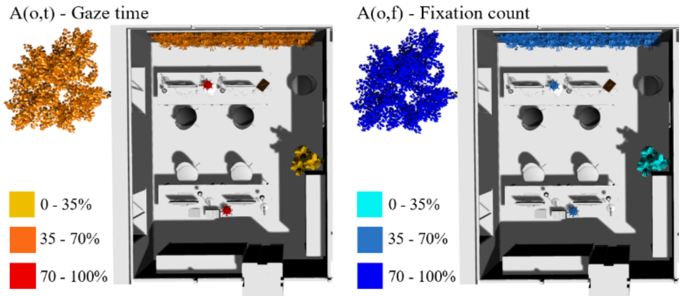

Figure V - 33 Chapter III: Participants' attention, in terms of attention time A(o,t) (a) and fixation counts A(o,f) (b)

Time to First Fixation (TTFF) and First Fixation Duration (FFD) were also computed to understand how greeneries were prioritized and how much they initially attracted attention. As reported in Table V - 16, the flowered plant had the lower TTFF (7.38s), which means that it was observed before the other natural elements, followed by the green wall (15.70s), the outdoor tree (15.74s) and lastly by the potted plant on the floor (45.12s). This result can be attributed to the spatial location of the greeneries and the proximity to the users who were sitting in front of the virtual monitor. For example, the plant on the floor was located behind the seat of the subjects who needed to turn around to get a full visualization, thus causing a higher TTFF, to catch any details and identify the object.
The flowered plant scored also the highest FFD (0.63s) due to its location on the desk inside the layout of the office environment. The green wall and the outdoor tree had the shortest FFD time (0.19s and 0.21s), maybe due to their dimensions, they were easier to identify and gained less attention. These results indicate that the flowered plant resulted to be very eye-catching among the three green objects (shortest TTFF, longest FFD).
Then, the average pupil diameter within the TTFF of each AOI was extracted. The flowered plant was considered as the baseline reference resulting in the most eye-catching object. However, the authors observed a pupil diameter 3% larger for the flowered plant than the green wall, and only 1% larger than the potted plant on the floor and the outdoor tree. These results are not significant thus indicating a consistent emotional experience of participants for all the green elements.

	Potted plant with flower	Green wall	Potted plant on the floor	Outdoor tree
A (o,t) [%]	100%	35%	33%	68%
A (o,f) [%]	60%	46%	29%	100%
TTFF [s]	7.38	14.67	45.12	15.74
FFD [s]	0.63	0.19	0.31	0.21
Pupil diameter [mm]	3.64 ± 0.43	3.55 ± 0.47	3.60 ± 0,50	3.60 ± 0.50

Table V - 16 Chapter III: Eye tracking indices across the three biophilic patterns integrated in the virtual model

In general, the participants' visual attention and interest in the presence of indoor and outdoor greenery seemed to be influenced by the spatial location of the greeneries and the distance to the users who were sitting in front of the virtual monitor (i.e., generated a higher number of fixation and gaze time). Indeed, the higher the proximity of participants to the natural element, the higher the visual interaction potential, and the stronger emotional attachment. In addition, a consistent emotional experience of participants for all the green elements (i.e., no differences in pupil dimension) was detected.

5.3.3.8. Eye-tracking metrics and cognitive performance relationship

To the authors' knowledge, there is a lack of literature in the field of eye-tracking metrics and cognitive task response in the presence of visual connection with nature which makes it difficult to compare the present outcomes. That is why this research activity was carried out as a first attempt to fill the literature gap and give researchers a landmark in the assessment of Biophilic Design intervention coupling traditional and innovative methods with users' gaze behaviour.

Correlation between cognitive tests and eye-tracking metrics

In absolute terms, Kendall's Tau correlation coefficient was calculated to investigate the relationship between eye movement metrics and cognitive function measures. Figure V - 34 presents the correlation plot which was useful to investigate the relationship between the metrics in terms of coefficients and p-values. Interesting correlations were detected (negative correlations are presented in blue squares while positive ones by a red scale):

- Fixation count correlated significantly with instruction reading time (positive, τ = 0.77), time to complete the Stroop test (positive, τ = 0.46), and number of errors in letters during the OSPAN test (positive, τ = 0.46).
- Fixation duration correlated significantly with instruction reading time (positive, τ = 0.90), time to complete the Stroop test (positive, τ = 0.63), and number of errors in letters during the OSPAN test (positive, τ = 0.41).
- Saccade count correlated significantly with instruction reading time (positive, τ = 0.75), time to complete the Stroop test (positive, τ = 0.30), and number of errors in letters during the OSPAN test (positive, τ = 0.46) and Stroop test errors (positive, τ = 0.21).
- Despite that, no correlation was detected with blinks and pupil dilatation.

Concerning the relationship between the eye-tracking metrics and errors detected in the Magnitude & Parity test and Stroop test, the absence of significant correlations emerged (p-value > 0.05).

The eye-tracking analysis reflected a common assumption in literature: the more the amount of fixation and duration, the increasing workload [133,135,143,144] which could be translated into the longer time it takes participants to understand instructions, complete the test and lower accuracy. These findings suggest that cognitive load measured by eye-tracking and performance results could potentially influence each other, as highlighted in previous literature [143,144] and that the fixations and saccades are the strongest determinants of time of completion and accuracy. Indeed, no relationship was detected with blinks in all three cognitive tasks. This result supported previous studies [137] but it is in contrast with others [147]. In addition, no relationship was detected between pupil dilatation and cognitive performance results, suggesting that it might not be the best indicator of workload in VR. Thus, blink and pupil parameters did not seem to capture cognitive task load differences for the specific tests performed in this research activity, as accurately as fixation count, fixation duration and saccade count variations. However, these findings did not align with the literature reporting higher pupil size for higher task load [137,142,147].

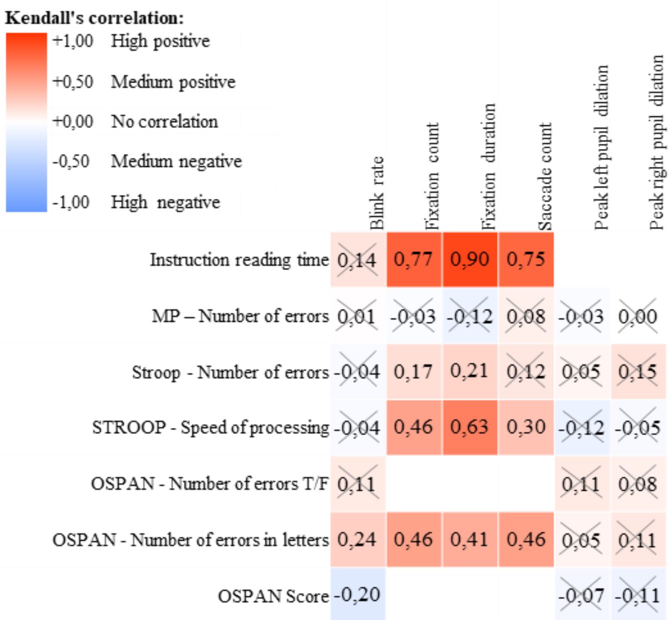

Figure V - 34 Chapter III: Kendall's Tau correlation matrix between eye tracking features and performance features in the cognitive tests: non-significant coefficient and p-values > 0.05 are indicated with a cross.

Instruction reading time

Then, differences in eye-tracking metrics between IG, OG and NB in task execution were analysed.

Considering the total instruction reading time, revealed significant differences ($\chi^2(2) = 28.22$, $p < 0.05$) within the three visual conditions with lower reading time in Indoor Green (39.30± 33.51s) than in Non-Biophilic (98.15±26.64s) and Outdoor Green (81.94±29.94s). Figure V - 35a shows the pairwise comparison. In accordance with post-hoc results, the reading time was significantly lower with indoor greenery than in outdoor greenery ($p < 0.05$, 60%) and no-greenery at all ($p < 0.05$, 17%) conditions. The magnitude of the effect highlighted (cf. Table V - 17) that visual factors had a moderate effect on instruction reading time. The results of the eye-tracking metrics also confirmed that the mental load was lower in the indoor green condition in comparison with OG and NB (cf. Table V - 18). Except for the blink rate ($p > 0.05$, Figure V - 35e), participants in IG showed significantly lower eye-tracking metrics ($p < 0.05$, Figure V - 35b,c,d). In comparison with NB and OG, participants showed lower fixation count (58% and 55%, respectively), fixation duration (64% and 53%, respectively) and saccade counts (53% and 58%, respectively) when in the presence of indoor natural elements. Instead, OG and NB have no statistically significant difference in terms of eye-tracking metrics.

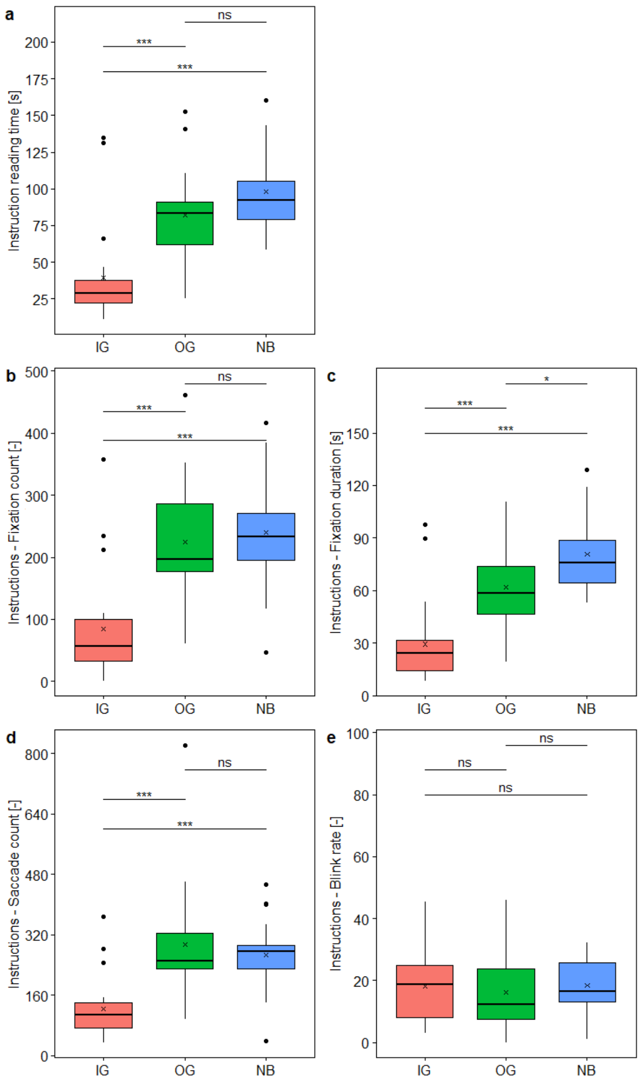

Figure V - 35 Chapter III: Instruction tasks: boxplot of the results of reading time and eye-tracking features in the IG, OG and NB conditions

Magnitude - Parity test (task-switching executive function)

Considering the errors in the classification of the digits in the Magnitude - Parity test, the results of the statistical analysis indicated the absence of significant differences between the three visual conditions ($\chi^2(2) = 2.05$, $p = 0.36$). despite that, a slight number of errors occurred for OG (0.24±0.54) and IG (0.62±1.36) in comparison with NB (1.05±1.75) (see Figure V - 36a). On average, although participants scored higher when in indoor green (41%) and outdoor green environments (77%) in comparison with

non-biophilic settings, those improvements were not statistically significant. Even if the increased accuracy seemed relevant in the presence of natural elements, this result is in line with the trend highlighted in the (indoor) VR-based BD literature on cognitive assessments [56,85].
For eye-tracking features, there were no statistically significant differences between the three conditions, except for the number of saccades ($\chi^2(2) = 7.98$, $p < 0.05$). Thus, this type of metric seemed not suitable for assessing mental load due to the nature of the Magnitude & Parity test. Indeed, as explained in section 3.3.1, digits and dots were presented in the middle of the screen, thus, this test did not require as not much eye movement to complete the task, as shown in the heatmap (Figure V - 39). Indeed, the gaze behaviour did not differ across the IG, OG and NB conditions and it was stable in the centre of the virtual monitor.

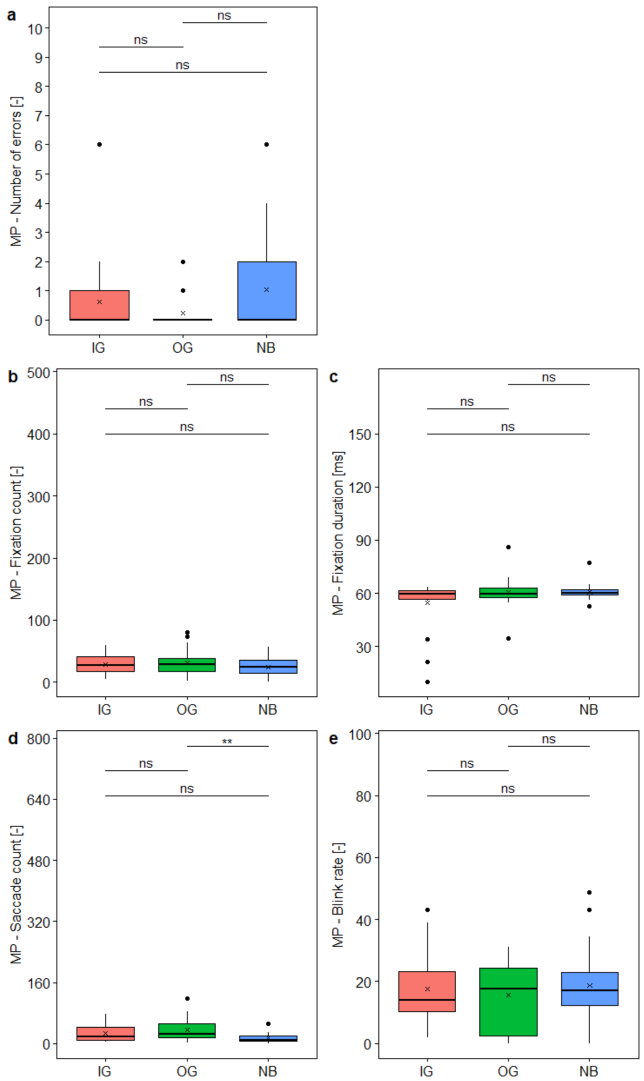

Figure V - 36 Chapter III: Magnitude and Parity test: boxplot of the results of the test and eye-tracking features in the IG, OG and NB conditions

OSPAN test (working memory cognitive function)

Regarding the OSPAN test, a significant effect of the visual condition (χ^2 (2) = 13.93, $p < 0.05$, $\eta^2 = 0.20$) was found for the errors in the true-false string. According to the post-hoc for the pairwise comparison (Figure V - 37a), participants were more accurate in Indoor Green (0.05±0.22) than in Outdoor Green (0.19±0.51) and Non-Biophilic (0.57±0.60) scenarios (75% and 92% respectively). However, the presence of indoor and outdoor greenery did not elicit relevant differences for this task. There were no differences in the number of errors in the letters memorised and in the OSPAN score but comparing the mean values of the number of errors (Table V - 17), participants scored fewer errors and a higher OSPAN score in the IG condition (0.90±1.45, 9.05±1.43) in comparison with OG (0.17 ±

0.48, 8.29±2.12) and NB (0.24 ± 0.53, 7.67±2.11). However, the improvement in working memory due to visual biophilic elements is in line with previous studies [56,57].
Considering the eye-tracking metrics during the OSPAN test, significant differences were highlighted for the fixation count ($\chi^2(2) = 10.25$, $p < 0.05$), fixation duration ($\chi^2(2) = 13.32$, $p < 0.05$) and saccade count ($\chi^2(2) = 7.78$, $p < 0.05$). For all these metrics, the pairwise comparisons revealed significantly lower values in the indoor green condition compared to outdoor green and non-biophilic scenarios (between 40% and 70% of reduction). This result suggested that, in the absence of significant differences in the number of letters, subjects mental load was lower to recall the correct order of letters in the IG condition. Thus, it seemed that they spent more time gazing at the screen and searching for the letters to recall in OG and NB conditions. However, no differences were found between OG and NB. As shown in Figure V - 39, in the heatmap, it was found that participants in the IG focused their attention on the goal-related task (i.e., the correct order of letters memorised). This outcome suggests a more efficient search for the correct information; whereas participants in OG and NB showed attention to the other letters displayed demonstrating a more inefficient gaze behaviour with longer fixations on multiple letters indicating a higher effort in remembering the correct order.

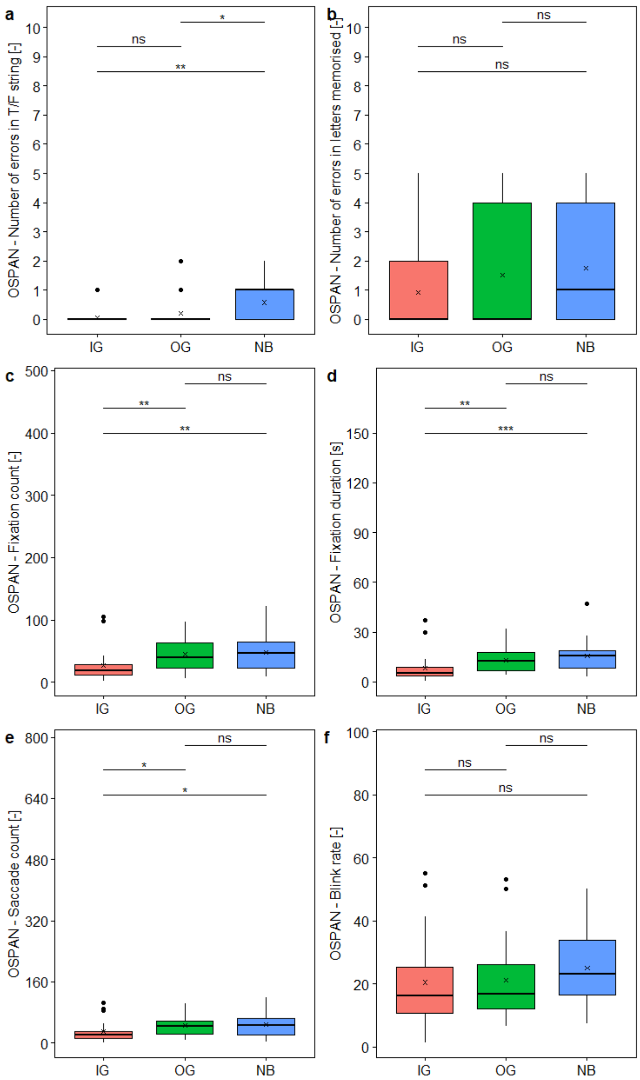

Figure V - 37 Chapter III: OSPAN test: boxplot of the results of the test and eye-tracking features in the IG, OG and NB conditions

Stroop test (inhibition executive function)

Concerning the Stroop test, significant differences between the scenarios were detected only for the speed of processing ($\chi2$ $(2) = 22.82$, $p < 0.05$, $\eta^2 = 0.35$) with lower time with indoor greenery (28.21±12.00s) than in outdoor greenery (37.01±6.95s) and no-greenery at all (37.74±9.47s) conditions,

as confirmed by the pairwise comparison (Figure V - 38b). Participants performed faster in the presence of natural elements indoors if compared with non-biophilic and outdoor natural environments (24% and 28%, respectively). This finding is consistent with existing literature which reported a positive correlation between greenery and cognitive function (e.g. [56,85]).
Regarding eye-tracking metrics within the Stroop test, significant differences were detected for the fixation count ($\chi^2(2) = 20.65$, $p < 0.05$), fixation duration ($\chi^2(2) = 23.60$, $p < 0.05$) and saccade count ($\chi^2(2) = 15.37$, $p < 0.05$). According to the post-hoc test and the pairwise comparison the lowest fixation count (Figure V - 38c), and duration (Figure V - 38d) occurred for IG: in comparison with NB and OG, the presence of natural element indoors induced participants to stare at the word fewer times (15% and 50%, respectively) and for a lower time (38% and 50%, respectively), thus completing the task faster. Heatmaps presented in Figure V - 39 showed that participants in the indoor green condition showed a more effective and efficient gaze movement (i.e., uniform gaze attention looking at the whole set of coloured words); whereas participants in IG and NB displayed a less efficient and uniform gaze behaviour.

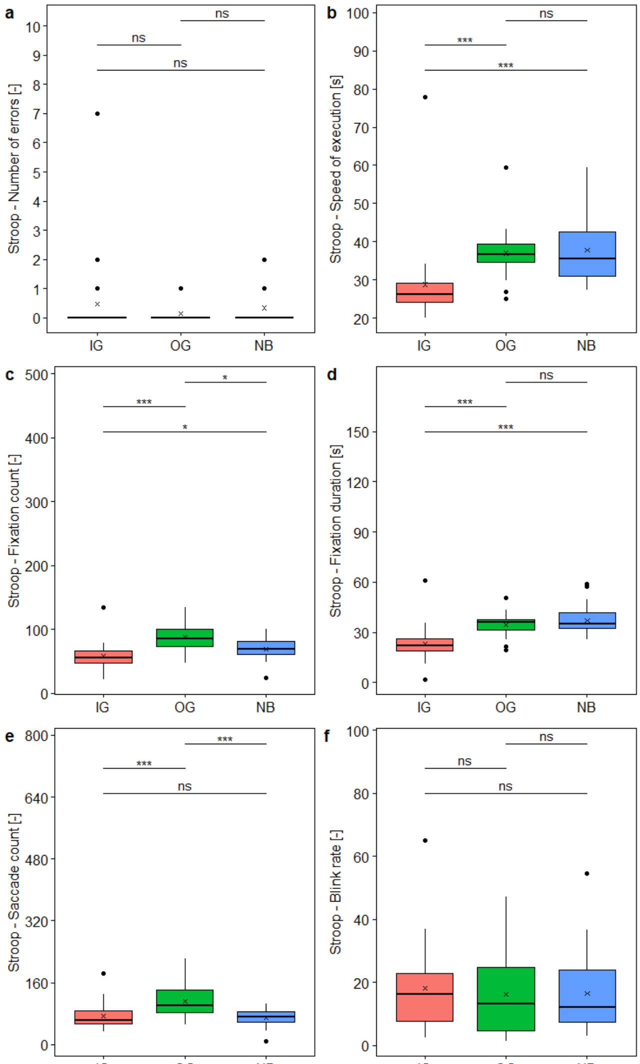

Figure V - 38 Chapter III: Stroop test: boxplot of the results of the test and eye-tracking features in the IG, OG and NB conditions

In addition, no relationship was detected between pupil dilatation and cognitive performance results. These findings did not align with the literature reporting higher pupil size for higher task load [137], while supporting the results reported by Que [2] which did not detect differences in change of pupil size and blink rate. However, Joseph [146] and Skaramagkas [142] highlighted a drawback of pupil dilation in the large deviation caused by changes in gaze angle and illuminance. As a result, Kim [147] suggested adopting the number of blinks as an involuntary eye-tracking metric in the assessment of cognitive load

[269]. It is important to note that such references deal with different contexts and stimuli than the one tested in the present research activity (e.g., robotics, acoustical stimuli domain) which limits the comparison of the results with previous literature in Biophilic Design interventions. Moreover, a possible explanation of the current results could be that pupil metrics might not be the best indicator of workload in this research activity. Indeed, blink and pupil parameters did not seem to capture cognitive task load differences for the specific tests performed in this research activity (i.e., Stroop test, OSPAN test, Magnitude and Parity tests). In the presence of those tests, other metrics, such as fixation count, fixation duration and saccade count were more effective and sensitive in capturing variations in users' gaze behaviour depending on visual stimuli.

To sum up, a significant improvement in reading time, speed of processing for the inhibition function and fewer errors in the working memory performance seemed to be dependent upon the presence of nature within the working environment. This is in agreement with existing literature, even if previous VR-based studies evaluated the impact of nature exposure with a limited assessment of cognitive responses.
These results corresponded to eye-tracking metrics which analysis confirmed a lower cognitive load and a more efficient search for the correct information in the IG compared to OG and NB scenarios even in the absence of significant differences in performance results. According to the literature, a more efficient search deals with the time participants' took to identify the correct information (e.g., the letters to be memorised in the OSPAN test): the lower the time the better the accuracy in searching information. This results in heatmaps more focused in the "zone" with the correct answers. Such interpretation agrees with previous literature showing more effective and efficient gaze movements in looking at information relevant to the goal [147] as users can discern and discriminate between relevant and irrelevant information in problem-solving [143,270] which occurred in the presence of indoor greenery in the present activity.
In conclusion, the resulting trend indicates a promising relationship between eye-tracking metrics and cognitive response depending on the visual connection with nature, confirming the RQ2.

Task	Parameters	Scenario	Mean(sd)	Kruskal-Wallis test	η^2	Pairwise comparison	Pairwise comparison result
Instruction	Reading time	NB	98.15(±26.64)	$\chi^2(2) = 28.21$, **$p < 0.05$**	0.44	NB – IG	**$p < 0.05$**
		IG	39.30(± 33.51)			IG – OG	**$p < 0.05$**
		OG	81.94(±29.94)			OG - NB	$p = 0.15$
Magnitude-Parity test	number of errors in the classification of the digits even/odd and greater/lower than "5"	NB	1.05(±1.75)	$\chi^2(2) = 2.05$, $p = 0.36$			
		IG	0.62(±1.36)				
		OG	0.24(±0.54)				
OSPAN test	the number of errors in the true/false string	NB	0.57(±0.60)	$\chi^2(2) = 13.93$, **$p < 0.05$**	0.20	NB – IG	**$p < 0.05$**
		IG	0.05(±0.22)			IG – OG	$p = 0.44$
		OG	0.19(±0.51)			OG - NB	**$p < 0.05$**
	the number of errors in letters memorised	NB	1.76(±1.87)	$\chi^2(2) = 3.10$, $p = 0.21$			
		IG	0.90(±1.45)				
		OG	1.52(±1.89)				
	OSPAN score (the sum of the number of the right true/false and the letters correctly memorised)	NB	7.67(±2.11)	$\chi^2(2) = 5.28$, $p = 0.07$			
		IG	9.05(±1.43)				
		OG	8.29(±2.12)				
Stroop test	number of errors in the colour naming	NB	0.33(±0.66)	$\chi^2(2) = 0.88$, $p = 0.64$			
		IG	0.48(±1.57)				
		OG	0.14(±0.36)				
	speed of processing	NB	37.74(±9.47)	$\chi^2(2) = 22.82$, **$p < 0.05$**	0.35	NB – IG	**$p < 0.05$**
		IG	28.21(±12.00)			IG – OG	**$p < 0.05$**
		OG	37.01(±6.95)			OG - NB	$p = 0.77$

Table V - 17 Chapter III: The results of the unpaired-sample Kruskal-Wallis test on the instruction reading and the three cognitive tests

Task	Eye tracking features	Scenario	Mean(sd)	Kruskal-Wallis test	η^2	Pairwise comparison	Pairwise comparison result

Instructions	Blink rate [-]	IG	18.12(±11.75)	$\chi^2(2) = 1.69$, $p = 0.43$			
		OG	16.21(± 13,91)				
		NB	18.45(±9.16)				
	Fixation Count [-]	IG	109.14(±82.85)	$\chi^2(2) = 25.05$, **$p < 0.05$**	0.38	IG-NB	**$p < 0.05$**
		OG	243.76(±88.46)			IG-OG	**$p < 0.05$**
		NB	257.76(±83.00)			NB-OG	$p = 0.62$
	Fixation Duration (s)	IG	29.31(±23.93)	$\chi^2(2) = 29.99$, **$p < 0.05$**	0.20	IG-NB	**$p < 0.05$**
		OG	61.94(±20.64)			IG-OG	**$p < 0.05$**
		NB	80.67(±22.19)			NB-OG	$p = 0.05$
	Saccade Count [-]	IG	124.43(±81.96)	$\chi^2(2) = 24.04$, **$p < 0.05$**	0.37	IG-NB	**$p < 0.05$**
		OG	294.10(±146.92)			IG-OG	**$p < 0.05$**
		NB	266.76(±91.41)			NB-OG	$p = 0.85$
Magnitude-Parity test	Blink rate [-]	IG	17.57(±10.90)	$\chi^2(2) = 0.10$, $p = 0.95$			
		OG	15.64(±10.33)				
		NB	18.62(±12.41)				
	Fixation Count [-]	IG	33.48(±32.49)	$\chi^2(2) = 1.31$, $p = 0.52$			
		OG	31.86(±20.95)				
		NB	24.90(±15.27)				
	Fixation Duration (s)	IG	54.54(±14.39)	$\chi^2(2) = 1.60$, $p = 0.45$			
		OG	60.64(±8.84)				
		NB	60.81(±4.69)				
	Saccade Count [-]	IG	26.57(±20.96)	$\chi^2(2) = 7.98$, **$p < 0.05$**	0.10	IG-NB	$p = 0.05$
		OG	35.05(±29.90)			IG-OG	$p = 0.40$
		NB	14.81(±14.71)			NB-OG	**$p = 0.01$**
	Peak left pupil dilation (%)	IG	11.49(±12.02)	$\chi^2(2) = 1.26$, $p = 0.53$			
		OG	11.47(±12,73)				
		NB	13.92(±12.42)				
	Peak right pupil dilation (%)	IG	12.55(±12.38)	$\chi^2(2) = 0.50$, $p = 0.78$			
		OG	13.65(±15.70)				
		NB	14.30(±12.86)				
OSPAN test	Blink rate [-]	IG	20.46(± 14.62)	$\chi^2(2) = 1.71$, $p = 0.43$			
		OG	21.15(± 12.87)				
		NB	25.06(± 13.15)				
	Fixation Count [-]	IG	26.38(± 27.28)	$\chi^2(2) = 10.25$, **$p < 0.05$**	0.14	IG-NB	**$p < 0.05$**
		OG	44.90(± 25.05)			IG-OG	**$p < 0.05$**
		NB	47.43(± 30.32)			NB-OG	$p = 0.96$
	Fixation Duration (s)	IG	8.19(± 9.01)	$\chi^2(2) = 13.32$, **$p < 0.05$**	0.19	IG-NB	**$p < 0.05$**
		OG	12.97(± 7.51)			IG-OG	**$p < 0.05$**
		NB	15.84(± 10.09)			NB-OG	$p = 0.50$
	Saccade Count [-]	IG	29.14(± 29.60)	$\chi^2(2) = 7.78$, **$p < 0.05$**	0.10	IG-NB	**$p < 0.05$**
		OG	45.71(± 26.87)			IG-OG	**$p < 0.05$**
		NB	47.62(± 32.81)			NB-OG	$p = 0.90$
	Peak left pupil dilation (%)	IG	15.33(± 10.39)	$\chi^2(2) = 2.97$, $p = 0.23$			
		OG	18.93(± 12.11)				
		NB	14.21(± 12.57)				
	Peak right pupil dilation (%)	IG	15.43(± 15.77)	$\chi^2(2) = 4.92$, $p = 0.09$			
		OG	22.14(± 15.22)				
		NB	12.97(± 10.62)				
Stroop test	Blink rate [-]	IG	18,11(±14,68)	$\chi^2(2) = 0.22$, $p = 0.89$			
		OG	16,24(±12,92)				
		NB	16,55(±13,13)				
	Fixation Count [-]	IG	58,86(±22,68)	$\chi^2(2) = 20.65$, **$p < 0.05$**	0.30	IG-NB	**$p < 0.05$**
		OG	88,19(±22,23)			IG-OG	**$p < 0.05$**
		NB	69,14(±16,88)			NB-OG	**$p < 0.05$**
	Fixation Duration (s)	IG	22,86(±11,34)	$\chi^2(2) = 23.60$, **$p < 0.05$**	0.36	IG-NB	**$p < 0.05$**
		OG	34,35(±7,34)			IG-OG	**$p < 0.05$**
		NB	37,15(±9,15)			NB-OG	$p = 0.69$
	Saccade Count [-]	IG	37,15(±9,15)	$\chi^2(2) = 15.37$, **$p < 0.05$**	0.22	IG-NB	$p = 0.85$
		OG	74,38(±34,20)			IG-OG	**$p < 0.05$**
		NB	112,29(±44,00)			NB-OG	**$p < 0.05$**
	Peak left pupil dilation (%)	IG	18.45(±12.74)	$\chi^2(2) = 5.48$, $p = 0.055$			
		OG	10.61(±7.48)				
		NB	9.70(±5.36)				
	Peak right pupil dilation (%)	IG	15.69(±14.47)	$\chi^2(2) = 2.04$, $p = 0.36$			
		OG	13.73(±10.77)				
		NB	10.07(±6.09)				

Table V - 18 Chapter III: Results of the statistical analysis for the eye-tracking features from each task in the IG, OG and NB conditions

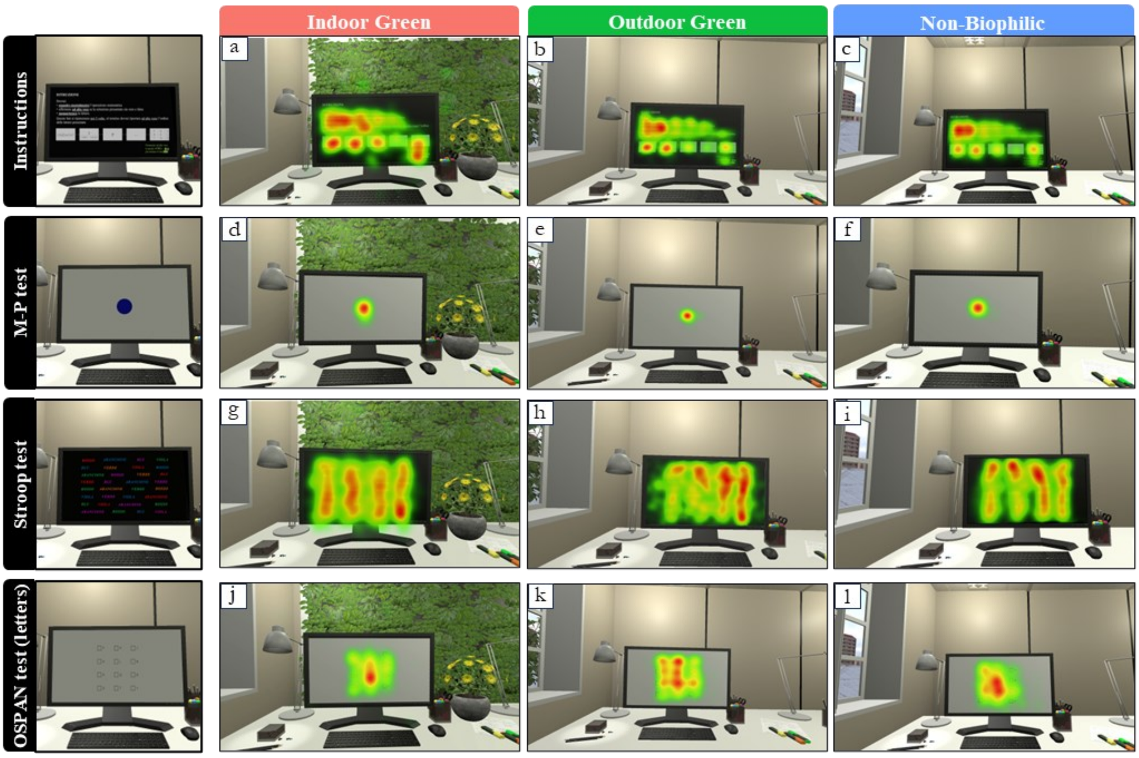

Figure V - 39 Chapter III: Heatmaps for IG, NB, and OG conditions during each cognitive test. The coloured areas indicate how many respondents looked at something, and how long each of the individual respondents looked at it.

5.3.3.9. Effect of visual connection with nature on visual distraction from task execution (operative phase)

The visual distraction potentially induced by greenery in the virtual office environment was assessed by considering the "eye-off-task." which occurs if participants look away from an intended target [271,272]. In this study, it was identified as the virtual monitor during the execution of the three cognitive tasks as the AOI.

In particular, the authors analysed: the number and percentage of respondents who gazed out of the AOI (distracted subject count and ratio); the average amount of fixations detected outside the AOI (fixation count); the ratio between the time spent gazing out of the AOI and the duration of each cognitive test (gaze time). If participants were visually distracted and shifted their gaze out of the AOI for at least 1 fixation (which is computed for a dwell time higher than 300ms), their gaze was then identified as an "eye-off-task".

The results (Table V - 19) indicated that for all tests between 43% and 62% of subjects were distracted in the presence of indoor greenery (IG) and between 14% and 52% in the presence of outdoor greenery. Otherwise, in the absence of greenery (NB scenario) a lower number of subjects looked away from the virtual monitor (between 10% and 38%). Moreover, in IG the number of off-monitor-fixations was higher, and the subjects looked outside the computer monitor for a longer time in comparison with OG and NB for all three cognitive tests.

In comparison with the indoor green condition, in the outdoor green scenario, participants scored less fixation and gaze time.

Additionally, participants' visual distraction during the cognitive tasks was induced by the more prominent green element in terms of dimension and spatial location (i.e., the green wall, larger number of distracted subjects, fixation counts and time spent gazing in relation to the test duration). Despite that, this is in contrast with the cognitive performance metrics which revealed a higher accuracy in the presence of natural elements. Such a result is of relevant interest because allows to understand that the introduction of green elements has the potential to increase users' interest in the indoor environment even during the task execution while not damaging the related work efficiency. These outcomes supported both the hypothesis that the visual connection with nature could elicit users' visual attention and interest and could potentially lead to visual distraction from task execution. However, the lack of literature in this field makes it difficult to look for comparable and generalizable results.

Eye-tracking metrics	Biophilic pattern								
	Magnitude-Parity test			Stroop test			OSPAN test		
	IG	OG	NB	IG	OG	NB	IG	OG	NB
Distracted subjects count	9	3	2	11	7	6	13	11	8
Distracted subjects ratio	43%	14%	10%	52%	33%	29%	62%	52%	38%
Fixation count	4.71	1.00	2.00	5.50	4.20	2.50	3.42	2.33	3.02
Gaze time (%)	1.95%	0.53%	0.58%	5.19%	2.57%	1.68%	2.20%	0.82%	1.81%

Table V - 19 Chapter III: Tye-tracking metrics across the three scenarios: Indoor Green (IG), Outdoor Green (OG) and Non-Biophilic (NB)

Then, to assess which natural elements in the IG condition elicited most visual distraction from task execution, the authors analysed the fixation count and gaze time of participants looking at the flowered plant and the green wall during the execution of cognitive tests. The results indicated that eleven of the twenty-five subjects (44% of the sample) looked away from the virtual monitor to look at the greeneries at least once. In particular, 5 of them focused on both the flowered plant and the green wall, while 6 on the green wall only. Hence, the green wall seemed to elicit most participants' visual distraction ($A_{o,t}$ = 100%, $A_{o,f}$ = 100%) during the operative phase. The reason why the flowered plant scored less fixation and gaze time ($A_{o,t}$ = 26%, $A_{o,f}$ = 21%) might be because it was not as prominent as the green wall in spatial location.

5.3.4. Concluding remarks

The application of the developed framework and validated model allowed to address the need for a new audio-visual design approach to support researchers in understanding the potential effects of visual and non-visual connection with nature on individuals' work efficiency and comfort while limiting time and cost-consuming research activities through VR technology.

Toward this end, the present study investigated the virtual experience and cognitive response of participants in an Immersive Virtual Environment (IVE) to explore the positive potential of audio-visual Biophilic Design interventions. A 3x3 factorial design experimental activity was employed with three between-participants levels of Visual Factor office layout (Factor V: Indoor Green, Outdoor Green and Non-Biophilic) and three within-participants levels of Acoustic Factor (Factor A: Office, Office + Traffic and Office + Nature sounds). A total of 198 participants, divided into three groups, were recruited to perform one test session (IG, NB, OG) at a constant indoor air temperature (24 °C) while completing three short-term cognitive tasks and surveys for each acoustic condition (O, O+T, O+N). Physiological signals and eye-tracking data were also acquired.

The experiment results highlighted the following findings:

- A great sense of presence and immersivity through a realistic representation of the IVE from a visual and an acoustic point of view and no relevant cybersickness disorder levels were highlighted. The authors confirmed the ecological validity of the model. Thus, VR has been identified as an effective way to conduct pre-occupancy evaluations of the potential of Nature-Based Solutions and Biophilic Design research interventions during the early indoor design stage.
- Visual and non-visual connections with nature can positively contribute to shaping a more supportive office environment through VR. The results from the study showed that participants performed worse on the three cognitive tests when they were exposed to traffic noise, while a greater accuracy occurred when exposed to natural elements from both a visual and an acoustic point of view. In general, acoustic factors had a higher magnitude on cognitive function than the visual factors and, according to the results, the best visual*acoustic condition for improving participants' work efficiency occurred with Natural sounds in the Indoor Green condition.
- Results highlighted a primary effect of acoustic stimuli on the perceptual dimensions of pleasantness and eventfulness, with audio-visual interaction effects on pleasantness. While the reference acoustic condition (office noise) was assessed as uneventful, slightly pleasant but also somewhat monotonous, the addition of traffic sounds led to an increase in eventfulness and a decrease in pleasantness, resulting in a chaotic soundscape, while the addition of natural sounds

can improve the overall perception of the office space in terms of increased pleasantness and eventfulness (i.e., increased vibrancy). Pleasantness with natural sounds is particularly enhanced in the presence of indoor green, while outdoor green is beneficial in moderating traffic noise perception.

- Considering EDA and PR results, the exposure to the audio-visual connection with nature induced some positive changes in recorded physiology even if the literature on these themes is still inconsistent and in its infancy. No relevant results were detected concerning Skin Temperature.
- A relationship between the recorded physiology and the subjective assessment of the pleasantness and eventfulness of the sound was highlighted only for specific environmental conditions, thus limiting the generalizability of the results.
- Participants' visual attention was influenced by the proximity of users to the natural element (i.e., the nearer the object the higher the visual attention) while visual distraction from tasks was influenced by the spatial location and dimension of the greenery (i.e., the larger the object the more it potentially distracts the users).
- Participants in the presence of indoor greenery seemed to experience a lower level of cognitive load and a more efficient search for the correct information resulting in improved performance (i.e., much less time to read and complete the task, fewer errors).

The novelty of the proposed methodology and research activity can be seen in many aspects concerning the existing development of VR and IVE applications to a salutogenic and user-centred design approach in the built environment questions.

Inevitably, there are some limitations to this study.

Firstly, participants were young adults, which could lead to selection bias. In that case, the generalizability of the results is limited to university students. Moreover, the sample was limited due to voluntary participant availability. Hence, a more generalized and broader sample needs to be recruited to investigate the potential beneficial effect of nature according to gender, age, and education.

Secondly, due to time limitations to VR exposure and the design of the experimental methods as a mixed-between/within-subject design, each acoustic scenario was tested for about 7 minutes. Even if promising results on cognitive functions, soundscape assessment and physiological responses were highlighted, it is recommended to further examine the positive benefits of prologued exposure to visual and acoustical connection with nature, for instance by limiting the experimental procedure to a single scenario at a time (in order to limit the general exposure to the IVE).

Even short exposure to joint audio-visual natural conditions could trigger specific objective, subjective and physiological responses, it was demonstrated that, and could thus be orchestrated in office environments to achieve specific effects on workers in terms of well-being and performance. Such evidence promotes the advantages of adopting a combined audio-visual approach in human perception assessment in a built environment.

The results suggest that using the proposed audio-visual approach via VR can provide a relatively more affordable alternative approach to the study of the «human dimension» than laboratory-based studies and physical settings, which enables many research applications that may not be feasible without using VR. Additionally, the potential to integrate the Nature-Based Solution and Biophilic Design in an Immersive Virtual Environment, as demonstrated in this chapter, can facilitate professionals in the design of more supportive office environments by integrating the design interventions into a highly immersive virtual space that can be collectively reviewed by the design team and stakeholders.

Furthermore, the findings stressed the importance of investigating the relationship between the occupant and the building with a multi-domain approach, which considers the complexity of the user's multi-sensory perception in the built environment.

Part VI: Conclusions, limitations and future perspectives

The present chapter summarises the achievements of the thesis and outlines their impact on research and practice. Limitations and future directions of the research activity are then highlighted.

6.1. Main achievements

Based on the preliminary state-of-the-art analysis and core experimental activities, the answer to the research question of the present thesis is outlined as follows.

What is the most effective way to use VR as a research tool to investigate humans-buildings interaction and support the realisation of user-oriented indoor environments?

The idea of this PhD thesis is to suggest to researchers first how to strategically and effectively adopt VR technology to investigate the building occupants' work efficiency, comfort and adaptive behaviour, secondly to demonstrate its effectiveness and then the potential of such methodological approach to support multi-domain studies.

A significant barrier to the acceleration of knowledge in understanding how multiple indoor environmental conditions influence occupants is the difficulty of controlling the variation of indoor environmental conditions in multi-domain studies based on real environment experiments.
Virtual Environments are suggested as an alternative method that can facilitate the exploration of multi-domain assessments and leverage the adoption of advanced tools and experimental approaches to address and improve users' dimensions in buildings.

The focus of **Part II: Human dimension research in buildings: Immersive Virtual Reality applications in the fields of work efficiency, comfort and adaptive behaviour** relates to the design and methods of the literature of VR-based research on building occupants' work efficiency, comfort and behaviour in indoor office environments, as well as the content of the investigated metrics that are essential to address the research question of the present thesis.
This chapter pointed out the main research gaps and challenges in existing VR-based studies. These issues are related to single-domain assessments with a scarcity of multi-domain studies; limited attention to validation process and presence, immersion and disorders levels; experiments mainly centred on visual domain and indoor layout variations; few investigations on thermal settings adaptive behaviour; inhomogeneous administration of surveys and comprehensive work efficiency investigations; limited and homogeneous sample size.

Despite a growing interest in VR to support building occupants' research, the development of a mature and holistic science of human-centred indoor environments is still impeded by the lack of an agreed-upon conceptual framework. Hence, the methodological approach developed in the present thesis was determined by these drawbacks to ensure the validity and generalizability of the research findings while adopting VR technology as a "data collector".

Part III: Definition of an experimental framework for IVR applications constitutes a milestone in the development of this work of thesis.
A novel experimental framework to organise, carry out and enhance the adoption of VR technology in research studies was delineated. The framework was designed to couple the main validation types of the research study with dependent variables according to standards and literature, VR main attributes and a human-centred approach.
The step-by-step approach to organise the pre and post-trial procedures allows the researchers to establish a strict experimental design, produce trustworthy data (content – internal – face validity), correlate the results with existing studies looking for a cause-effect relationship between variables (criterion-validity) and make general conclusions (external-ecological validity).
Effectiveness and replicability are the key features and potentialities of the defined framework. The primary outcome of having such a methodological valuable instrument is a mitigation of the

shortcomings in VR-based studies. Another key aspect is the opportunity to expand the use of virtual Environments to support the research in the built environment, building design practises and theories on human-centred comfort, work efficiency and behaviour avoiding the time and cost-consuming physical settings.

Part IV: Validation of the experimental framework shifts the flow of the thesis to demonstrate the suitability of the framework and addresses the necessity of more research attention and validation to enhance the reliability and effectiveness of the data collected in virtual environments. This chapter compared a fully immersive office environment and the corresponding real environment to test the participants' comfort, work efficiency, behaviour, sense of presence and cybersickness. Therefore, the aim was not only to validate the virtual model but to show how to integrate the step-by-step- framework in VR experimental activity for building occupants' work efficiency, comfort and behavioural research.
The findings (in terms of correspondence between real and virtual settings) confirmed the suitability and potential of using the framework and the model in empirical studies against real mock-ups. This outcome partially addresses the core research question of this thesis, which is about how to effectively use VR as a research tool.

Finally, **Part V: Applications of the experimental framework in the fields of work-efficiency, comfort and adaptive behaviour** deals with the major complexity of the present thesis, focusing on the practical use of the developed framework in the fields of work-efficiency, comfort and adaptive behaviour by investigating the influence of indoor environment characteristics on users. Within this chapter, the proposed experimental activities bring attention to the multi-domain analysis concept. The developed framework and the validated model are applied across two cross-modal and one combined effect study.
In **Chapter I: Investigation of users' response to varying thermal environment in a mixed-IVE** the same-modality and cross-modal effects of two indoor air temperatures (hot - 24°C and cold - 16°C) on users' thermal and visual comfort, work efficiency and adaptive behaviour were analysed within a test room with controlled climatic conditions. The achieved outcomes confirmed the external-ecological validity of the model created and the potential to replicate the thermal state of participants and correctly detect the effect of the independent variable (temperature set-point) on the dependent variables (interactions, thermal and visual comfort, cognitive functions). Namely, the temperature did not influence the subjects' executive functions and no crossed-effect on visual comfort was detected. As expected, it had a significant impact on thermal comfort and the type of interactions with the building system.
In **Chapter II: Identifying the effect of indoor noise through Acoustic Virtual Reality**, the second studied stimuli to illustrate the applicability of the developed framework and the validated model, consist of varying the indoor acoustical environment. The selection of this stimulus arises from the need to overcome the literature gaps (Part II: Human dimension research in buildings: Immersive Virtual Reality applications in the fields of work efficiency, comfort and adaptive behaviour) in terms of limited attention on the acoustical domain despite being well-established and quantified disrupting effect of noise on employees' cognitive performance.
Five disrupting sound sources (phone rings, machine noise of a laptop and a copier, mechanical systems, human-based sounds and acoustical effects of the closing door, paper and pens) were selected to create a binaural soundtrack integrated within the validated virtual office environment. The application of the framework allowed to confirm the effectiveness of the model (ecological validity), and criterion validity in terms of the effects of acoustics on users' comfort and cognitive performance. As expected, ambient noise has a disrupting effect on work efficiency with a relevant decrease in performance in each cognitive test. Indeed, the sound environment was assessed to be uncomfortable, chaotic and boring and had also a negative impact on the subjects' thermal comfort.
These were the first attempts to apply the new proposed framework to fully immersive standalone virtual environments. The relevant contributions of this chapter are numerous. Firstly, the fundamental challenge in adopting VR to support human-dimension research was addressed by demonstrating the possibility of enhancing the overall realistic perception by integrating the visual dimension with the thermal and acoustical one.
Secondly, the results suggested the adequacy of the proposed framework and immersive model IVE in providing an accurate representation of the measured variables.

Thirdly, the possibility of demonstrating the development of an effective and efficient testing procedure to apply VR in further analysis suitable at investigating the influence of indoor environment characteristics on users and delivering valid and generalisable results. This kind of finding expands the range of usability of the framework and the validated model. Indeed, the possibility of strengthening and facilitating research about human comfort through multi-domain analyses carried out in standalone virtual environments by varying other stimuli is stressed out.
The last experimental activity presented in **Chapter III: Exploring the impact of virtual audio-visual Biophilic Design interventions** investigates a combined-effect study type in which the effect of multiple stimuli in combination (i.e., visual and acoustical connection with nature), was assessed on individuals' responses. Namely, three office layouts (Indoor Green, Outdoor Green and Non-Biophilic) were combined with three acoustical scenarios (Office, Office + Traffic and Office + Nature sound). The framework is maintained within this last work and the validated model was slightly modified according to the visual scenarios. A realistic representation and sensory congruency within the IVE from a visual and an acoustic point of view was experienced by the participants.
The results showed that visual and acoustical connections with nature can positively contribute to shaping a more supportive and comfortable office environment with lower levels of cognitive load, better performance and enhanced pleasantness when exposed to natural elements both visually and acoustically. The exposure to the audio-visual connection with nature resulted in some positive changes in recorded physiology. Moreover, thanks to the eye-tracking integrated within the head-mounted display it was possible to find that participants' visual attention was influenced by the proximity of users to the natural element while visual distraction from tasks was influenced by the spatial location and dimension of the greenery.
This chapter is significant because it attempts to demonstrate how VR can be adopted to determine how overall experience varies depending on visual and acoustical intervention indoors. In a salutogenic design approach, the purpose of this experience is to exhibit the effectiveness of VR in identifying the positive effects of attributes to enhance the well-being and work efficiency of individuals.

6.2. Impacts on academia, building design, standards and society

The present PhD thesis has the potential to have a positive impact on scientific, building standards and social levels.
On a scientific level, these three years of experience have contributed to advancing a highly inhomogeneous research field about the application of VR technology as a valuable method that can facilitate, improve, and quantify the exploration of the human dimension in indoor environments.
The results leverage the adoption of innovative and advanced methodologies, tools and novel experimental approaches to address and improve research fields on users' well-being, behaviour and working efficiency.
Thanks to the adoption of a defined, standardized and validated experimental framework, the validity and generalizability of the VR-based research findings can be fostered. Moreover, the developed framework has the potential to allow IVEs to become more effective data collectors for developing probabilistic or stochastic predictive models.
Compared to the current state of the art on the topic, since in-field monitoring campaigns or laboratory experiments are difficult for researchers to set up and scale towards application, this thesis attempts to make it more accessible by grounding a first experimental framework that could be implemented and enriched in the future depending on the research aims.
The benefits of virtual environmental manipulations and the presented framework which are low-cost and logistically easy to integrate, represent crucial factors to facilitate researchers in a deeper understanding of human responses to their complex surrounding environment. These results support the spread of multisensory investigations to evaluate the effects of all the sensory variables that can be found within buildings.
Thus, researchers have the chance to overcome the barrier to the acceleration of knowledge in multi-domain assessments due to the difficulty of controlling the variation of real indoor environmental conditions.
This allows to bridge the gap between VR-based research and practice in providing effective human-dimension models and theories, at the base of building energy software, decision-making and design practices.

The findings obtained in the present thesis allow the developed framework and models to be used as an interface for data generation and access. The way the Architecture, Engineering and Construction sectors are set up may be positively influenced by the convergence of such advanced technologies and approaches. Indeed, the evidence about its suitability and applicability can reinforce the role of VR to adequately support evidence-based indoor design practices and could lead to a convergence between prototypes and design simulation.
In the context of project-based building design, the evidence collected from these valuable instruments can be extended in testing, interpreted, and adopted to quantify the impacts on the human dimension.

Professionals are then provided with the basis necessary to couple advanced evidence-based design and building practices. The resulting design guidelines would be suitable to encourage not arbitrary design choices in a variety-built environment practice and to provide long-term value and quality of life in indoor environments.
The inclusion of such VR-evidence-based knowledge in building systems, design and maintenance is a crucial point to deliver personalised building systems capable of supporting the optimal operation of the building, reducing energy consumption and increasing the overall building system efficiency.
In this context, such evidence-based indoor design practices currently do not include outcomes established by immersive virtual experiments. Thus, at a building standards level, this can lead to the development of new regulations incorporating virtual reality sessions and then supporting a new generation of smart buildings.

On a social level, the integration of such a valuable experimental framework for immersive virtual reality applications on buildings occupants' work efficiency, comfort, and behavioural research, can provide scientific evidence for the negative and positive impacts of multiple indoor environmental conditions on individuals. Moreover, this can challenge many current design practices and user-centred services based on oversimplified empirical approaches determining which attributes of the indoor environment matter most to building occupants.
The present thesis contributes to demonstrating that it is possible to use VR to foster user-centred approaches and empower the overall human-building interaction thanks to pre-occupancy assessments. This contribution could allow a more tangible possibility of ensuring a sustainable, acceptable and conducive indoor environment for the health and well-being of the people. Providing long-term value and quality of life are crucial aspects of the overall building performance to facilitate the shift toward a more sustainable paradigm coupled with technological innovation.

6.3. Current limitations

Despite the very promising and encouraging outcomes presented in the previous section, there are still some limitations that need to be pointed out to interpret the results. These shortcomings concern the technology itself, the recruitment, and the dependent and independent variables object of interest, as follows.

Firstly, it should be considered that there is often an upfront "cost" to using IVEs due to the time, technological expertise, and resources needed to create virtual environments as suitable simulations of real settings.

The sample in the whole experimental activities (Part IV: Validation of the experimental framework, Part V: Applications of the experimental framework in the fields of work-efficiency, comfort and adaptive behaviour) was recruited voluntarily. Since experiments were carried out inside the university facilities, most of the participants' sample was composed of young adults, which could lead to selection bias. In that case, the generalizability of the results is limited to university students. Hence, a more generalized and broader sample needs to be recruited to investigate the potential beneficial effect of nature according to gender, age, and education.

Concerning the dependent variables, some issues could be pointed out.
Even if relevant results and differences were detected between the selected and investigated stimuli, an introductory test of "basic cognitive abilities" should be administered to participants as a baseline to reduce any bias related to the between or within-subject experimental design.

Due to the time exposure constraints in virtual environments to limit cybersickness, three short-term cognitive tasks were investigated. However, the method to measure work efficiency strictly depends on the research purpose. Thus, future studies could carry out mid-term assessments (e.g., integrating the executive functions tests with reading passages and comprehension tasks), and then integrate the experimental schedule. This will be possible thanks to the development of a flexible experimental framework.
Moreover, in the context of this work, individuals' visual comfort was addressed focusing on participants' perceptions. Future activities should also integrate the main visual sensation, preference and comfort votes with glare and brightness assessments, to deepen the adequacy of IVE concerning the visual and lighting domain.

Regarding the independent variables, even if the ecological validity revealed an excellent sense of presence and immersivity throughout the experimental sessions, another issue needing further attention is the modelling of the light characteristics and parameters via proper lighting software to reproduce more photorealistic renders that will enhance users' virtual experience.
In addition, the experimental activity presented in Part V: Applications of the experimental framework in the fields of work-efficiency, comfort and adaptive behaviour-Chapter I: Investigation of users' response to varying thermal environment in a mixed-IVE took place during the winter season of 2022. Only extreme thermal conditions for a winter period simulating the lack and an excess of use of the heating systems (16°C and 24°C, respectively) were set up.

6.4. Future research perspectives

This thesis made important contributions to the field of building occupants' work-efficiency, comfort and behavioural research, introducing a novel experimental framework that facilitates the conduction of empirical research in VR to broaden the knowledge about the influence of indoor environmental conditions on human factors.
Firstly, this final section covers the identification of practical opportunities to implement the research activity and the developed framework based on the identified limitation of the present thesis.
Starting from improvements in technological instruments, VR systems have been recognized as still immature technologies [36]. Some issues related to VR headsets should be resolved (e.g., the field of view, image quality, resolution per eye, and vision correction capabilities,) to reduce the risk of any blurred images that can potentially disrupt individuals' experiences in the immersive environment creating experimental bias.
Moreover, it would be of interest to advance the experimental framework that was developed in this thesis by allowing user interaction in the scene. Indeed, the enhancement of individuals' interaction with the immersive model has the potential to increase the overall sense of presence and immersivity within the virtual environment contributing to perceptual accuracy. On the other side, difficulty in using such tools may increase the negative perception of participants toward the instrument itself thus leading to biased results. Thus, this is a crucial aspect to investigate.

This thesis focused on varying the thermal and acoustical environments and the layout of the indoor office space while keeping the geometry, and material constant within each experimental study.
Referring to the experimental activity presented in Part V: Applications of the experimental framework in the fields of work-efficiency, comfort and adaptive behaviour-Chapter I: Investigation of users' response to varying thermal environment in a mixed-IVE, this thesis showed no significant influence of extreme heating temperature set-point on individuals' work efficiency. Additional studies employing more traditional working environmental conditions are necessary to compare the collected data with the prescription of current national and regional standards establishing an indoor air temperature of about 20°C.
Moreover, considering the current environmental concerns and urban overheating, VR coupled with climate chambers simulating extreme summer conditions to analyse individuals' responses and behaviour. Additional studies that investigate the effect of other stimuli (e.g., olfactory and indoor air quality) are also necessary to broaden the knowledge of the joint impact of environmental conditions on individuals.

Secondly, the research directions for future works are discussed. Such perspectives are related to the application of VR and IVE to fast advance new strategies for building design and practice.
A promising research direction is the possibility of integrating VR systems with other software systems used in the Architectural, Engineering and Construction sectors such as Building Information Modelling (BIM). Virtual Environments have the potential to make these systems more user-friendly in generating a participatory approach to the overall design system and building life cycle. This integration will create a robust technology ecosystem by opening new use cases and would offer a great opportunity to improve operational efficiencies and support decision-making. Considering that every building is unique, simulating the in-situ experiences of individuals using IVEs is the only cost-effective method.
For such applications is also essential to enrich the virtual environments with real-time data.
Namely, it would be of interest to integrate the virtual environment with the outcomes of Building Energy Models (BEM) and Building Management Systems (BMS).
A suitable context could be the comfort and behavioural domain which was one of the metrics investigated in the present thesis. Human comfort is a very subjective matter and is the major trigger of individuals' behaviour. The current environmental concern led to the need for energy-saving practices. In this context, the use of energy in the built environment can be compromised by a lack of training above all in the case of inexpert users about the overall building performance or newly installed building systems. Erroneous behaviours are widely established from BMS data (e.g., opening windows while air conditioning is operating, opening blinds during summer days). Thus, immersive training for energy efficiency awareness and more sustainable behaviour could be generated to explore their potential. Indeed, VR can provide realistic scenarios in which the users coexist in the same virtual space with information visualisation to acquire knowledge and skills from performing simulations of real activities or interaction potentials. VR can be useful to support building occupants in the operation of building equipment and adjustment procedures. If the virtual model is integrated with data visualisation, individuals would be allowed to understand the consequences of their choices. This application could allow to reduce the cost of training and operative use of the building, as well as improve health and comfort. In the meanwhile, the analysis of behavioural patterns in such applications has the potential to deepen the development of adaptive behavioural models suitable for filling the gaps between real and simulated energy performance in BEMs.
To conclude, an ambitious future research perspective is to explore the readiness of the building sector to use results generated from IVE-based experiments to support the revision of building design, standards and operation practices.

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