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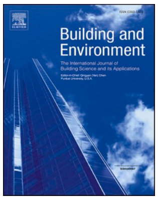

Effects of Biophilic Design interventions on university students' cognitive performance: An audio-visual experimental study in an Immersive Virtual office Environment

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ABSTRACT

The human-nature connection should be a key component in the design of supportive and comfortable indoor environments. An interest in introducing Nature Based Solutions indoor via Biophilic Design (BD) intervention recently emerged. Related benefits for work efficiency have been identified in lab-studies without the possibility to perform preliminary design assessments. Recently, VR has been adopted thanks to its advantages for data collection in highly realistic environments. To date, most of the research on BD has been focused on the visual connection with nature even if people experience multiple senses simultaneously. In this paper, a new design approach for preliminary assessment of BD intervention in VR is presented. A 3x3 between-subjects design study is presented, comparing three office layouts (Indoor Green, Outdoor Green and Non-Biophilic) and three acoustic scenarios (Office, Office + Traffic and Office + Nature). 198 participants performed one test session completing three cognitive tasks for each acoustic condition, and survey. The results of the sense of presence and immersivity (visual), the sensory congruency (acoustic) and cybersickness disorders suggested that VR is an effective tool to preliminary evaluate the potential of BD interventions (ecological validity). The findings of the cognitive tests revealed that audio-visual connection with nature can positively influence working memory, inhibition and task-switching performance. The acoustic factor exhibited a higher improvement effect compared to the visual factor, between 23 % and 71 % against 12 %–39 %. Moreover, the Natural sound in the Indoor Green condition was the most supportive visual*acoustic condition while Traffic in the Non-Biophilic environment was the most disruptive one.

1. Introduction

The relationship between individuals and their built environment has a relevant influence on human quality of life [1]. Hence, a user-centric design approach to shape spaces that inspire, energize and support the people who use them is a global imperative for the Architectural, Engineering and Construction sectors community. Building rating standards and certifications (e.g., LEED, WorldGBC) originally focused on energy-related aspects and Indoor Environmental Quality (air quality, thermal comfort, lighting, acoustics), interior layout and ergonomics. More recently, they have increasingly shifted to health and wellbeing issues (e.g., WELL), thus catalysing a global concern and scientific attention to a sustainable and healthy building sector. In particular, enhancing work efficiency in the workplace has been a primary driver with private and public sectors recognising the importance of an occupant-focused indoor environment. In addition, the COVID-19 pandemic heightened employee concern about the effectiveness of their working spaces, wondering if they correctly answer their needs and foster well-being as well as their home workplaces during smart-working periods.

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The present research focuses on the potential of biophilic interventions to enhance the office environment through auditory and visual stimuli in a virtual reality study. The research is situated within an extensive literature on the subject, addressing various research gaps as described in the following.

1.1. Biophilic design for office environments

Beyond Indoor Environmental Quality, one factor upon which this research focused, is the potential of incorporating Nature-Based Solutions (NBS) in buildings [2]. In this context, NBS are powerful approaches central to achieving the challenge of the EU strategies for 2030 aiming for sustainability, climate resilience, and increased biodiversity-rich ecosystems [3]. [4]. 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 [5]. 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 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 [6–8].

[9–11]A multitude of psychological-oriented theories emphasized the benefits of NBS exposure, which can promote a positive impact on human comfort (hygrothermal conditions) [12], health and well-being (e.g., anxiety and stress reduction) [13,14] and emotions (e.g., happiness, satisfaction, visual preference) [13,15].

The positive effects elicited by nature involved the development of the Attention Restoration Theory (ART) by Kaplan [14,16] and Stress Reduction Theory (SRT) by Ulrich [13]. ART states that a restorative effect on human attention can be achieved through exposure to natural elements. According to SRT, experiencing nature aesthetic and emotional value can reduce stress levels, which in turn can improve cognitive performance. Both theories acknowledge nature-related benefits for cognitive functioning.

1.2. Benefits provided by visual and acoustical connection to nature on cognitive performance

According to the “14 Patterns of Biophilic Design” [17], BD can be integrated into indoor built environments in several manners: Nature in the Space (e.g., a view to elements of nature, auditory, olfactory, or gustatory stimuli), Natural Analogues (e.g., biomorphic forms and patterns, material connection with nature), and Nature of the Space (e.g., prospect). Thus, nature’s potential can be leveraged by several sensory stimuli which led to the need of applying a holistic multisensory approach to study the human-nature connection. Indeed, ignoring the possible connections between human senses could lead to ineffective design resulting in building performance issues, occupant discomfort or decreased performance [18].

Despite that, 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 [18].

Several studies were carried out to examine the restorative effects of BD interventions (e.g., Refs. [19–24]), while fewer experiments focused on the effect of visual connection with nature on occupants’ performance in a working office situation [25]. In order to address this gap, the present ams to look for correlations between natural patterns and improvements in workplace performance, as people spend about 60 % of their time in office environments every week [26].

Concerning the introduction of visual greenery, several experiments have shown that introducing indoor plants into workplaces can improve self-reported productivity. According to Lohr [27] and Khan [28] participants in the room with plants reported feeling more attentive than people in the room with no greenery.

Nieuwenhuis et al. [29] showed improvements in perceived concentration, speed of completion and accuracy in task execution after introducing plants in the office. This is consistent with Shibata and Suzuki [30,31], Raanaas [25] and Hähn [32] who reported higher task performance scores in plant-based offices.

Contrarily, Larsen [33] found that performance decreased as the number of plants increased in the office even if higher attractiveness of the environment was detected. More recently, Ayuso [34] evaluated the combination of different greenery sizes (i.e., small, medium, big) and daylight (i.e., no daylight, daylight tube) demonstrating improvements in subjective workload but not in simulated work tasks.

The use of different study designs (e.g., type of performed task, exposition time, number of participants) may partially explain the slight inconsistency between results concerning the visual domain even if promising effects of nature on cognitive performance were highlighted.

Beyond vision, literature revealed that across other sensory modalities, acoustic stimuli of nature were highly considered as a noise masking strategy for supportive office soundscapes. To the authors’ knowledge, a small body of literature focused on the effect of natural sound scenarios on cognitive performance, while individuals’ perception, stress recovery and emotional responses have been the principal research domains (e.g., Refs. [21–24]).

Jahncke reported higher participants’ attention restoration and cognitive performance during exposure to river and bird sounds [35] and later demonstrated that masking background noises with natural sound can attenuate distractions and improve accuracy in task execution [36]. More recently, Van Hedger [37] administered participants two cognitive tasks under three acoustic scenarios (i.e., no soundscape, urban, natural). Significant and positive improvements in cognitive performance for individuals exposed to nature were detected. In the same vein, Stobbe [38] replicated the experiment. Conversely, outcomes highlighted a better but not significant cognitive performance in the natural condition.

Aristizabal [39] tested four experimental conditions: baseline, visual biophilic, natural sounds, and combined audio-visual biophilic interventions. Results highlighted that participants’ cognitive performance improved in all biophilic conditions with less stress perceived in the multisensory condition.

When evaluating the influence of auditory stimuli on occupants in office environments, it’s important to assess their impact on both the emotional and cognitive aspects. While traditional focus has been on noise annoyance or acoustic (dis)satisfaction, it’s crucial to examine the effects that sounds and noises have on the dimensions underlying the perception of the acoustic environment within the context (i.e., the soundscape [40]). This comprehensive approach reveals potential emotional consequences, whether positive or negative, allowing for the evaluation of the mediating effects of the emotional sphere on cognitive tasks based on the type of auditory stimulus [41–47]).

1.3. Using virtual reality to assess the benefits of biophilic design interventions

The 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., Refs. [39,48]), resulting in time and cost-consuming research activities, depending on the complexity and scale of experiments. Recent studies have highlighted the opportunities of implementing digital technology in the BD of indoor environments, to facilitate studies on the effects of green elements on occupants, with less expenditure of resources [49]. One of the most widely exploited technologies within the Internet of Things is Virtual Reality (VR).

Recently, researchers adopted VR to study NBS thanks to its many advantages as a low-cost and flexible solution that facilitates the collection of complex data in highly realistic one-to-one environments [50]. VR and Immersive Virtual Environments (IVE) are valid means to simulate alternative design configurations, without the limitation of laboratory-based studies [51]. Researchers and professionals are then supported to improve the integration of the «human dimension» from the early design stages, for example, to measure end-user behaviour, collect feedback in real-time, and improve communication for a better understanding of the project via multisensory 3D environments [52]. Another crucial advantage is the possibility to properly manipulate the desired variables (e.g., visual and acoustic dimensions). This results in a greatly shortened design procedure [53].

Despite that, BD-based studies in indoor VR environments are still limited, mainly focused on stress and anxiety levels reduction [54–57], self-emotion assessment [58–60], physiological responses [54,56, 60–63], thermal state [56], single [58] or multiple cognitive tests [62, 64], thus, rarely including a comprehensive evaluation of work efficiency potentials. In addition, a crucial step of VR is the need to assess the ecological validity of results which refers to the ability of virtual environments to adequately represent real settings. Indeed, the generalization of the study conclusions could be reduced in case of inadequate sense of presence and immersivity and high disorder levels related to cybersickness [50]. However previous validation studies confirmed the reliability and effectiveness of VR as a research tool in this domain (e.g., Refs. [51,52,65,66]).

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) [54–58,60–64], «Prospect» (e.g., natural view from windows) [55,57,59,61] and «Material Connection with Nature » [55,61]. Few studies carried out a combination of the above-mentioned patterns [55,57,61].

In general, VR-environmental exposure had often been based on a simplistic visual dichotomy (e.g., nature vs non-natural scenarios) with few studies incorporating other sensory elements in indoor settings (i.e. «Non-Visual Connection with Nature»). Since people experience different environmental factors simultaneously, these studies investigated sensory perception through a multi-domain approach as a key to identifying combined and cross-modal effects [67,68], which are not assessable in single-domain studies.

Lyu [66,69] simulated a semi-outdoor environment combining two distinct thermal conditions with two visual scenarios with and without shading. Results confirmed the restorative benefits of thermal pleasure associated with semi-outdoor environmental exposure, including improved cognitive performance. Shin [70] designed a busy university space via a Computer Automatic Virtual Environment to understand the restorative effects of closed and open windows with views of nature on restoration outcomes after cognitive task stressors. The scenario with an open window was integrated with the smell and sounds of nature coming from the virtual outdoors (multi-sensory condition). However, no relevant differences in psychological restoration potentials were detected between the two conditions and no assessment of cognitive test results was carried out.

The literature analysis revealed that underdeveloped is the application of VR to study the potential effects of visual and non-visual connection with nature on human work efficiency and comfort through a multi-domain approach.

1.4. Research questions

Building upon the existing literature and the identified research gaps, the goal of the study was to examine the experience of participants in a combined audio-visual Immersive Virtual Environment (IVE) and to understand the potential of Biophilic Design interventions in shaping more supportive and comfortable office environments. To achieve these goals, the authors designed an experimental procedure evaluating participants' sense of presence and immersivity, cybersickness, while performing cognitive tests, and perceptual and physiological assessments under combined audio-visual scenarios involving NBS.

In particular, the authors were interested in the following research questions:

- RQ1. Is VR effective in investigating Biophilic Design research interventions in terms of a high sense of presence and immersivity and low cybersickness?
- RQ2. Does visual and acoustic connection with nature confer benefits in terms of occupants' working memory, inhibition, and task-switching cognitive performance?

2. Material and methods

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, productivity tests and surveys are presented, followed by the experimental schedule.

The experiment was approved by the Research Ethics Committee of the Università Politecnica delle Marche (No. 0216363, 01/12/2022), and data was gathered anonymously throughout the process.

2.1. Test room equipment

The testing room is a renovated office space inside the Department of Building and Civil Engineering and Architecture (Università Politecnica delle Marche, Ancona, Italy). The size is about 5.93 (L) x 4.38 (W) x 3.00 (H) m. It was equipped with air and operative temperature, humidity and air velocity sensors of HD32.1 Thermal Microclimate Station by DeltaOHM [71] 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-min intervals. DeltaLog10 software [72] 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 0.06 m/s.

To provide additional physiological signals, an Empatica Embrace-Plus wristband [73], 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 sensors equipment are shown in Table 1.

2.2. Sound material

During the tests, participants were exposed to three sound scenarios (Office, Office + Traffic and Office + Nature sounds) via headphones (integrated in 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 at 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

Table 1
Sensors specifications.

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	0.1–5 m/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)

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 in the presence of four people performing office-type activities (i.e., quietly talking on the phone, tapping on the keyboard, 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 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-min 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). The two scenarios (O + T and O + N) are presented at equal and plausible sound pressure levels, enabling a comparison of the impact of introducing external traffic noise (e.g., through open windows) or natural sounds (e.g., from noise masking systems or by opening windows in natural environments) in contrast to a baseline with office noise.

2.3. Virtual environment

In this study, several key factors were addressed due to their contribution to the sense of reality testing during the development of the Immersive Virtual Environment. At first, achieving visual realism in virtual reality involves the adoption of high-quality graphics, textures, and accurate spatial representation, ensuring alignment with real-world dimensions. Indeed, the generation of the immersive virtual environment involved the modification of a previously validated office model [52]. The design of the office was slightly modified into a 3D four-occupancy office room with two windows 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 [17] 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 [74] 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 cover 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°) [75]. Except for the integration of biophilic pattern, all three offices scenarios were identical (see Fig. 1 and Video 1).

Supplementary video related to this article can be found at https://doi.org/10.1016/j.buildenv.2024.111196

Unity game engine [76] (Version 2018.4.14f1) was adopted to virtualise the 3D model. In addition, to gauge participants' visual attention, it was integrated with iMotion [77] (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 [78].

Secondly, spatially accurate audio heightens the sense of presence in virtual environments by offering realistic cues about the direction and distance of sounds, thereby enhancing the overall authenticity of the experience.

Thus, 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 (Fig. 2), 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 2.2), so that the traffic and natural sounds actually seemed to come from the open window (as actually confirmed by the participants, see section 3.1).

Lastly, the model was characterized by an adequate motion tracking system to align the participants' virtual perspective with physical actions (e.g., head-tacking movement in the first player control), thus increasing the feeling of visual and acoustical realism while decreasing the chance of motion sickness.

2.4. Survey design

The survey comprised two sections. The first section detected information about participants' demographics (gender, age, eyesight and hearing problems, education level) and daily habits related to previous experience with VR, and videogames usage. In addition, participants were asked to tick the characteristic of their working environment and the most wanted elements in the office, in terms of access to natural light and ventilation, 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.

The second section included four aspects: the sense of presence and immersivity, cybersickness disorders and soundscape assessment.

To gain a holistic understanding of the level of realism and immersion achieved in the present VR experiments, subjective user experiences was investigated. Concerning the former, validated and reliable assessment methods were considered according to the most recent literature on VR applications for human-dimension research in buildings. Well-established surveys in this field are the *Slater-Usoh-Steed* (used in Refs.

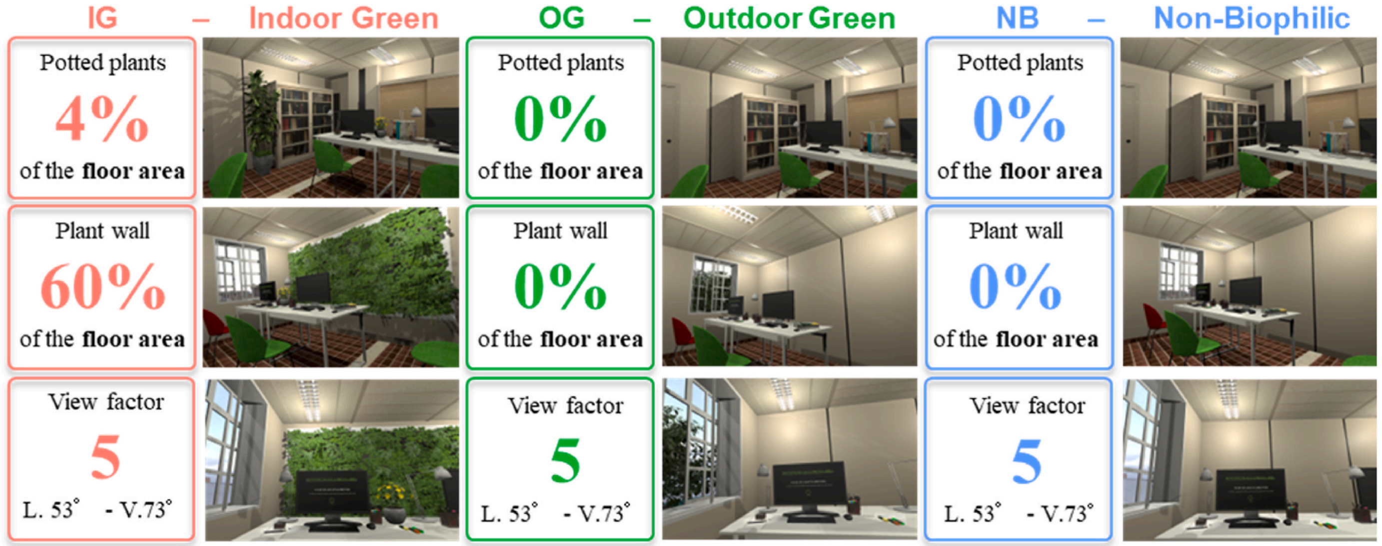

Fig. 1. The Visual Factor Levels: Indoor Green, Outdoor Green and Non-Biophilic scenarios with greenery percentages related to the virtual room floor area and the View Factor from the participants position during the test. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

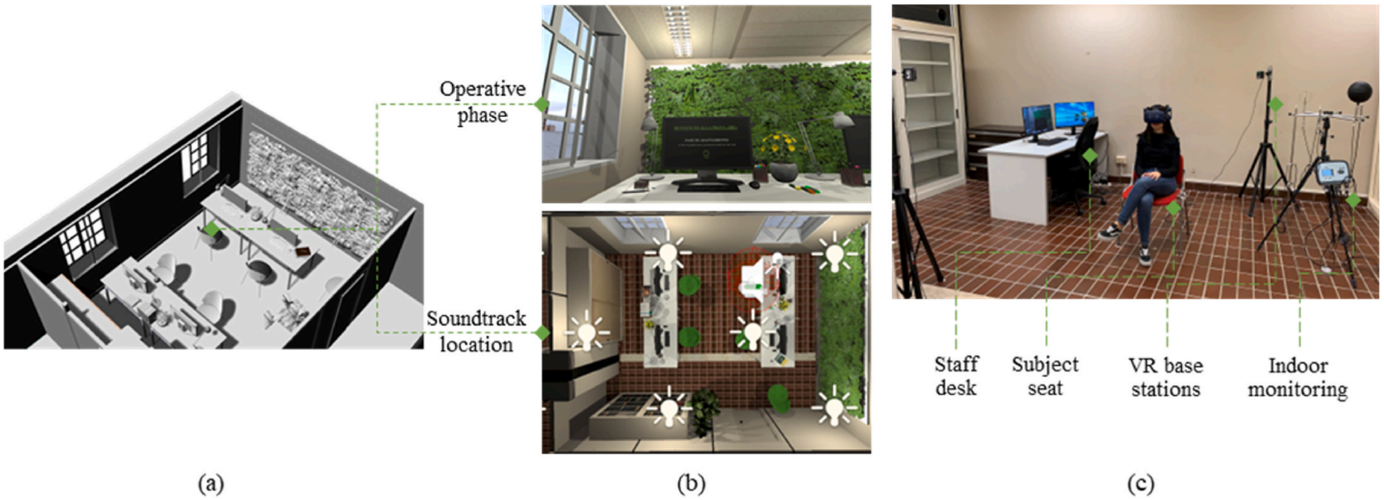

Fig. 2. (a) 3D model, (b) Operative position (first player control in virtual rendered model) and soundtrack location inside the Unity Environment, (c) the test room setup.

[3–7]), the *Igroup Presence Questionnaires* (*IPQ*) (used in Refs. [6,8–11]) and the *Virtual Reality Sickness Questionnaire, VRSQ* (used in Refs. [5,10, 15–17]) [2]. The subjects' visual sense of presence and immersivity within the VE was evaluated by four indicators [50]: Graphical Satisfaction (GS), Spatial Presence (SP), Involvement (INV), and Experienced Realism (REAL), on a seven-point Likert scale ranging from «strongly agree » to « strongly disagree». Finally, the cybersickness disorders were measured using the Virtual Reality Sickness Questionnaire (VRSQ) [16] concerning six disorders: general discomfort, fatigue, eye strain, difficulty in focusing, headache, and vertigo, that were assessed on a five-point scale ranging from «not at all » to «a lot».

The nine questions and rating scales related to the post-experimental assessment of the virtual environment are reported in Table 2.

In addition, participants were asked to verbally describe the indoor office environment they were experiencing considering the visual and the acoustic domain through the open-ended question "*You are free to experience the virtual model, please describe the environment visually and acoustically*".

In the absence of an indoor soundscape assessment model for office buildings (such as present for residential buildings [79]), participants' perceived affective quality of soundscapes was measured through eight perceptual attributes rated on a five-level Likert scales (from «strongly agree » to « strongly disagree»), following the model by Axelsson et al. [42] and ISO/TS 12913–2 technical specification [80] for (outdoor) urban environments: pleasant, exciting, eventful, chaotic, unpleasant, monotonous, uneventful, and calm.

2.5. *Work efficiency measure*

As previously suggested by the authors [50], in this study work efficiency was assessed through three cognitive functions: «inhibition » by the *Stroop test* [81], «working memory » by the *OSPAN test* [82], and «task switching » by the *Magnitude-parity test* [83].

The *Stroop test* was developed by J.R. Stroop to measure the ability to control attention and override habits and impulses. The participants were asked to name the colour of 32 coloured words written in red, green, blue, pink and orange ink on a black background as fast as possible, ignoring the text of the word while the authors collected the

Table 2
Question and rating scale about sense of presence and immersivity and cybersickness questionnaire.

Factor	Question	Rating scale
Graphical satisfaction (GP)	I appreciate the graphics and images of the virtual model	totally disagree/ totally agree
Spatial presence (SP)	I perceived the office space as a place I visited rather than a photo I saw During the experience, I felt present in the office space I perceived the virtual model as immersive	totally disagree/ totally agree
Involvement (INV)	During the experience, I was not aware of the real world around me	totally disagree/ totally agree
Experienced realism (REAL)	I perceived the objects inside the virtual office as proportionally correct (i.e., they had about the right size and distance from me and other objects) I had the feeling of being able to interact with the office space (e.g. grab objects) How realistic did you find the virtual model of the office space?	totally disagree/ totally agree
Cybersickness	Did you experience.? GENERAL DISCOMFORT – FATIGUE - EYE STRAIN - DIFFICULTY IN FOCUSING – HEADACHE - VERTIGO	not at all/a lot

speed of processing (e.g., “red” in case of word “green” printed in red ink). The test was presented as an image on the virtual computer monitor.

The authors adopted the *OSPAN test* to evaluate the working-memory ability. It consists of a sequence of slides: in the first one a simple math operation was displayed (3 s) and participants had to solve it in mind; in the second one (3 s) a possible solution to the equation was displayed and participants were invited to tell the researchers whether it was true or false; in the last one, a letter to be memorised was displayed for 800 ms. A total of five sequences composed of a math equation - a true/false solution – a letter to be memorised were displayed, and in the end, the participants were instructed to correctly recall the order of all the five letters presented.

Finally, the *Magnitude-Parity test* aims to assess the ability to flexibly switch from one activity to another and keep attention. It consists of a sequence of white background slides (200 ms each) where black-inked digits from “1” to “9” except “5” were displayed preceded by red or blue dots. After the red dot (parity stimulus), participants expressed whether the displayed number was odd or even and whether was smaller or larger than “5” after the blue one (magnitude stimulus). There was a total of eight parity-magnitude stimuli, thus participants were asked to rank 16 digits.

Both the *OSPAN test* and *Magnitude-Parity test* were displayed as timed videos on the virtual monitor.

The overall metrics to assess work efficiency are reported in Table 3.

Table 3
The description of the cognitive functions tests metrics.

Cognitive function test	Performance metrics	Test duration
Magnitude-Parity	number of errors in the classification of the digits even/odd and greater/lower than “5″	63 s
OSPAN	the number of errors in the true/false string the number of errors in the letters memorised OSPAN score (the sum of the number of the right true/false and the letters correctly reported)	69 s
Stroop	number of errors in the colour recalled speed of processing	dependent on subjects’ speed of processing

2.6. Experimental procedure

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) after adjusting their clothing levels to feel comfortable, read and signed a consent form, received information about the test procedure, and completed the pre-experimental questionnaire. This period is considered adequate to allow participants to get used to the environmental conditions and to reduce any fluctuation related to the 30 min-prior-test physical activity that might have influenced their metabolic rate [84].

Then, they were invited to wear the Empatica wristband and the head-mounted display, properly calibrate the eye-tracking and rested 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 [50]. 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 cognitive tests and the soundscape assessment. This procedure was repeated three times, one for each Factor A level (O + N, O, O + T, within-subjects independent variables). To reduce the risk of carrying out long-term studies that might generate higher disorder levels, this experiment was divided into shorter test sessions (one for each Factor A level) providing a break between them. Indeed, the experimental schedule included 30 s of rest with eyes closed between each acoustical condition which allowed the researcher not to remove the head-mounted display so as not to affect participants’ immersivity.

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.

The overall experimental procedure is presented in Fig. 3. The test had an overall duration of about 35 min, as recommended by the literature to avoid the occurrence of any disturbances that could invalidate the test due to discomforting participants [85–87].

2.7. Participants

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 [88] considering not only main effects but also interactions ones, with an effect size $f = 0.25$, $\alpha = 0.05$. The sample size was adequate to detect significant effects with a statistical Power equal to 80 % for 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 4. In general, participants had an average age of 23 ± 3.85 years, distributed as follows: 79 % between 20 and 25 years old ($\mu = 21.5$), 17 % between 26 and 30 ($\mu = 27.37$), 4 % between 31 and 39 ($\mu = 34.38$). 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

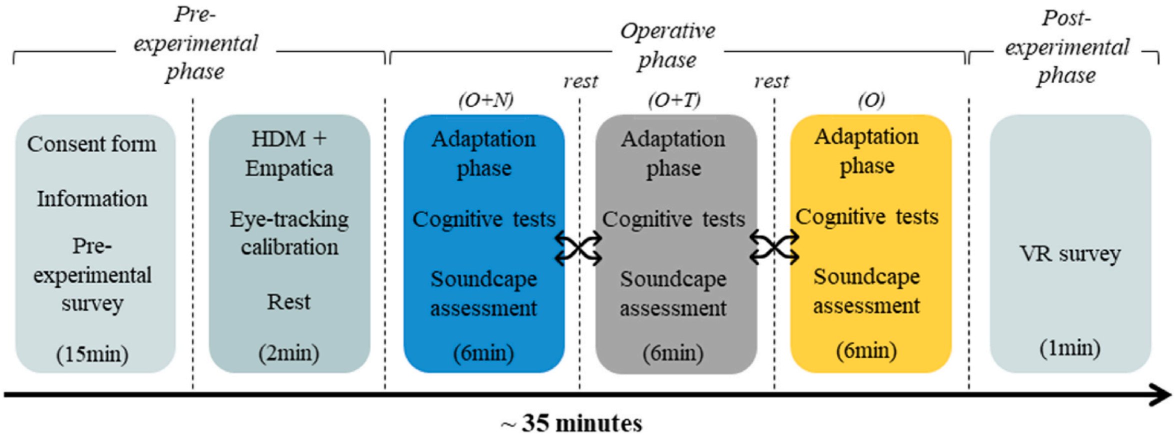

Fig. 3. Experimental procedure.

Table 4

Characteristics of study participants (n = 198) in general and across the three experimental visual scenarios.

	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 %

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 play video games.

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 subject experienced co-working environments. A quieter workplace from indoor and outdoor noises were the second and third most desired elements (50 %, 41 %).

In Fig. 4 are reported, in order of relevance, desirable features that subjects would like to introduce into their work or study environment to improve it.

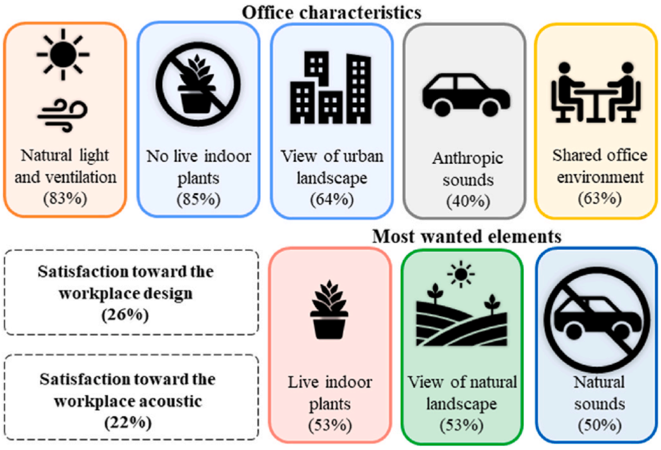

Fig. 4. Characteristics of participants' work environments and most wanted elements.

2.8. Statistical analysis

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.

Data were insight through Generalized Linear Mixed-Effects Models (GLMM) using the statistical software R [89] and the R packages *glme4*, considering a separate GLMM for each dependent variable.

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. Whenever the order term in which the participants were randomly assigned to an acoustic condition and gender did not meet significance effects, it was excluded from the final model.

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.

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^2_m) and conditional (R^2_c) coefficients of determination were generated for each model.

The specification of the final model and additional details (i.e., AIC, R^2_m, R^2_c) are included in Appendix.

3. Results

Section 3.1 presents the results of the ecological validity of the IVE while section 3.2 provides a comparative analysis of benefits between visual and non-visual connections with nature responding to research question 2. The latter allowed to address the criterion validity of the virtual environment which establishes if behavioural (e.g., performance, comfort) responses realistically reflect the effect of stimuli presented in the virtual environment.

The results of the physiological parameters and soundscape assessment are not presented in this paper.

3.1. RQ1. Is VR a promising tool to investigate Biophilic Design research interventions in terms of a high sense of presence and immersivity and low cybersickness?

Before the empirical analysis of the collected data, researchers need to establish the ecological validity of the virtual model which refers to the ability of IVE to adequately represent real settings [50]. There are two fundamental steps: to provide a high level of immersion during the test through the experimental procedure and virtual model development (see sections 2.3 and 2.6), and, afterwards, the analysis of the self-reports, as follows.

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 by the authors [50] on other studies, the average values of each indicator of the visual sense of presence and immersivity were compared to other literature studies that adopted the same questionnaire, while ensuring that these values 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. The reference literature studies for the comparison are Latini et al. [52,90], Tawil et al. [91], Yeom et al. [92], Hong et al. [93], Chamilatori et al. [94], Abd-Alhamid et al. [95], which carried out VR-based studies in indoor settings adopting the same assessment methods. As reported in Table 5 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). In addition, all mean values are higher than the references and almost similar to Refs. [52,90], concerning GS, INV and REAL and [92] concerning INV. However, the differences between the mentioned indicators and the reference study are not relevant (between 0.02 and 0.18).

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 Ref. [52], these results are consistent with the sickness symptoms analysis from previous studies.

Finally, 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:

- 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.
- 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.
- 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.

3.2. RQ2. Does visual and acoustic connection with nature confer benefits in terms of occupants' working memory, inhibition, and task-switching cognitive performance?

3.2.1. The Magnitude-Parity test

Considering the errors in the classification of the digits even/odd and greater/lower than "5" in the Magnitude - Parity test, the results (cf. Table 6) revealed a significant main effect of the acoustic factor ($\chi^2(2) = 51.50$, $p < 0.05$, $\eta^2 = 0.96$). 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. The paired comparison (Fig. 5b) 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, (see means and standard deviation in Table 7).

The result indicated no significant effect of the Visual Factor, nor interaction effects with Factor A.

3.2.2. The Stroop test

Considering the accuracy in Stroop test execution, a significant main effect of the Acoustic Factor, ($\chi2\ (2) = 30.51$, $p < 0.05$, $\eta^2 = 0.77$), was detected. Results indicated a lower number of errors in the Natural sound condition (0.18 ± 0.45) and in the Office (0.22 ± 0.69) than in the Traffic condition (0.55 ± 0.94). The Post-hoc test (Fig. 6a) shows a significant increase in the number of errors with Traffic sounds in both

Table 5

Comparison of scores on a five-point scale of the four indicators (* highlight the indicators higher than the present study).

Indicator	This study	[52]	[90]	[91]	[92]	[93]	[94]	[95]
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 6

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.

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, **$p < 0.05$**			

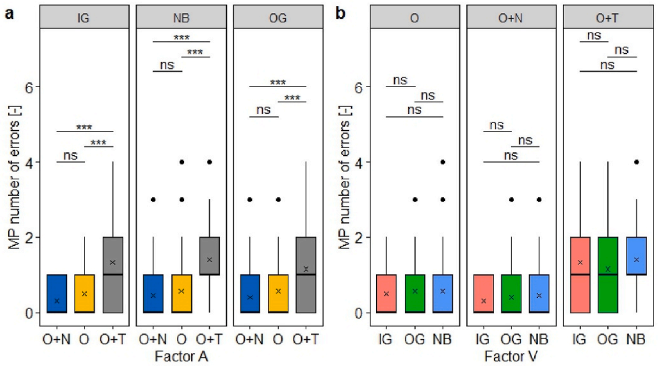

Fig. 5. Boxplot of the number of errors within the MP test. Data are grouped by Factor V and pairwise comparisons are shown. Inside the boxplots, the cross is the mean value, and the line is the median value. ns.: non significative, *p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.001.

the IG and OG conditions compared with Nature and Office conditions ($p < 0.05$).

There were no main effects of Visual Factor ($\chi 2$ (2) = 1.48, $p > 0.05$). with a tendency for participants scoring 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) (see Table 7). However, the interaction effect was significant ($p < 0.05$). The plot in Fig. 8a indicates that Indoor Green resulted in a good accuracy in the Stroop test when participants experienced Nature Sounds but quite lower accuracy when exposed to Traffic sound.

As regards the speed of processing, the analysis revealed a significant main effect of the Acoustic Factor (χ^2 (2) = 9.31, $p < 0.05$, $\eta^2 = 0.17$).

Indeed, the speed of processing was significantly lower with Natural sounds (31.02 ± 6.39s) than Traffic (33.99 ± 6.50s, $p < 0.05$) and not significantly different from the Office sounds (31.71 ± 6.87s, $p > 0.05$) in all IG, OG and NB conditions (see Fig. 6c and d and Table 6).

As presented in Fig. 6d, there was also a significant effect of Visual factor (χ^2 (2) = 145.62, $p < 0.05$, $\eta^2 = 0.81$). A lower speed of processing was detected in Indoor Green (28.27 ± 5.25s) than in Outdoor Greenery (34.21 ± 6.89s, $p < 0.05$) and Non-Biophilic (33.24 ± 6.67s, $p < 0.05$) conditions for each acoustical scenarios.

Comparing the mean values (cf. Table 7), participants more rapidly completed the test when exposed to Natural sounds in the IG condition (26.98s ± 5.28s).

3.2.3. *The OSPAN test*

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

Table 7
Data mean and standard deviation of the cognitive tasks across Factor V and Factor A scenarios.

Factor V	Factor A	MP test	Stroop test		OSPAN test		
		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

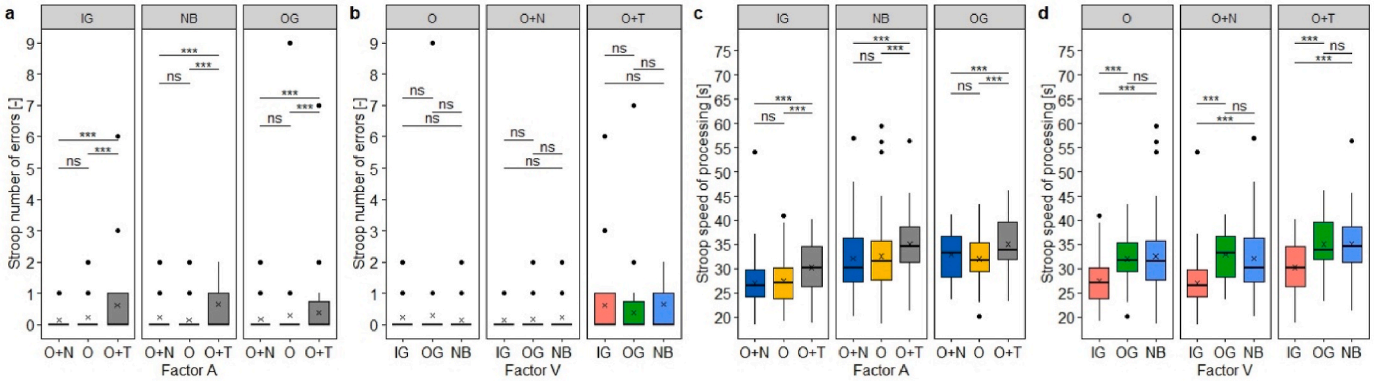

Fig. 6. Boxplot of the number of errors (a,b) and speed of processing (c,d) within the Stroop test. Data are grouped by Factor V (a,c) and Factor A (b,d), and pairwise comparisons are shown. Inside the boxplots, the cross is the mean value, and the line is the median value. ns.: non significative, *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.

string. Participants were more accurate in Indoor Green (0.28 ± 0.52) and Outdoor Green (0.33 ± 0.52) than in Non-Biophilic (0.41 ± 0.61, $p < 0.05$) conditions.

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 Nature (0.21 ± 0.43) and Office (0.25 ± 0.49, $p < 0.05$) than in Traffic (0.56 ± 0.72, $p < 0.05$) conditions in all IG, OG and NB layouts.

The magnitude of the effect highlighted (cf. Table 6) that acoustic factors had a higher effect compared to that of visual factors.

The highest accuracy (cf. Table 7) occurred with Indoor Green in the O + N condition (0.20 ± 0.40).

Moreover, the interaction effect was significant ($p < 0.05$). The plot in Fig. 8b shows that the Non-Biophilic and Indoor Green scenarios results in highest accuracy when participants experienced Natural sounds. In the presence of traffic noise, the NB condition is by far the most detrimental when compared to conditions with indoor or outdoor greenery.

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, $p < 0.05$) than in Outdoor Green (2.22 ± 1.57, $p < 0.05$) and Non-Biophilic (2.62 ± 1.34, $p < 0.05$) 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) and in Office (1.94 ± 1.48) than in Traffic (2.87 ± 1.29, $p < 0.05$) conditions in all IG, OG and NB conditions. In addition, higher accuracy was detected in Natural sounds condition than in Office in the presence of Outdoor Green.

The magnitude (cf. Table 6) of the impact acoustic factors ($\eta^2 = 0.54$) was larger compared to that of indoor layouts ($\eta^2 = 0.36$).

Comparing the mean values (cf. Table 7), the higher accuracy occurred with Indoor Green in the N condition (1.09 ± 1.25).

Fig. 8c shows an interaction effect, confirmed by GLMM results (p-value <0.05) resulting in lower accuracy for OG compared to NB scenario within Office scenario and slightly better accuracy within Natural sound condition.

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, $p < 0.05$, $\eta^2 = 0.05$) was detected with higher scores in Indoor Green (8.11 ± 1.57) than in Non-Biophilic (7.16 ± 1.31, $p < 0.05$) and Outdoor Green (7.46 ± 1.68, $p < 0.05$) conditions (see the pairwise comparison Fig. 7d).

There was also a main effect of Acoustic Factor (χ^2 (2) = 33.21, $p < 0.05$, $\eta^2 = 0.11$) with higher OSPAN scores in Natural (8.15 ± 1.65) and Office sounds (7.79 ± 1.59) compared to Traffic (6.79 ± 1.33, $p < 0.05$) condition in all IG, OG and NB conditions (see the pairwise comparison Fig. 7e). The magnitude of the effect highlighted (cf. Table 6) that acoustic factors had a higher effect on OSPAN score compared to that of visual factors.

The lowest mean scores (cf. Table 7), occurred with Indoor Green in the O + T condition (7.18 ± 1.58) with the same disrupting effect of Traffic for all three visual levels.

The interaction effect was also significant (χ^2 (4) = 10.54, $p < 0.05$, $\eta^2 = 0.03$). Fig. 8d shows similar scores between Non-Biophilic and Outdoor Green scenarios if participants experienced Natural of Office sounds, while lower OSPAN scores were obtained in NB within the Traffic sound condition.

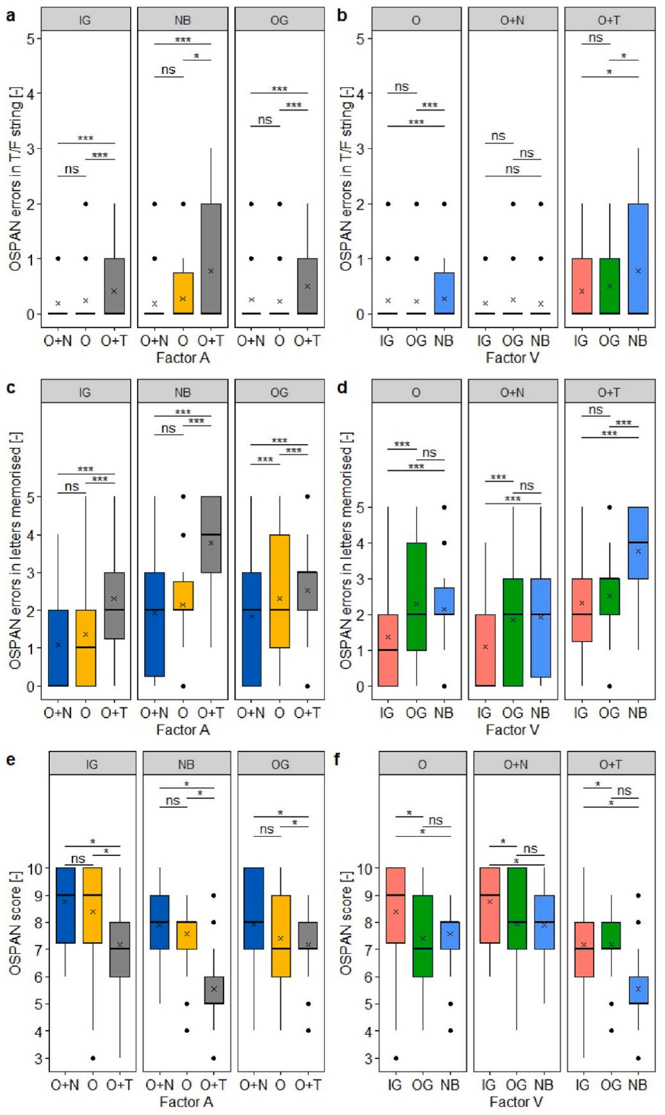

Fig. 7. Boxplot of the errors in T-F string (a,b), errors in letters memorised (c,d) and OSPAN score (e,f) within the OSPAN test. Data are grouped by Factor V (a, c,e) and Factor A (b,d,f), and pairwise comparisons are shown. Inside the boxplots, the cross is the mean value, and the line is the median value. ns.: non significative, *p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.001.

4. Discussion

This study presented the results of a combined audio-visual Immersive Virtual office Environment (IVE) experience with the purpose of exploring the potential of Nature-Based Solutions and Biophilic Design interventions to bring visual and sound stimuli resulting in positive outcomes on participants' cognitive responses. In the following paragraphs, the two research questions underpinning the study are discussed according to the qualitative and statistical results of the experimental activity.

4.1. RQ1. Is VR a promising tool to investigate Biophilic Design research interventions in terms of a high sense of presence and immersivity and low cybersickness?

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 user-centred design approach in the built environment questions.

Firstly, the capacity to achieve a great sense of presence and immersivity through a realistic representation of the IVE from a visual and an acoustic point of view was highlighted. A previously validated model was adopted in this experimental activity properly modified for the research purposes with the integration of visual and acoustical cues.

Indeed, results suggested on average that the virtual model offered the participants a very good experienced realism (REAL = 4.45), presence (SP = 4.29) and involvement (INV = 4.05) within the virtual environment and graphics satisfaction (GS = 4.40) of the model. More precisely, looking at the percentage of participants that assigned a score to the grade "agree" and "totally agree" in the sense of presence and immersivity indicators (see questions in Table 2), the majority of participants appreciated the graphics (92 %), perceived the office space as a place visited rather than an image (85 %), felt present in the office space (82 %), perceived the model as immersive (85 %), and were not aware of the real world during the test (87 %),. The objects were rated as proportionally correct (95 %) and participants had the feeling of being able to interact with them (87 %) and reported a very excellent realism associated with the model (90 %). These results confirmed an accurate, consistent and logical spatial representation of the office room and the proper calibration and render of VR system which allowed to get an accurate depth perception and scale of the environment.

In addition, the methods of generating and integrating acoustic scenarios into VR allowed a realistic and spatially accurate audio representation to provide cues about the direction and distance of sounds, involving participants in a more authentic 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.

Another feature is the applied methodology based on a previously developed experimental protocol [50], which considers the need of limiting the VE exposure time below 25/30 min. This experimental strategy allowed participants not to suffer from relevant cybersickness disorders even if determined a short-term exposure to the acoustic scenarios.

Thus, 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.

4.2. RQ2. Does visual and acoustic connection with nature confer benefits in terms of occupants' working memory, inhibition, and task-switching cognitive performance?

In general, 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 sounds in each visual layout condition. Even if expected, no better accuracy was detected in the presence of Natural sounds in comparison with the baseline Office condition.

Considering each cognitive task, in the Magnitude & Parity test where a higher number of errors in the classification of the digits even/odd and greater/lower than "5" means worse task-switching executive function, participants scored on average 71 % lower in the Traffic sound environment compared to Natural one, and 58 % lower compared to Office sound environment, as in Ref. [90]. In addition, a 31 % of 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

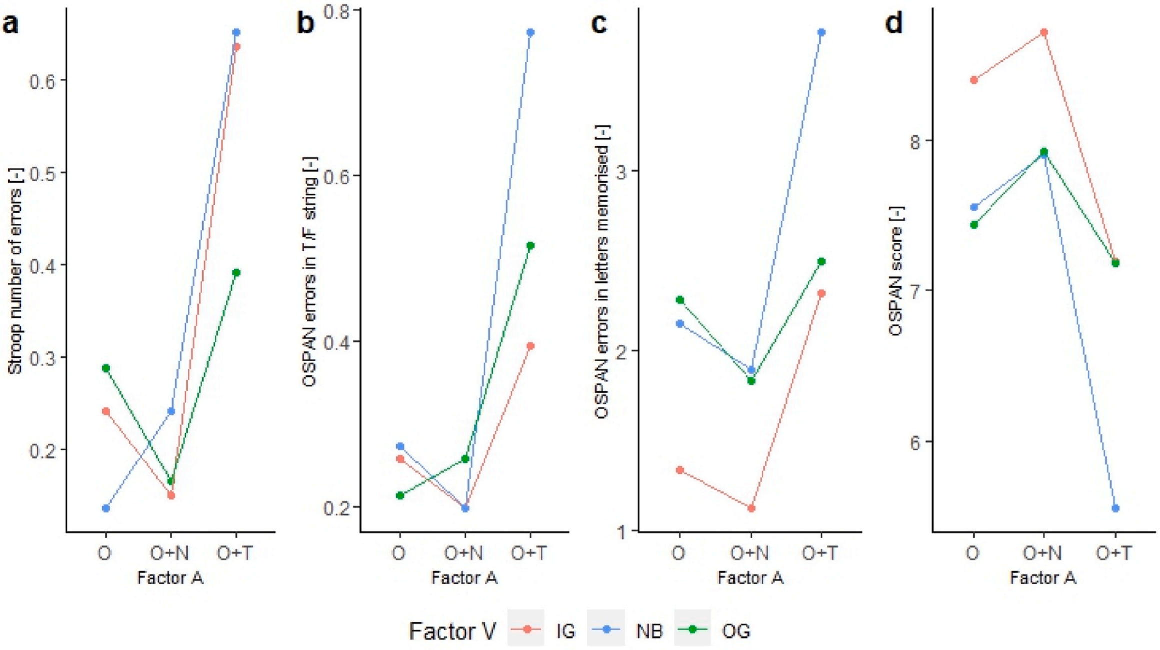

Fig. 8. Interaction plot for the Stroop test (a) and OSPAN test considering the errors in T/F string (b), errors in letters memorised (c) and OSPAN score (d).

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 [62,64].

In the Stroop test (inhibition cognitive function), participants were more accurate in the Natural sound environment than Traffic sound environment (67 %) and performed faster (speed of processing 9 % lower). In addition, a statistically significant improvement was detected regarding visual exposure to the indoor natural environment for the speed of processing: 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. Refs. [62,64]). 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 (cf. Table 7 and Fig. 8a).

Considering the OSPAN test (working memory cognitive function), the author analysed the results in terms of errors in the true-false string, errors in the order of the letters memorised, and the OSPAN score. 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, a statistically significant effect was detected regarding the acoustic scenarios: the exposure to the indoor Traffic environment reduced the accuracy by 56 % and 62 % in comparison with the Office sound and the Nature condition, respectively. In addition, participants memorised a higher number of letters (39 %) when in the Indoor Green environment than in the Non-Biophilic and Outdoor Green environments. Moreover, they scored 15 % higher in the OG in comparison with NB. 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. [90]) 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, 23 % lower OSPAN scores occurred compared to Natural sound condition. 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 Green environments (16 % and 8 %, respectively), and 7 % higher in the OG in comparison with NB. 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 (cf. Table 6). However, the improvement in working memory due to visual biophilic elements is in line with previous studies [58,62]. 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 (cf. Table 7 and Fig. 8d).

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 (Ref. Section 1).

The benefits of NBSs on human well-being have so far been studied mainly from an urban (outdoor) perspective, and rarely considering the combined visual and acoustic benefits of indoors. If included amongst the full suite of advantages of NBSs, this knowledge could lead to greater strength in the adoption of nature-based solutions by policy makers, urban planners and building designers. Visual access to natural elements can be made through natural interior features, and the creation of urban green corridors, living walls and green facades, which can also lead to improved biodiversity at an urban level. These choices can also bring natural soundscapes in urban areas that we can access through opening windows (to carry out natural ventilation) [96,97]. As an alternative, sound masking systems reproducing Natural sounds can be employed, albeit with some hesitation on the part of the scientific community and with the need for negotiation with the occupants [98]. The study shows a potentially interesting positive impact that sound stimuli can bring in terms of cognitive performance, in relation not to the sound level but to the type of sound per se and the semantic meaning it carries. It should be noted, for example, that at the same sound level, the impacts of the two acoustic scenarios (Traffic and Natural) are completely different and with interesting phenomena of interaction with the visual environment. This is in line with the recent literature on indoor soundscaping [79,99], which aims at a perceptive characterisation of sound stimuli in order to use sound as a resource for the design of supportive and healthy living and working spaces. Furthermore, this stresses 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.

5. Conclusions

The authors addressed 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 (Indoor Green, Outdoor Green and Non-Biophilic) and three within-participants levels of Acoustic Factor (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).

Regarding the research questions, the experiment results highlighted the main following findings:

1. Virtual Reality has been identified as an promising way to conduct pre-occupancy evaluations of the potential of Nature-Based Solutions and Biophilic Design research interventions during the early indoor design stage (ecological validity). Indeed, an excellent level of sense of presence and immersivity was provided to participants considering the visual and acoustical dimension and no relevant cybersickness disorder levels were experienced.
2. Visual and non-visual connections with nature can positively contribute to shaping a more supportive office environment through VR. There was a positive change in the users' task switching, inhibition and working memory functions in the Indoor Green and Outdoor Green scenarios in comparison with the non-biophilic scenario. Higher accuracy was detected in the Natural sound scenario while the Traffic sound scenario was the most disruptive acoustic environment. According to the results, the best visual*acoustic condition for improving participants' work efficiency occurred with Natural sounds in the Indoor Green condition.

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, even if relevant differences were detected between Factor V levels, an introductory test of "basic cognitive abilities" should be administered to participants as a baseline to reduce any bias related to the between-subject design. Thirdly, 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 min. Even if promising results on cognitive functions were highlighted, it is recommended to further examine the positive benefits of prologued exposure to visual and non-visual 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). In addition, future research activity could extend the administered survey to investigate participants' mood, preferences and satisfaction related to the combined audio-visual stimuli.

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 paper, 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.

CRediT authorship contribution statement

Arianna Latini: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Simone Torresin:** Writing – review & editing, Writing – original draft, Software, Methodology, Conceptualization. **Tin Oberman:** Writing – review & editing, Writing – original draft, Software, Methodology. **Elisa Di Giuseppe:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Francesco Aletta:** Supervision. **Jian Kang:** Supervision. **Marco D'Orazio:** Supervision, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix

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 [100–102]. 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.

A Poisson distribution was used to analyse cognitive function scores (performance accuracy), whereas the speed of processing was analysed by a Gaussian and a Gamma (log-ink function) distribution, respectively.

Concerning the generation of the model, the visual layout and acoustic scenarios were used as fixed effects. Participants were treated as a random factor. In addition, by-subject random intercept and by-subjects random slope for the effect of acoustics [103] 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.

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 3.84, 5.99, 9.49, and 11.07 for 1, 2, 4 and 5 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 authors considered both the order term in which the participants were randomly assigned to an acoustic condition and their gender. However, a preliminary analysis (see Table 8) revealed that these terms did not meet significant effects. Thus, the gender and order-fixed effects were excluded from the final model.

Table 8

Summary of the main effects of gender differences and order types on the parameters of the three cognitive tests from the GLMM Anova test. The table presents the Chi-squared statistic and the p-values.

Cognitive function parameter	Anova, type "III" (GLMM) - gender	Anova, type "III" (GLMM) - order
MP number errors	$\chi^2(1) = 0.05$, $p = 0.83 > 0.05$	$\chi^2(5) = 2.66$, $p = 0.75 > 0.05$
Stroop number errors	$\chi^2(1) = 0.31$, $p = 0.58 > 0.05$	$\chi^2(5) = 6.93$, $p = 0.22 > 0.05$
Stroop speed of execution	$\chi^2(1) = 1.39$, $p = 0.24 > 0.05$	$\chi^2(5) = 3.28$, $p = 0.65 > 0.05$
OSPAN errors T/F	$\chi^2(1) = 1.38$, $p = 0.24 > 0.05$	$\chi^2(5) = 4.86$, $p = 0.43 > 0.05$
OSPAN errors in letters	$\chi^2(1) = 1.26$, $p = 0.26 > 0.05$	$\chi^2(5) = 2.98$, $p = 0.70 > 0.05$
OSPAN score	$\chi^2(1) = 0.74$, $p = 0.38 > 0.05$	$\chi^2(5) = 2.15$, $p = 0.83 > 0.05$

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 Akaike Information Criterion (AIC), the marginal (R^2_m) and conditional (R^2_c) coefficients of determination were generated for each model and are reported in Table 9. 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 [104].

Table 9

AIC, marginal and conditional R^2 of the LMM for each dependent variable

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

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