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Virtual reality application to explore indoor soundscape and physiological responses to audio-visual biophilic design interventions: An experimental study in an office environment

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ABSTRACT

Among the major sources of disturbance in offices, noise and poor acoustics consistently rank at the top. Moreover, the positive impact which connecting with nature has on individuals is well-documented, yet still not investigated in-depth in terms of office soundscapes. In the present study, a methodology using Virtual Reality (VR) technology is employed to analyse the benefits of Biophilic Design interventions in office spaces. Notably, the study investigates the independent and interaction effects of audio-visual connection with nature on 1) office soundscape, and 2) physiological parameters, and 3) explores potential correlations between physiological and soundscape response. Three different visual scenarios (Indoor Green, Outdoor Green and Non-Biophilic) and three sound environments (Office – O, Office + Traffic – O + T and Office + Nature – O + N) for a virtual office environment were combined in a between-subjects design experiment. During their exposure to each acoustical scenario, 198 participants' responses on perceived affective quality of soundscapes (ISO/TS 12913-2) and physiological reactions (Electro-Dermal Activity - EDA, Pulse Rate - PR, Skin Temperature -ST) were collected. The results show a major effect of the sound factor on soundscape assessment, with the O + N scenario resulting in increased pleasantness and eventfulness compared to the O scenario, i.e. a more vibrant office soundscape. Moreover, an interaction between sound and visual stimuli on pleasantness was detected, with IG being more effective in O + N, while OG being more beneficial in the O + T scenario. Significant positive physiological responses were more elicited in the presence of an acoustical connection with nature than a visual one: pleasant soundscapes of nature were associated with lowered EDA and PR with an additional improvement in EDA in the presence of indoor greenery. Moreover, a more pleasant sound (O + N) tended to decrease skin temperature in the presence of indoor greenery, while a more unpleasant and eventful acoustical scenario (O + T) gave the largest PR increase in the absence of nature-related elements indoors. This research provides first insights for the biophilic design of office spaces through nature-related audio-visual stimuli.

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1. Introduction

The indoor environment is influenced by various factors like air quality, temperature, lighting, acoustics, layout, and biophilia, which collectively impact occupants' perception, satisfaction, health, well-being, and performance [1]. Among these, noise and poor acoustics are significant concerns in modern office designs [2], affecting work efficiency and satisfaction. Studies highlight issues such as irrelevant speech, phone conversations, and speech privacy or low background noise levels as major challenges in workplaces (e.g., Refs. [2–4]). While existing standards provide acceptable ranges for environmental parameters to mitigate negative effects, research emphasizes the importance of attributes that promote positive effects on task performance and perception, going beyond mere absence of problems or diseases [5].

In this context, the connection to nature plays a significant role in creating supportive and healthy office environments, with Biophilic Design (BD) interventions showing promise in enhancing comfort and productivity [6]. Studies indicate that exposure to natural environments is linked to various positive outcomes, including improved health, well-being, thermal comfort, and positive physiological responses [7–18]. The World Green Building Council framework [19] and Green Building Rating Standards [20] increasingly advocate for BD interventions in sensorial design approaches. Nature-related sensory stimuli, such as visual, acoustical, and olfactory elements, can trigger nature's potential. While visual connections with nature have received the most attention, there is a growing recognition of the importance of other sensory modalities, particularly acoustical stimuli. Nature sounds, like bird songs and flowing water, have been shown to positively impact individuals' perception, stress recovery, and emotional responses (e.g., Refs. [21–24]), offering benefits as masking strategies by improving privacy, and positive affective outcomes [2,4].

The soundscape framework, as defined by ISO 12913 standards [25], aligns with current research trends focused on understanding human perception of acoustic environments (i.e., the "soundscape.") to create comfortable and healthy environments. This research aims to create comfortable environments and generate positive impacts on people through acoustic design [26] by integrating engineering, physical, social, and psychological approaches [27]. Soundscape studies seek to enhance pleasant sounds and diminish unpleasant ones [28], initially in outdoor urban contexts [29,30], and more recently in indoor built environments, known as the "indoor soundscape" [5,31]. These studies cover various building types, including residential spaces [26], libraries [32], schools [33], and offices [34,35]. Perception models have been developed to characterize emotional responses to acoustic environments, moving beyond mere disturbance assessments [36,37]. Despite the growing interest in nature connection promotion, there's a lack of scientific evidence supporting its potential through soundscapes [38].

Recent research highlights the importance of considering the interplay between auditory and visual stimuli in indoor environments [39]. Studies have shown that combining sound and visual cues can enhance perception, with auditory perception benefiting from visual cues and vice versa [40,41]. Neglecting these connections may lead to design flaws, discomfort among occupants, or reduced performance [42]. Therefore, there is a growing need for holistic approaches that explore the combined visual and acoustical components and their interactions to improve building performance and occupant well-being [43]. Multi-domain approaches, such as those advocated by IEA EBC Annex 79 [44], are crucial for understanding indoor environmental effects and behavioural research. While previous studies have primarily focused on cross-modal and multi-domain investigations, they often face limitations in manipulating variables and generalizing results due to constraints in setup time and cost [45]. Despite these challenges, there remains a significant gap in understanding multi-sensory dimensions compared to single-domain studies [46]. Efforts towards user-centred design could leverage the salutogenic aspects of nature contributing to the creation of positive indoor environments aligned with occupants' preferences and well-being [47].

That is why, the advancements in technology, particularly in human-computer interaction, have facilitated the widespread use of Virtual Reality (VR) to study the effects of changes in environmental conditions creating realistic experience with visual and acoustical reproduction. VR offers realistic experiences by replicating visual and acoustic environments [48], enabling users to feel present in the simulated space [49]. It has been extensively used to simulate real settings with high ecological validity (e.g. Refs. [45,50,51]). In addition, spatial audio in VR has been increasingly utilized for immersive soundscape research [40,52], investigating the combined effects of audio-visual parameters on perceived indoor quality [35,40]. To the best of the authors' knowledge, while previous studies have explored the perceptual (e.g., Refs. [40,53,54]) and physiological implications of human-nature connections (e.g., Refs. [55–58]) focusing primarily on the visual dimension (e.g., natural elements in space [9,55–62], views from windows [58,61,63]), a gap in understanding the audio-visual interaction, especially in office environments, emerged [64]. Therefore, there is a need for novel methodological approaches, adopting VR and Immersive Virtual Environments (IVEs), to explore the effects of Biophilic Design interventions on office spaces.

Thus, the fundamental goal of the study is to understand the effect of different audio-visual connections with nature on soundscape and physiological parameters to determine how overall perception varies depending on BD intervention indoors. The present study represents the first example of applying the soundscape framework to evaluate the theoretical advantages of biophilic design within office spaces. Specifically, the questions intended to be answered in this paper are threefold: (RQ1) How does the audio-visual connection with nature influence the perceived affective quality of soundscape in office environments?; (RQ2) How do participants physiologically respond to audio-visual connection with nature in office environments?; (RQ3) Is there a relationship between the recorded physiology and the subjective assessment of the sound environment in office spaces?

These questions will be answered by subjectively and objectively assessing the difference between nine scenarios obtained by combining three office layouts (Indoor Green, Outdoor Green and Non-Biophilic) with three acoustic scenarios (Office, Office + Traffic and Office + Nature) in an experimental activity involving 198 participants. The overall methodology of the present research activity is presented in Section 2. The outcomes of the experiments related to the first and second research questions will be analysed in Sections 3.2–4.1 and 3.3–4.2, respectively. Finally, the third research question will be discussed in Sections 3.4–4.3.

2. Methodology

The paper is part of a larger research activity [65] aimed at evaluating the effects of Biophilic Design intervention on university students' cognitive performance, soundscape, and physiological responses.

Notably, this study aims to investigate the combined effect of audio-visual connection with nature on participants' perceptual response to the acoustic environment and physiological responses. A 3 × 3 factorial experimental design was carried out and included a between-subject *Visual Factor* study (Factor V: Non-Biophilic, Indoor Green, Outdoor Green) and a within-subject *Acoustical Factor* study (Factor A: Office, Office + Traffic, Office + Nature sounds). The use of Factor A as a repeated measure allowed the authors to eliminate the effect of variance between participants, as each one was exposed to all three acoustical scenarios. In particular, an Office sound condition (O) was used to provide a benchmark of a commonly acoustic working scenario with people quietly talking, keyboard and steps sounds against an Office + Traffic (O + T) and Office + Nature (O + N) conditions consisting of outside traffic and birdsongs recordings, respectively, that could be typically experienced in a naturally ventilated office building.

Considering Factor V, the Non-Biophilic (NB) indoor condition represented the basic scenario of a typical four-occupancy office room to be compared with enhanced layouts with «Visual Connection with Nature » occurring indoors (Indoor Green, IG) and «Prospect » consisting of a natural view from the window (Outdoor Green, OG) [66]. To avoid possible confounding variables and reduce learning effects and time-related factors, the presentation order of the acoustic stimulus was counterbalanced, and subjects were randomly assigned to a visual scenario (66 participants per Factor V level).

2.1. Independent variables

Hereunder the characteristics of the environment set-up used to control the independent variables are described.

- Sound material set-up (left-hand side of Fig. 1): The sound material for the office and traffic scenarios was measured and recorded in a real office environment of similar geometry to the virtual one ($T30_{500\text{-}2k\ Hz}$ = 0,30 s). The two signals comprised four people engaging in office-related activities (such as quiet phone conversations, keyboard typing, and movement around the office) and traffic noise, respectively. A First Order Ambisonics (FOA) tetrahedral microphone (Sennheiser AMBEO VR Mic) with a portable multi-channel audio recorder (Sound Devices MixPre-10T) was used to make the recordings at 1.2 m height above the floor and oriented matching the orientation of a worker, with the window on the side. All the recordings were edited to obtain 1-min excerpts and then transformed to an AmbiX B-format. We captured natural sounds (i.e., mainly birdsong) using a binaural head-mounted microphone kit (specifically, the Head Acoustics BHSII connected to Squadriga III) positioned inside a room near open windows. During the tests, participants were exposed to the sound scenarios via headphones integrated into the head-mounted display. Thus, the playback level in Unity was following calibration using the binaural head and torso simulator (HMS II.3 LN by Head Acoustics) to match sound levels similar to those experienced in the real environment (L_O = 45 dB(A), L_{O+T} = L_{O+N} = 54 dB(A), higher value of left and right ear).
- VR environment set-up (in the middle of Fig. 1): A 3D simulation of an office room was developed using the Unity game engine [67] and represented the NB scenario of the study with textures extracted from a physical environment to achieve maximum realism. The other two Factor V scenarios were generated by adding a living wall and potted plants (IG) and a view of trees from windows (OG), respectively. The quantities of indoor greenery exceeded the minimum requirement of the WELL Standard [68] (see Fig. 2). The sitting position within the virtual model ensured the subjects a View Factor [69] of outdoor equal to 5. The Unity Oculus Spatializer package provided an immersive soundscape experience through the head-tracking binaural rendering of

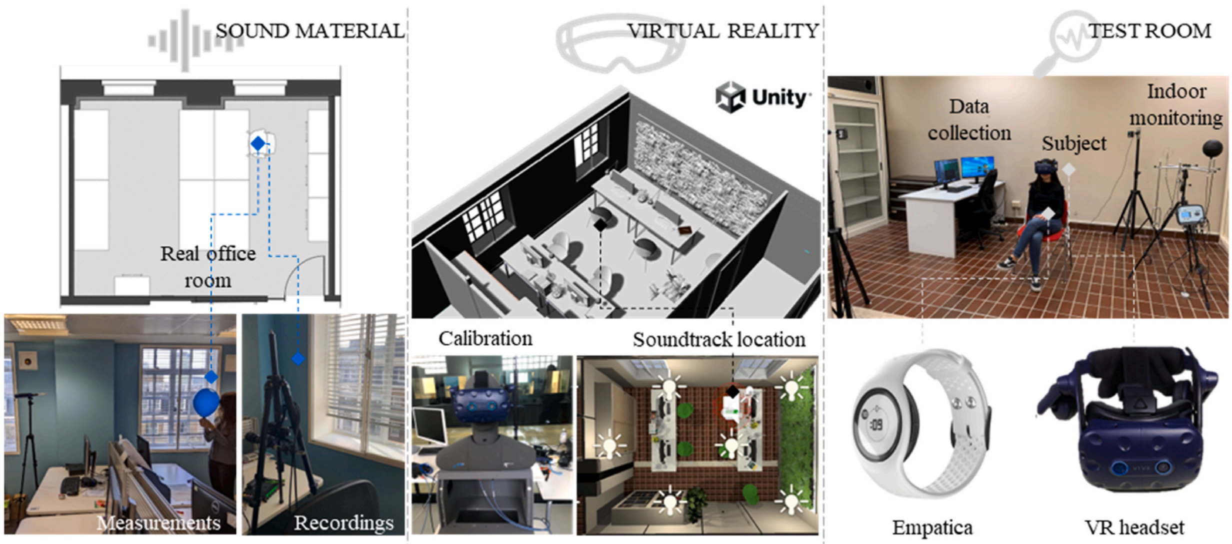
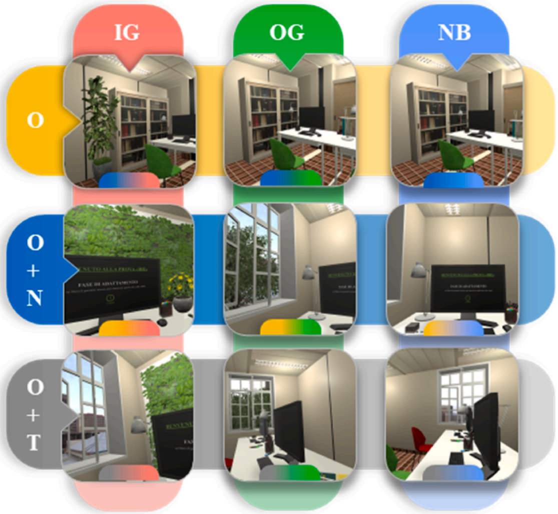


Fig. 1. Sound material, virtual environment and test room set-ups.



	IG	OG	NB
Potted plants	4%	0%	0%
Plant wall	60%	0%	0%
Outdoor plants	no	yes	no
View factor	5	5	5
Sample	66p	66p	66p

Fig. 2. 3 × 3 factorial design overview (IG: Indoor Green, OG: Outdoor Green, NB: Non-Biophilic, O: Office, O + N: Office + Nature, O + T: Office + Traffic). Greenery percentages are referred to the office room floor area. WELL Standard proposed potted plants covering at least 1% of floor area per floor and a plant wall covering a wall area equal or greater than 2% of the floor area. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the acoustic environment. The soundtracks were implemented within the VR model in correspondence of the first player control which was also the position where measurements and recordings took place in the real office room. As a technological device, the HTC Corporation VIVE PRO Eye head-mounted display was used (1440 × 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).

- Test room set-up (right-hand side of Fig. 1): An office space (5.93 × 4.38 × 3.00 m) inside the Department of Building and Civil Engineering and Architecture (Università Politecnica delle Marche, Ancona, Italy) was dedicated to the experiments. It was equipped with a HD32.1 Thermal Microclimate Station by DeltaOHM [70] to monitor indoor air temperature (measure range: −40 to +100 °C; accuracy: ±1.5 + 1.5% of the measurement), radiant temperature (measure range: −10 to +100 °C; accuracy: Class 1/3 DIN), and air velocity (measure range: 0.1–5 m/s; accuracy: ±0.2 m/s for 0.1–1 m/s) at 1.1 m – height. The indoor climatic condition was kept constant by the HVAC system of the office space. Throughout the experimental sessions, at 1-min intervals, DeltaLog10 software [71], detected the following mean of the zone air temperature, radiant temperature and velocity: 23.32 ± 0.45 °C, 23.21 ± 0.38 °C, 0.06 ± 0.01 m/s.

Further details on the specific settings used during measurements and the creation of visual and acoustical simulation are available in an extended description of the methodology by Latini et al. [65].

2.2. Dependent variables

To answer the research questions, perceptual attributes related to soundscape assessment were collected and physiological measurements were recorded.

2.2.1. Soundscape assessment

While exposed to each immersive audio-visual virtual environment, participants were invited to rate the perceived affective quality of the soundscape through the following eight perceptual attributes using a five-point Likert scale («totally disagree», «slightly disagree», «neither agree nor disagree», «slightly agree», «totally agree») "For each of the 8 scales below (pleasant, exciting, eventful, chaotic, unpleasant, monotonous, uneventful, and calm) judge to what extent those attributes are applicable to the acoustic environment you are experiencing". In particular, any potential unclear aspects in the questionnaire instructions or main text were resolved during the pre-experimental phase. Moreover, participants were given practical examples for their ratings. For instance, they were instructed that selecting « totally agree » for the «pleasant » attribute indicates that their perception the acoustic environment was entirely pleasant)."

Due to the absence of an indoor soundscape assessment model for office buildings (such as present for residential buildings [37]), this study adopted the model developed by Axelsson et al. [36] and included in ISO/TS 12913–2 technical specification [72] for (outdoor) urban environments. The choice is justified by the fact that at least the two main perceptual dimensions underlying Axelsson's model 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), as already demonstrated for other indoor settings, e.g., residential ones [37]. In addition, for sake of comparability with previous ISO-based studies the ISO/TS 12913–2 standardised attributes were adopted.

2.2.2. Physiological evaluation

Throughout each experimental session, while the participant was immersed in VR, three physiological signals were recorded on the Empatica Health Monitoring Platform using the EmbracePlus wearable device [73].

- Electro-Dermal Activity (EDA) (measure range: 0.01 to 100 μS, fixed sampling rate of 4 Hz), is the physiological response reflecting sweat glands activity and is sensitive to the activation of the sympathetic nerve due to psychological stimuli [74,75]. It is adopted as an indicator of psychological and physiological arousal and to assess stress [76]. Indeed, when a stimulus (e.g., an object, a person, a situation) is perceived as personally significant, a subject experiences an increase in stress level or emotional arousal, the brain sends a signal through the sympathetic nerve to the eccrine sweat glands to activate them thus increasing EDA and promoting the sudomotor [57,77–79]. 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, fixed sampling rate of 64 Hz), which 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 [80]. Similarly to heart rate, it is commonly adopted as an objective measure of psychological stress and arousal [75,76]. At a stable status, if the subject is in a calm or relaxed state and even in the presence of positive emotions (e.g., affection, amusement, happiness), the pulse rate slows down as the parasympathetic nerve is activated. Conversely, when the sympathetic nerves are activated, the heart rate increases which usually happens in the presence of negative emotions (e.g., anger, sadness, fear) and stress load [81,82].
- Skin Temperature (ST) (measure range: 0 to +50 °C; accuracy: ±0.1 °C from 30 °C to 45 °C, sample rate of 4 Hz), which is a physiological response that changes as the peripheral blood vessels contract or relax [83]. During negative-valenced, high-arousal emotional states (e.g., stress status sadness), the sympathetic nervous system is activated leading to a reduction in peripheral circulation and causing a reduction in skin temperature while the increase is significant during calm and positive-valenced emotion [76,84,85].

Since the authors were interested in assessing the differences between the tested scenarios on participants' physiology, the mean responses to each audio-visual stimulus were computed after 2–3 min of stimulus presentation. This period corresponds to the initial exploration and adaptation time to each scenario (see Section 2.3) experienced by the subjects to facilitate immersion in the virtual environment [49,86]. In order to detect the most effective responses to the scenarios, it was necessary to exclude this initial orientation period and the related emotional reaction to virtual environments [79]. Experimental changes in EDA, PR and ST indices were analysed by looking at the differences between the tested audio-visual scenarios.

2.3. Experimental protocol

The experimental activity was conducted in individual sessions of 35 min (Fig. 3), over twenty-nine non-consecutive days in winter 2023.

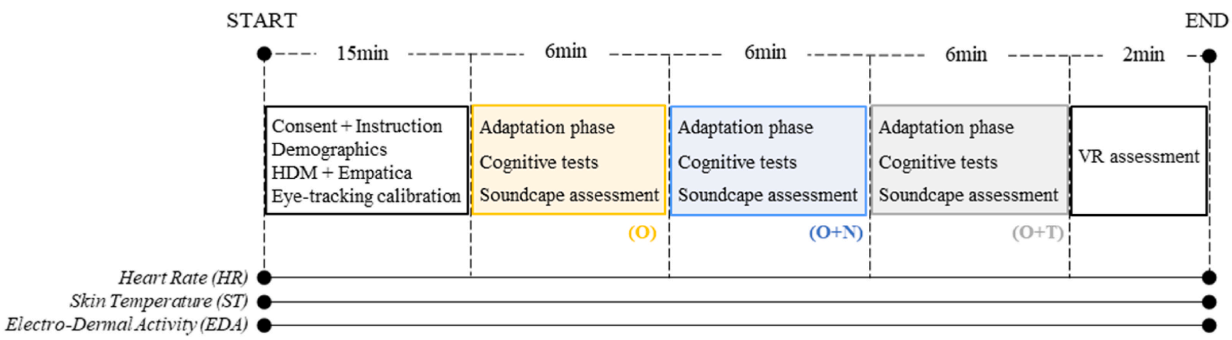


Fig. 3. Experimental protocol.

After reading the information about the study and signing the consent form, participants responded to a series of demographic questions. They were then instructed to wear and adjust the VR headset and rest with their eyes closed for 30 s. This pre-experimental period lasted about 15 min to properly allow participants' adaptation to the indoor environmental conditions and reduce any fluctuation related to the 30 min-prior-test physical activity that might have influenced their metabolic rate [87]. The three Acoustic Factor variations were presented one at a time in a randomized order. For each condition of Factor A, participants were instructed to explore the scene for 3 min (adaptation phase [14]), while verbally describing the visual and acoustical dimensions of the scene, to perform three cognitive tests (described elsewhere [65]) and assess the perceived affective quality of soundscapes. To support internal validity [49,88], the execution of the three tests and the presentation order of the soundscape attributes and the acoustical scenarios were randomized (e.g. *OSPAN, M-P, Stroop* vs *M-P, OSPAN, Stroop*) to counterbalance the order effect and time-related factors.

The total exposure time to each acoustical scenario was 6 min. The Visual Factor scenario was specified before starting the experimental session, by indicating to the participant to "Imagine this is your office.", "Imagine this is your office with indoor greenery." or "Imagine this is your office with outdoor greenery.", for the NB, IG and OG scenarios, respectively, to reduce the process of abstraction required by the participant.

After performing all three Factor A scenarios, subjects evaluated the sense of presence and immersivity and the cybersickness disorders that were previously processed to demonstrate the ecological validity of the virtual environment. The whole set of questions was integrated inside the virtual model as images on the virtual monitor to ensure an effective immersive experience and reliable data [14], while answers were given verbally and collected by the researchers. Since subjects provide feedback inside the virtual environment, authors will be allowed to avoid the *break-in-presence* [89] which can threaten the validity of the experiment.

The physiological responses of the subjects were measured throughout the test.

2.4. Data processing

Generalized Linear Mixed-Effects Models (GLMM) were used to analyse the association between Visual and Acoustical factors on collected data, while considering the mixed experimental design, the non-normality and the non-homogeneity of residual data distributions [90–92]. The basic theory of the GLMM is that subjects' responses are the sum of fixed factors, which are the variable 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 [93] and the R packages *glme4*, considering a separate GLMM for each dependent variable. In particular, a Gaussian and a Gamma (log-ink function) distributions were used to analyse physiological data (continuous decimal data) and soundscape results (continuous response variable), 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 [94] 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:

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

The statistical significance of the effect of each term was calculated using Analysis of Variance (ANOVA, Type II, Wald χ^2 tests) through 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.

Table 1 shows the Akaike Information Criterion (AIC), and the marginal (R_m^2) and conditional (R_c^2) coefficients of determination of each model distribution. The statistical significance of the effect of each term was calculated using Analysis of Variance (R *car* package, Type II, Wald χ^2 tests, $\chi^2_{crit}(2) = 5.99$, $\chi^2_{crit}(4) = 9.49$). In the case of a significant effect, post-hoc pairwise comparisons of estimated marginal means were undertaken to investigate the difference between groups with Bonferroni correction (95% level of significance).

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 [72,95]. The scores collected from the eight attribute values were reduced through trigonometric

Table 1
AIC, marginal and conditional R^2 of the GLMM for each dependent variable. Threshold values: minimum (0.20), moderate (0.50), and strong (0.80) effect size [66]. GLMM model: *DependentVariabile ~ AcousticFactor * VisualFactor + (1| VisualFactor) + (0 + AcousticFactor |ParticipantID)*.

Group variable	Dependent variable	AIC	$R^2_{marginal}$	$R^2_{conditional}$
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

transformation into a pair of coordinates suitable to be plotted in the Pleasant-Eventful diagram, according to the methodology described in the Part 3 of ISO/TS 12913 [72] and in the scientific literature [95]. 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.

3. Results

In the following section, the results of the analyses for the main and interaction effects of Visual and Acoustical Factors on participants' soundscape assessment and physiological responses (Sections 3.2 and 3.3), as well as the correlation between soundscape attributes and physiological variables (Sections 3.4), are presented. In a previous study by the authors, the ecological validity of the proposed virtual model to investigate audio-visual Biophilic Design interventions was confirmed in terms of a high sense of presence and immersivity and low cybersickness levels.

3.1. Participants

A total number of 198 participants took part in the experiment on a voluntary basis. The pre-selection process was based on the following criteria: participants needed to be at least 18 years of age, free from cardiovascular, neurological and other major diseases and had no hearing impairments and vision problems (e.g., colour blindness, strabismus). The recruited participants presented the following demographic features.

- Gender: 123 males (64%) and 75 females (36%).
- Age distribution: 79% from 20 to 25, 17% from 26 to 30, and 4% from 31 to 39, with overall mean and standard deviation equal to 23 and 3.85 years, respectively.
- Eyesight problems: 56% of the sample of the pilot study had common eyesight problems, (astigmatism, myopia), but wore corrective lenses during the tests.
- Educational level: 34% of the sample was composed of university students, the majority (60%) were graduated participants, while 6% had a higher educational level.
- Previous VR experience: About 54% of participants were not familiar with virtual reality, while the other 46% experienced a virtual environment at least once.

The *a priori* power analysis using G*Power software [96] revealed 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 (effect size f = 0.25, α = 0.05). The research was approved by the Research Ethics Committee of the Università Politecnica delle Marche (No. 0216363, 01/12/2022).

3.2. RQ1. How does the audio-visual connection with nature influence the perceived affective quality of soundscape in office environments?

Fig. 4 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 [95].

Considering Factor V (Fig. 4a), it can be noticed that the visual factor is not effective in determining the affective response to the indoor soundscape. Indeed, 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, Fig. 4b 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 characterize each perceptual attribute for Fac-

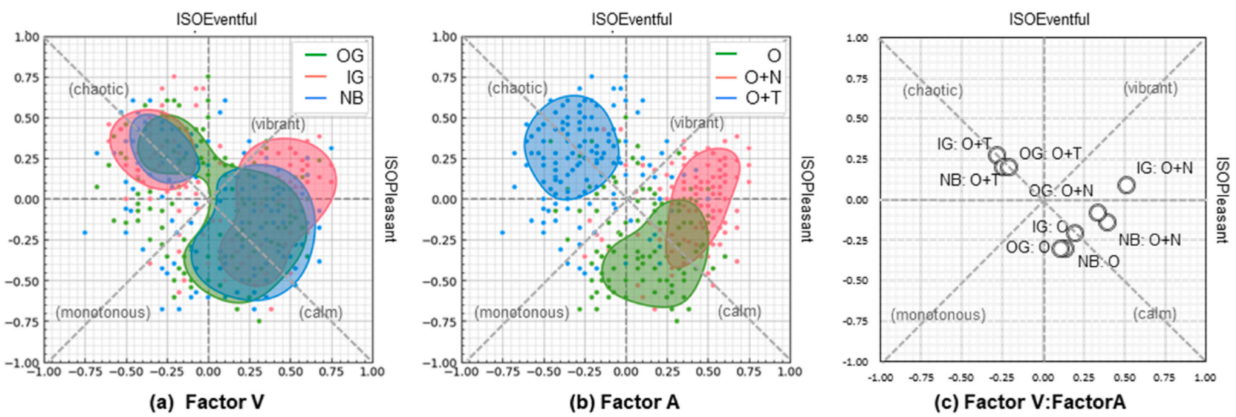


Fig. 4. Comparison of the soundscape of the three Visual scenarios (a) and of the three Acoustical scenarios (b); the dots representing the median ISOPleasant and ISOEventful responses for each Factor V: Factor A scenarios (c).

tor 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 in overall vibrant (58%).

Fig. 4c shows the relative change in the soundscape perception of the mean ISO coordinates for each combined Factor A * Factor V scenario.

To test the above hypothesis, the results of the GLMM models for the ISO coordinates were analysed.

Considering the ISOPleasant score, the results of the statistical analysis revealed a significant main effect for Acoustic (χ^2 (2) = 605.98, $p < 0.05$, $\eta^2 = 0.96$) and for Visual Factor even if the effect size was negligible (χ^2 (2) = 7.7, $p < 0.05$, $\eta^2 = 0.02$). The same result occurs for the ISOEventful scores with a significant main effect for Factor A (χ^2 (2) = 415.49, $p < 0.05$, $\eta^2 = 0.92$) and a significant but negligible effect for Factor V (χ^2 (2) = 28.40, $p < 0.05$, $\eta^2 = 0.06$). 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 2).

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. Fig. 5 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.

Table 2
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.

Parameters	Factor	Level	Mean (sd)	Anova, type "III" (GLMM)	η^2	Pairwise comparison	Pairwise comparison result
ISOPleasant	V	NB	0.09 (0.23)	χ^2 (2) = 7.77, **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)	χ^2 (2) = 605.98, **p < 0.05**	0.96	O < O + N	**p_{adj} < 0.05**
		O + N	0.41 (0.19)			O + N > O + T	**p_{adj} < 0.05**
		O + T	−0.25 (0.25)			O + T < O	**p_{adj} < 0.05**
	VxA			χ^2 (4) = 15.68, **p < 0.05**			
ISOEventful	V	NB	−0.08 (0.25)	χ^2 (2) = 28.40, **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)	χ^2 (2) = 415.49 **p < 0.05**	0.92	O < O + N	**p_{adj} < 0.05**
		O + N	−0.04 (0.23)			O + N < O + T	**p_{adj} < 0.05**
		O + T	0.23 (0.26)			O + T > O	**p_{adj} < 0.05**
	VxA			χ^2 (4) = 8.11, p = 0.08			

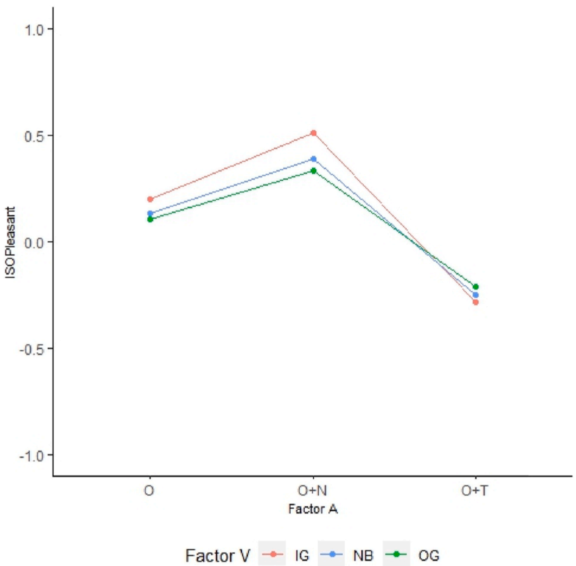


Fig. 5. Interaction plot for the ISOPleasant scores.

3.3. RQ2. How do participants physiologically respond to audio-visual connection with nature in office environments?

Considering the participants' Electro-Dermal Activity, the results of the statistical analysis revealed a significant main effect of Visual Factor (χ^2 (2) = = 9.07, p < 0.05, η^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 (χ^2 (2) = = 9.07, p < 0.05, η^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 3).

According to the post-hoc test results and the pairwise comparison presented in Fig. 6a, 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 4), 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 (Fig. 6b), a significant difference occurred only in IG compared to both NB and OG (p_{adj} < 0.05): IG resulted in lower EDA

Table 3
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.

Physiological parameters	Factor	Level	Mean (sd)	Anova, type "III" (GLMM)	η^2	Pairwise comparison	Pairwise comparison result
Electro-Dermal Activity (EDA) [μS]	V	NB	0.73 (1.24)	χ^2 (2) = 6.12, **p < 0.05**	0.78	NB – IG	**p_{adj} < 0.05**
		IG	0.40 (0.77)			IG – OG	**p_{adj} < 0.05**
		OG	0.75 (1.50)			OG – NB	p_{adj} = 0.57
	A	O	0.64 (1.21)	χ^2 (2) = 9.07, **p < 0.05**	0.91	O–O + N	p_{adj} = 0.51
		O + N	0.44 (0.91)			O + N–O + T	**p_{adj} < 0.05**
		O + T	0.81 (1.39)			O + T – O	p_{adj} = 0.82
	VxA			χ^2 (4) = 0.43, p = 0.98			
Pulse Rate (PR) [bpm]	V	NB	79.95 (13.10)	χ^2 (2) = 0.18, p = 0.91			
		IG	80.63 (10.45)				
		OG	78.05 (12.48)				
	A	O	79.32 (12.14)	χ^2 (2) = 58.48 **p < 0.05**	0.94	O–O + N	**p_{adj} < 0.05**
		O + N	74.84 (11.52)			O + N–O + T	**p_{adj} < 0.05**
		O + T	84.48 (12.37)			O + T – O	**p_{adj} < 0.05**
	VxA			χ^2 (4) = 2.79, p = 0.59			
Skin Temperature (ST) [°C]	V	NB	30.58 (1.53)	χ^2 (2) = 0.34, p = 0.84			
		IG	31.48 (2.09)				
		OG	30.76 (1.65)				
	A	O	30.90 (1.71)	χ^2 (2) = 4.51, p = 0.11			
		O + N	30.74 (1.79)				
		O + T	31.19 (1.77)				
	VxA			χ^2 (4) = 2.59, p = 0.63			

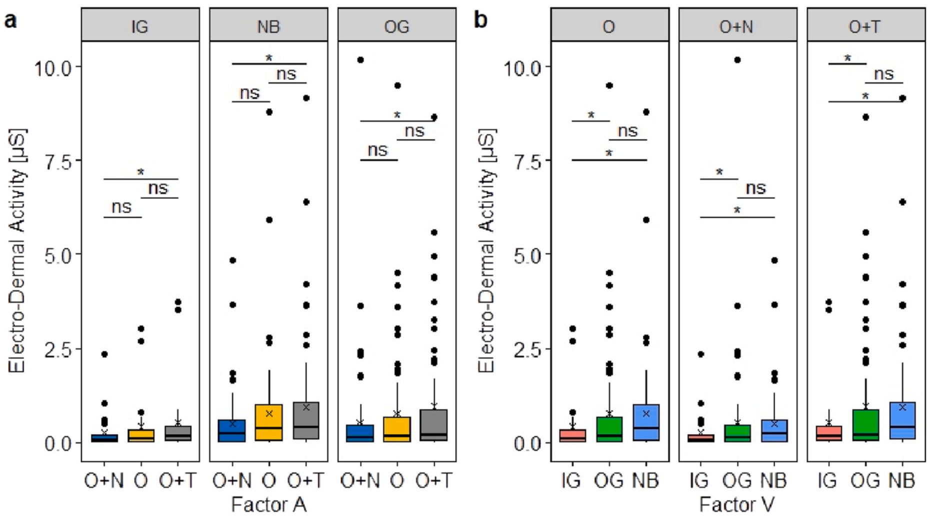


Fig. 6. Boxplot of the participants' Electro-Dermal Activity expressed in μS. Data are grouped by Factor V (a) and Factor A (b) and pairwise comparisons are shown. Inside the boxplots, the cross is the mean value and the line is the median value. ns.: non significative, *p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.001.

Table 4
Data mean and standard deviation of the physiological parameters across Factor V and Factor A scenarios.

Factor V	Factor A	EDA	PR	ST
		[μS]	[bpm]	[°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

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 (χ^2 (4) = 0.43, p = 0.98).

A significant main effect for the Acoustic Factor, (χ^2 (2) = 58.48 p < 0.05, η^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 (Fig. 7a) 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 (χ^2 (4) = 2.79, p = 0.59), and the interaction effect was not significant (χ^2 (2) = 0.18, p = 0.91). Indeed, comparing the distributions (Fig. 7b) and mean values reported in Table 4, 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).

Lastly, regarding the Skin Temperature (cf. Table 3 and Fig. 8), the statistical analysis revealed the absence of significant effects of Visual Factor (χ^2 (2) = 0.18, p = 0.91), Acoustical Factor (χ^2 (2) = 4.51, p = 0.11) and their interaction (χ^2 (4) = 2.59, p = 0.63).

3.4. RQ3. Is there a relationship between the recorded physiology and the subjective assessment of the sound environment in office spaces?

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 (Fig. 9) 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). 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 Refs. [97,98]. 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).

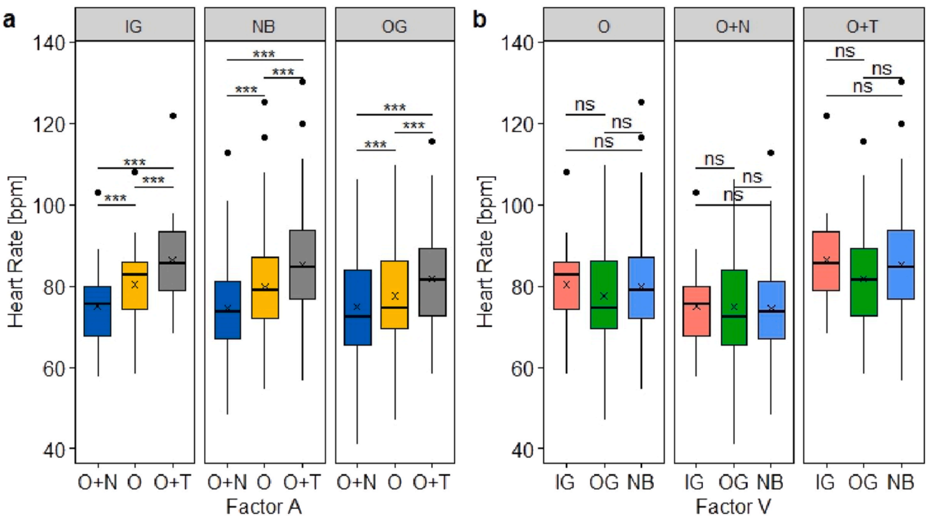


Fig. 7. Boxplot of the participants' Pulse Rate expressed in beats per minute. Data are grouped by Factor V (a) and Factor A (b) and pairwise comparisons are shown. Inside the boxplots, the cross is the mean value and the line is the median value. ns.: non significative, *p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.001.

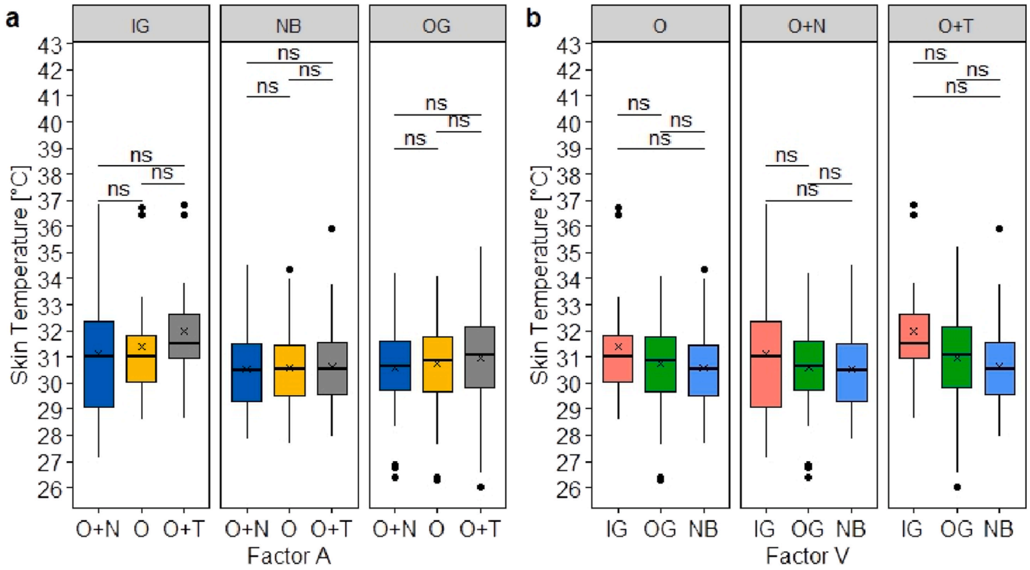


Fig. 8. Boxplot of the participants' Skin Temperature expressed in beats per minute. Data are grouped by Factor V (a) and Factor A (b) and pairwise comparisons are shown. Inside the boxplots, the cross is the mean value and the line is the median value. ns.: non significative, *p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.001.

4. Discussion

In the following paragraphs, the three research questions underpinning the study are discussed according to the outcomes of the experimental activity presented in Section 3.

4.1. RQ1. Influence of audio-visual connection with nature on soundscape assessment

One of the main objectives of this research was to assess the main and interaction effects of audio-visual connection with nature on soundscape perception in order to test potential positive effects provided by biophilic design strategies.

The results of the GLMM model highlighted a primary effect of acoustic stimuli on the perceptual dimensions of pleasantness and eventfulness. 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 [53,97,98] due to the fact that it was considered a negative component [36,99].

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 [36,54] 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 [38,100,101], and provide masking opportunities over traffic noise [102]. 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 [36,37,103–105]. Those findings supported restorative potentials consistently with the Attention Restoration Theory [106]. 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 [107]. This may indicate that the positive effect of natural sounds on pleasantness might be overperformed when people are in «Visual Connection With Nature » [66] 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 has the ability to improve pleasantness in the presence of traffic noise, although the effect is relatively small. This outcome accords with the one presented by Sanchez [53] 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., Refs. [108–110]). 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 [110]. Indeed, Jo [54] proposed to increase natural elements as an effective way to improve both acoustic and visual satisfaction.

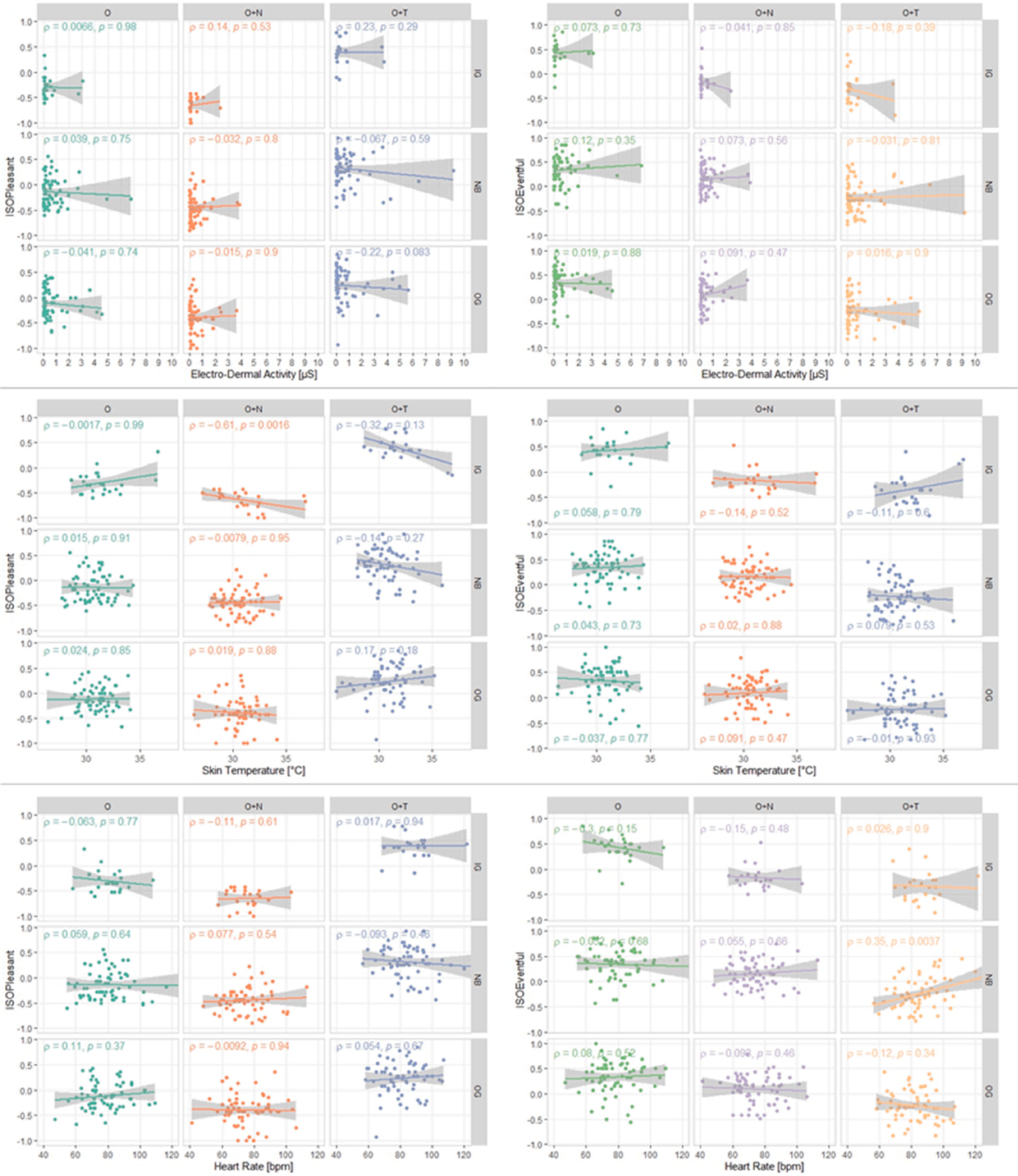


Fig. 9. Correlation plot of the physiological parameters and the ISO coordinates.

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 [5], accompanied by VR scenarios that have been recognized as useful soundscape evaluating tools [111].

4.2. RQ2. Physiological responses to audio-visual connection with nature

Participants' physiological responses, such as Electro-Dermal Activity, Pulse Rate and Skin Temperature, were measured and analysed based on the acoustical and visual scenarios and their interactions. It was hypothesized that visual and acoustical exposure to more pleasant indoor conditions would result in a greater decrement in mean EDA and ST, and deceleration of PR compared to unpleasant scenarios.

In summary, the analysis of the three physiological responses showed a common decrease in PR and EDA, and no relevant results concerning ST. In particular, the values of EDA were significantly lower in the presence of natural sounds and greenery-related elements than in traffic and non-biophilic scenarios. Considering participants' PR, a positive contribution, within all the visual conditions, rises considering the natural sounds scenario. Indeed, pulse rate significantly slowed down in the natural sound condition compared to traffic and office. On the contrary, no significant positive changes in bpm were highlighted considering the presence of greenery elements.

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., Refs. [23,97,112,113]) and pulse rate in both VR [112] and real settings studies [113]. However, this did not agree with other works [97,105], which found an opposite relationship between unpleasantness and deceleration in bpm, while Irwin et al. [98] 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., Refs. [56–58]), and urban context (e.g., Refs. [55,114]). Considering PR, the findings are not consistent with previous empirical studies [55,114] 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 Ref. [9], 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 [9]. However, this is inconsistent with the expectation that visual connection with nature and natural sound exposure will be associated with positive changes in ST.

Such discrepancies between the physiological responses are relevant also in the existing literature [64]. A possible explanation for yielding invaluable insights and profoundly impacting human physiology is the fragmented experimental settings related to the duration of exposure within the acoustic environment manifesting inconsistency in physiological responses [115]. Additionally, these outcomes acknowledge the infancy and inconclusiveness of research on the relationship between physiology and soundscapes stressing the complexity of understanding human responses to environmental stimuli.

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 [76], 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., Refs. [23,55,97,98,105,112,113,115,116]. 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., Refs. [16–18]). Moreover, most studies examining the potential of natural features on stress recovery [117] analysed one sensory stimulus at a time, even if human perception of the environment is highly multisensory. Since this is a brand-new topic and interest in this research domain is emerging, the practical application of these results could be useful for the scientific community. Indeed, the measure of objective physiological responses in association with the subjective perceptual dimension in VR could support researchers in developing meaningful patterns of response as the starting point for a more comprehensive assessment of the indoor built environment since the early design stages. As a result, practical applications for building design would be offered to practitioners after a deeper understanding of such processes.

4.3. RQ3. Physiological parameters and soundscape assessment relationship

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). At a general level, no significant positive changes were detected for ST across the audio-visual connection with nature (see Sections 3.3–4.2). 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. Similarly, the positive correlation between PR and ISOEventful 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., Refs. [112,113]). However, it is generalizable 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 [64]. 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 min) 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. As already emphasized in existing literature [118] the importance of studying prolonged soundscape exposure times is imperative and currently unexplored to account for insights on the physiological responses as a fundamental factor in nervous system adaptation, leading to either habituation or sensitization [115] and significantly influencing research outcomes. These aspects could lead to an increase in the external–ecological validity of the study, support further assessments of sound habituation underpinning physiological processes and allow for more detailed data collection, enabling deeper comprehension of underlying physiological mechanisms over time [97,105].

In addition, the research investigation on the physiology of soundscape is still in its infancy and inconclusive [115]. Indeed, as previously stated by Erfanian et al. [115] «physiological expressions of the soundscape are not always aligned with the perceptual attributes and may remain inconclusive».

Therefore, these outcomes reflect the complexity inherent in understanding human responses to environmental stimuli and underscore the necessity for continued investigation in this domain. Such balanced perspectives pave the way for a more robust and comprehensive understanding of the subject matter, ultimately driving forward the trajectory of research in this field.

5. Conclusions

This paper presents a new approach to investigate audio-visual Biophilic Design interventions in indoor virtual environments by means of physiological recordings in association with subjective assessments of soundscapes.

Three different visual designs and three sound environments for an office environment were compared in an immersive virtual audio-visual environment by 198 participants. During the experiment, physiological signals were acquired, and subjects were asked to rate their perceived affective quality of soundscapes. They also completed three cognitive tests and evaluated their sense of presence and immersion, and cybersickness but these results are not presented in this manuscript. Regarding the research questions, the experiment results highlighted the following findings.

1. Results highlighted a primary effect of acoustic stimuli on the perceptual dimensions of pleasantness and eventfulness, with audio-visual interaction effects on pleasantness ($p < 0.05$ for all factors). While the reference acoustic condition (office noise) was assessed as uneventful (76%), slightly pleasant but also somewhat monotonous, the addition of traffic sounds led to an increase in eventfulness and a decrease in pleasantness (81%, $p_{adj} < 0.05$), 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 (86%, $p_{adj} < 0.05$) and eventfulness (i.e., increased vibrancy) (58%, $p_{adj} < 0.05$). Pleasantness with natural sounds is particularly enhanced in the presence of indoor green, while outdoor green is beneficial in moderating traffic noise perception.
2. Considering EDA and PR results, the exposure to the acoustical connection with nature (pleasant soundscapes) induced a decrease in recorded physiology compared to unpleasant ones (traffic) which trigger stress, increasing sympathetic nerve activity as previously observed in the literature ($p_{adj} < 0.05$). In the presence of a visual connection with nature, a reduction of EDA was also highlighted similarly to previous studies in virtual indoor and urban settings (IG vs OG and NB, $p_{adj} < 0.05$). Conversely, a limited effect on parasympathetic activation was revealed by the lack of impact of visual settings on PR ($p = 0.91$) supporting previous studies with similar inconclusive results while contradicting others showing a reduced heart rate variability via parasympathetic activation. In general, the magnitude of the effect highlighted that acoustic factors (η^2 between 0.91 and 0.94) had a higher effect compared to that of visual factors ($\eta^2 = 0.78$). Moreover, no relevant results were detected concerning Skin Temperature which contradicts expectations of positive changes associated with nature-related stimuli as observed in previous literature. Potential reasons for the absence of significant findings might be related to the experimental settings related to the soundscape exposure time.
3. 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 (i.e., Natural sounds and Indoor Green exposure associated with positive changes in ST, $rho = -0.61$, $p < 0.05$ and Traffic sound in Non-Biophilic scenario gave the largest PR increase, $rho = 0.35$, $p < 0.05$), thus limiting the generalizability of the results.

The following main limitation can be pinpointed. First, selection bias may have occurred because the participants were young people. In such instances, results can be generalized to university students and younger adults and groups such as middle-aged and elderly people need to be recruited to enhance the generalizability of the results.

Second, the sample size was influenced by the voluntarily available participants. Therefore, in order to examine the possible positive impact of nature according to gender, age, and educational attainment, a more diverse and inclusive sample must be gathered. Third, each auditory scenario was examined for approximately 7 min due to time constraints on VR exposure and the mixed-between/within-subject design of the experimental methodologies. Thus, it is further suggested to look into the advantages of prologued exposure to visual and non-visual connections with nature even though encouraging outcomes on perceptual assessment and physiological responses emerged.

The benefits hypothesized and tested in the present study imply substantial economic, social, health and well-being benefits and have also important implications for building design. Even short exposure to joint audio-visual natural conditions could trigger specific 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. This approach can support building design practices by taking into account perceptual implications coupled with objective measurements, using emerging VR technology to provide occupants' satisfaction, achieve cognitive targets and enhance well-being.

CRediT authorship contribution statement

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

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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