

Perceptual and physiological virtual assessment of indoor Living Walls including lighting settings

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ABSTRACT

Living Walls (LWs) are increasingly introduced to improve air quality and aesthetics indoors, but the supplementary lighting required for plant vitality can disrupt occupant comfort. Thus, LW design should adopt an integrated approach, combining system requirements definition with users' comfort. Immersive Virtual Environments can support LWs prototyping, reliably creating and comparing alternative design scenarios. This study proposes a modular LW and employs virtual scenarios as a pre-design strategy to evaluate the influence of different configurations on users' visual perception and physiological state. The baseline scenario without greening is compared with the simple LW implementation (LW scenario) and with LW integrated by specific horticultural lighting, installed on an overhead supporting bracket, and properly shielded to ensure a proper work plane illuminance (LWL). The system is applied to a virtual university classroom, modelled and validated in respect of its real-world conditions. 41 subjects experienced each virtual scenario in a repeated-measure design study, rating realism, task suitability, visual comfort, and configuration preference, while physiological parameters were also monitored. Statistical analysis revealed a high realism in all scenarios, and similar perceived quality levels for task suitability. LWL, as expected, was perceived as 30 % brighter, 25 % more glare than baseline and LW, but physiological and eye-tracking metrics remained stable across scenarios, confirming no stress-related implications, thanks to proper trade-offs between LW design and dedicated lighting implementation. Presence in virtual scenarios was high and cybersickness negligible, validating the ecological fidelity, supporting the potential of this multi-step, user-centred methodology for optimising biophilic interventions during the pre-design phase.

1. Introduction

Current EU Research and Innovation agenda and Horizon 2020 Expert Group are promoting Nature-Based Solutions (NBS) to integrate action inspired by, supported by or copied from nature in urban and built environments as part of the Green Deal policy [1]. The NBS approach provides a scientific and operational foundation and focuses on the benefits to individuals and their environment [2]. While these strategies have traditionally focused on outdoor spaces, increasing interest is now being devoted to bringing nature indoors, since NBS offer scalable, low-impact strategies to create healthier, more sustainable, and climate-adaptive living and working spaces. This shift aligns with the concern of the time people spend indoors, where indoor environmental quality plays a crucial role in shaping their health and

well-being.

These principles are translated into an aesthetic and experiential approach within the built environment using the Biophilic Design approach [3,4]. Among its patterns, "Nature in the Space – Visual Connection" is one of the most investigated in literature experiments focusing on the direct and physical presence of nature satisfaction [3–5], such as indoor vegetation and green walls (i.e., plants integrated into vertical support structures). Those green infrastructures are being explored not only for their aesthetic, psychological and health [5–8], but also for their capacity to improve microclimatic conditions and indoor air quality by filtering pollutants [9,10].

Specifically, Living Walls (LWs) offer greenery presence with minimally occupied floor space thanks to their vertical greenery system configuration [11]. Their popularity has recently grown due to their recognized benefits indoor including: the reduction of air pollutants

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Nomenclature

B	Baseline virtual scenario (without greening)
EDA	Electrodermal activity
REAL	Experienced Realism
GS	Graphical Satisfaction
IPQ	Igroup-Presence Questionnaire
IVE	Immersive Virtual Environment
INV	Involvement
LW	Living Wall, and related virtual scenario (without dedicated horticultural lighting)
LWL	Virtual scenario comprising the Living Wall with dedicated horticultural lighting
NBS	Nature-Based Solution
PAR	Photosynthetically Active Radiation
PPFD	Photosynthetic Photon Flux Density
PR	Pulse rate
ST	Skin temperature
SP	Spatial Presence
VE	Virtual Environment
VR	Virtual Reality

particularly in spaces characterized by high occupant density, such as CO₂, VOCs, serving as bio-filters; sound absorption; temperature regulation allowing energy saving; aesthetic improvement; positive impacts on health and wellbeing offering restorative advantages [5,12–17].

Nevertheless, the design of LWs needs to take different issues generating specific requirements for their implementation in new and existing buildings (Section 1.1). Among them, specific attention should be provided to lightning, since it affects greenery photosynthesis and liveability, as well as psychological and physiological issues on occupants [42] (Section 1.2). At the same time, the definition and development of building components incorporating LWs could be supported by different strategies. Real-world prototypes and real-scale mock-ups can be able to measure how they can improve indoor environmental quality, also in combination with traditional solutions (such as HVAC while considering air quality [5,15,18,19]), while simulation models could be adopted to quantify their benefits according to different building performances. Virtual Reality (VR) solutions can contribute to the occupant involvement in the (co-)design process [20], and also add psychological and physiological parameters on the assessment of different designed configurations of LWs, thanks to the direct involvement of occupants in realistic and engaging Virtual Environments (VE) [21–23] (Section 1.3). On these bases, direct support [24–27] to the LWs design could be provided, as in this work aims (Section 1.4).

1.1. General requirements for LWs implementation

The successful implementation of indoor NBS through LW entails critical technical aspects such as the choice of vegetation and growing medium, irrigation system, structural support, HVAC and lighting conditions [18,28]. Each element is crucial to ensure vitality and longevity of greenery, the aesthetic appeal, and environmental benefits over time, along with proper levels of LWs life cycle performance, and these issues cannot be selected independently, while a multidisciplinary approach should be pursued.

In this context, the species selection surely plays a pivotal role in supporting many performances, starting from those related to air quality [19,26,29–32], but different issues should be considered in combination with this aspect. Starting from growth media, specific materials (e.g., soil-based or soilless) are needed to ensure adequate airflow, supply vital nutrients, hold moisture and support stable and effective microbial communities' growth and water systems [11]. Moreover, plant growth

and vitality need a proper irrigation flow rate and water uniformity [30]. However, the weight of plants combined with the water systems and substrate mass determines structural demands affecting the selection of support systems (e.g., pockets, panels or containers, affixed to the wall on steel beams or reinforced concrete) to prevent LW tilting or collapse [33]. These issues also lead to a balance in the effective greenery coverage of walls, which has notable implications considering acoustic effects [34]. In this sense, using modular solutions would better support the adaptability of LW systems in several application contexts (also in dimensional terms), especially considering carrier systems and planter systems, using felt and planter boxes, rather than support systems [30,35,36]. The strength and durability of the structure need to be ensured through the selection of a proper waterproofing and drainage system to reduce water buildup [37]. Moreover, the analysis of LWs in combination with HVAC should be also properly designed to ensure both plant health and occupants' comfort, by including [38–41]: the control of airflow direction and intensity to prevent plant stress; the regulation of humidity which is naturally increased by plants resulting in a worsened thermal comfort; the monitoring and regulation of CO₂ to properly support photosynthesis and human health; the combination of natural and mechanical filtration systems to prevent VOC accumulation. In complex settings, zoned HVAC systems can provide localised microclimate regulation near NBS.

Among the technical requirements, plants in indoor spaces require proper lighting conditions (Section 1.2), which directly influence the efficiency of photosynthetic activity, vegetation liveability and consequently CO₂ and pollutants sequestration capacity [42].

1.2. Lighting requirements for LWs and effects on building occupants

For the successful implementation of indoor LW, the light intensity is one of the fundamental parameters, being expressed as Photosynthetic Photon Flux Density (PPFD) [30]. According to previous works, a proper intensity of about 100 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ to maximise bio-filtering effectiveness in in-situ experiments has been noticed) [30], also considering the complexities in applying dedicated and homogeneous lighting systems in environments which are not initially conceived for horticultural uses [32,43,44]. Proper lighting systems should also have specific spectral composition to deliver a balanced proportion of blue and red wavelengths within the photosynthetically active radiation range (400–700 nm) for a maximal oxygen release [44]. For these reasons and to account for natural light variability, usually LWs require supplementary dedicated LED lighting systems, which directly influence the surrounding indoor environment [30]. This can result in exceeding threshold values for illuminance levels and glare index established in indoor lighting design standards (i.e., UNI EN 12464-1 for indoor workplaces [45]), turning into undesirable effects for occupants. For instance, office or classroom lighting typically requires 300–500 lx, approximately equivalent to 9 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ [46]. This becomes particularly critical when considering that the maximum PPFD for LWs correspond to illuminance levels several times higher than those prescribed for visual comfort.

Indeed, indoor workplace illumination is of paramount importance in influencing work efficiency, well-being and perception [47], impacting various psychological and physiological responses. Long exposure to inappropriate lighting conditions, particularly those involving excessive luminance contrast, glare, or illuminance fluctuations, can lead to physical symptoms, such as fatigue, eye strain and headache [48,49], and psychological symptoms such as annoyance and stress [3,50], all of which negatively impact overall well-being and productivity in the workplace. Conversely, well-designed lighting environments in terms of illuminance level and neutral correlated colour temperature are associated with improved concentration and alertness, task performance, and overall satisfaction, resulting in a more pleasant mood and engagement [51–54].

Furthermore, the synergy of such requirements includes, if considering sensitive contexts, where vulnerable occupants are present, such as

healthcare facilities or schools [12,55], or, as for other NBS applications, if considering the complexities of existing buildings [56]. As an output, it is worth noting that requirements for LWs directly affect occupants in the built environment and, if not properly considered, may compromise comfort, well-being, or overall indoor performance. This consideration underlines the importance of developing a multidisciplinary user-centred design approach to introduce nature indoors and incorporate performance, perceptual, and physiological evaluations. Such an approach allows for proper guidance in the design of indoor LWs to be operative, feasible and aligned with human needs for comfort, health, and connection with nature.

1.3. Virtual Reality as a tool for perceptual and physiological assessment of LWs

Given the complexity of balancing the technical requirements of LWs with the “human-dimension”, designers and researchers are increasingly interested in innovative tools and workflows that allow them to simulate, evaluate, and optimise LWs design in indoor environmental conditions before the implementation in the real world.

VR has become a valuable research tool to support building occupant-centric design due to its ability to provide realistic, immersive and interactive experiences with high ecological validity [57]. This technology is increasingly recognised as an efficient **design and prototyping** tool, allowing designers to develop and easily modify full-scale digital mock-ups during the earliest project stages, testing alternative lighting, materials and spatial layouts in real time [58]. Consequently, VR enables rapid, evidence-based comparisons, resulting in an effective reduction of risks of costly re-design later in the process.

A growing body of literature is exploring the use of Immersive Virtual Environment (IVEs) to investigate the effects of indoor NBS on users’ task performance, comfort domains, preferences and restoration [4,34]. However, among the studies investigating the presence of LWs [16,59–64], the effects of the technical requirements essential for the long-term plant liveability and functionality, such as appropriate lighting conditions, seem to be limitedly investigated.

On the other hand, several studies have specifically employed IVE to assess the variations of indoor electric lighting on users’ responses [65], independently of greenery systems. These investigations have demonstrated that immersive simulation can reliably capture how lighting parameters, particularly illuminance levels [3,66,67] and colour temperature [66,68–71] affect visual perception, mood, task performance, physiology and thermal indices. This kind of activity is possible since VR offers a highly controlled experimental setting, enabling researchers to isolate and manipulate specific design variables that are difficult to control in real spaces while maintaining consistent control over all other contextual variables. In these studies, subjective evaluations of lighting conditions are typically collected through questionnaires, often adapted from established standards or prior literature. These instruments typically include items evaluating, in relevance order, visual perception in terms of pleasantness, preference, uniformity [3,66,68,69,71], lighting colour [3,66,71], visual comfort and/or discomfort [3,66], and, rarely, overall satisfaction [3] and mood [70].

Moreover, VR facilitates the integration of advanced physiological data monitoring tools, such as eye-tracking [19,72–76], and wearable physiological sensors [16,60,77] to collect objective data on users’ reactions. By combining physiological indicators with subjective self-reported measures, researchers can gain a comprehensive understanding of how specific lighting conditions influence comfort, cognitive performance, and emotional state. However, despite this potential, in the field of VR-based assessment of indoor electric lighting variations, only a few attempts have been reported by [60,67]. In contrast, the integration of physiological parameters measurements is much more established in VR-based evaluations of NBS, where it has been frequently associated with restorative potential [4]. Therefore, VR provides a valuable opportunity to test research hypotheses and user-centred

design scenarios, identify potential trade-offs between general LW requirements and human comfort, and generate evidence-based guidelines for the implementation of greenery in indoor environments.

1.4. Research gaps and work aim

Despite the growing interest in Living Walls, advancements in Virtual Reality and ergonomic measurement tools, studies that combine physical measurements, physiological monitoring, and perceptual assessments to inform the design of NBS (especially living walls) in virtual environments remain scarce. In particular, the role of lighting is often overlooked in the design of Living Walls, even though it is crucial not only for ensuring plant vitality but also for shaping users’ visual comfort and perception. What is still largely missing in the literature is a comprehensive evaluation that couples the lighting requirements of vegetation with their consequences on human occupants. The limited assessment of dedicated lighting systems highlights the need for further studies to support informed decision-making during both the design and application feasibility phases. Hence, an integrated approach that addresses these aspects offers significant advantages to support evidence-based design, coupling the technical requirements of vegetation with the needs of building occupants.

In view of the above, the research question guiding this work is: “How does the application of indoor Living Walls influence users’ visual perception, eye-tracking metrics and physiological responses, also considering specific lighting conditions?”.

To this aim, this work defines a modular LW to be applied in a university classroom, as a sensible living environment for LWs application. Then, an Immersive Virtual Environment is developed to simulate the basic classroom condition and two different LWs configurations, without and with the implementation of a dedicated lighting system, which has been conceived as integrated within the LW module. A multimodal evaluation protocol was adopted, combining the collection of subjective visual comfort surveys, eye-tracking and physiological data, to assess users’ response to the LW indoor intervention, thanks to laboratory tests involving more than 40 volunteers.

The reminder paper is structured as follows: [Section 2](#) reports the developed and adopted methodology to answer the research question, [Section 3](#) and [Section 4](#), respectively, present and discuss the results obtained from the experimental sessions, while conclusions are drawn in [Section 5](#).

2. Methodology

The experiment was conducted in a laboratory setting. A sample of 41 participants was exposed to immersive virtual environments simulating a real university classroom with different indoor conditions. In particular, their perceptual and physiological responses were recorded in three scenarios (independent variable): Baseline (B) classroom replicating the real-world case-study; Living Wall only (LW) simulating the classroom with integration of living wall panels; Living Wall with dedicated horticultural lighting installed on an overhead supporting bracket (LWL) to satisfy the general requirement for living walls implementation in indoor environments. At this aim, a multi-step methodology has been developed and applied, involving: the selection of the real classroom and the design of a modular living wall system to be applied herein ([Section 2.1](#)); the field measurements and simulation of the artificial lighting performance in the three scenarios, faithfully replicated in the IVE modelling ([Section 2.2](#)); the selection of the dependent variables to be investigated on a recruited sample of 41 people ([Sections 2.3 - 2.4](#)).

2.1. Case-study selection and modular living wall design

The selected case study is a real classroom located in a university building in Italy (Engineering Faculty at Università Politecnica delle

Marche, Ancona), which served as the reference environment for developing the virtual lighting scenarios.

The classroom has a regular rectangular geometry with dimensions equal to 9.00(W) x 13.00(L) x 3.50(H) m, and one of the shorter sides consists entirely of windows, while two doors are located on the opposite side (also see Fig. 3). All the walls are composed of prefabricated panels (1.5*3.5 m), fixed at the ground and ceiling levels, stiffened by a stainless-steel profile at the edges, being able to hold concentrated loads (including wide whiteboards and screens). The walls' surface is painted with a light beige colour. The floor is covered with green linoleum, the ceiling is made of plasterboard, and workstations consist of wooden tables and chairs. Moreover, the classroom lighting system consists of 42 recessed, fluorescent Philips MASTER TL-D 36W/840 luminaires, each equipped with an internal reflector assembly to improve light diffusion. Each lamp provides a luminous flux of 3100 lumens and a Correlated Colour Temperature of 4000 K.

There are different living wall systems available on the market, ranging from container-based solutions to modular panels and felt (geotextile)-based configurations, including modular systems, which can be more easily installed, taking into account the same basic module, implemented depending on the application space features [18,23]. In this study, a modular textile system (1.35 × 2.50 m) was adopted, being consistent with the overall dimension of the room and of the panels composing the room walls, as well as being a lightweight and flexible option with high transpiration capacity and slim profile (Fig. 2). Industrially produced multilayer flexible modules are fixed on the galvanised-steel backing frame, directly secured to the wall. They consist of a matrix of pockets made of organic and synthetic fabrics for plants and their growing mediums. An integrated micro-irrigation line runs vertically behind each pocket, and a drainage gutter at the base is not necessary to collect the excess of water, simplifying LW installation. The total thickness is about 0.11-0.12 m. Considering that actual boundary aisles of the classroom are 1.2 m wide, the module thickness still meets Italian requirements for wheelchair accessibility in indoor environments (DM 236/89), implying 1 m wide aisles, which is also consistent with fire safety requirements for the assessed building (DM 26/08/1992). The selected plant is *Chlorophytum*, which is one of the most common species for LW application in indoor environments thanks to the recognized efficacy in reducing the room CO₂ under moderate-high PPF of 50-100 μmol m⁻² s⁻¹ (~3200-5000 lux) [78,79]. Consequently, to ensure optimal spectral quality and adequate light intensity for plant health to each LW module, a dedicated horticultural LED system was selected from those available on the market¹. The selected luminaire is mounted 0.5 m in front of the living wall, and the lighting fixture had a vertical inclination of 12° (thus from the vertical growing surface), based on literature recommendation [78]. 1 horticultural LED of 1.50 m per module was installed, secured to the backing frame through two galvanised-steel tubular profiles, having the aforementioned required length. The LED provides a luminous flux of about 34000 lumen, 160 W, 610 μmol s⁻¹, and a correlated colour temperature (CCT) of 4200. Since the LEB is assumed to be 2.5 m from the ground, or above, its position is consistent with the minimum height of the aisle according to reference accessibility and fire safety code requirements.

2.2. Virtual modelling

Main lighting design criteria determining the luminous environment were assessed through field measurement and simulations, considering that each tested scenario (B, LW and LWL) has been evaluated in compliance of EN 12464-1 standard for writing, reading, data processing (i.e., table 34) and computer work (i.e., table 44) activities in indoor workplaces [45]. This basic reference methodology has also been

assumed by previous works on LW design and assessment [30]. With respect to electric lighting, the EN 12464-1 criteria include: the luminance distribution, glare, colour rendering and colour appearance of the light, and illuminance. In both real-world and virtual environments, the reference measuring plane classroom was set to 0.8 m in height, corresponding to the real desks working plane height.

The luminance distribution in the visual field was evaluated by determining the reflectance of all interior surfaces and comparing the values with the recommended ones. The spectral reflectance of ceiling, wall, floor and desk surfaces in the visible wavelength region (380–740 nm) was measured in the real-world classroom, using a spectrophotometer (CM-2500d Konica Minolta, Fig. 1) in Specular Component Excluded mode. The overall spectral reflectance values were computed as a function of the measured spectral reflectance factor, the spectral luminous efficiency function in the CIE standard system of physical photometry (V(λ) ISO/CIE 11664-1:2019 [80]) and the relative spectral distribution (S(λ) ISO/CIE 11664-2:2022 [81]). The mean reflectance of the ceiling, wall, and floor is 0.87, 0.69, and 0.20, respectively, which satisfied the recommended reflectance ranges (ceiling 0.70-0.90, walls: 0.50-0.80, floor 0.20-0.60). The reflectance of major objects, like desks, was also in the range of 0.20-0.70 (0.28). These data have been used in simulations, being considered constant in all the assessed scenarios.

The discomfort glare was based on the Unified Glare Rating method for electric light, considering that measured/simulated values had to not exceed the limit value given in the standard tables ($R_{UGR} \leq 19$). In particular, the virtual models assumed that, in the real-world environment, existing light fixtures are recessed in the ceiling (0.10 m from the surface level) and shielded with horizontal slats, placed perpendicularly to the light bars. This solution avoids excessive discomfort glare. These installation settings were considered in all the assessed scenarios, instead, measuring the R_{UGR} by simulations.

The correlated colour temperature of the light source installed in the real classroom and selected for the LW system, respectively, corresponded to 4000 K and 4200 K (see Section 2.1), both corresponding to a neutral light source colour appearance and a colour rendering equal to 80. These data served as input for simulations, considering the lights presence depending on the specific scenario.

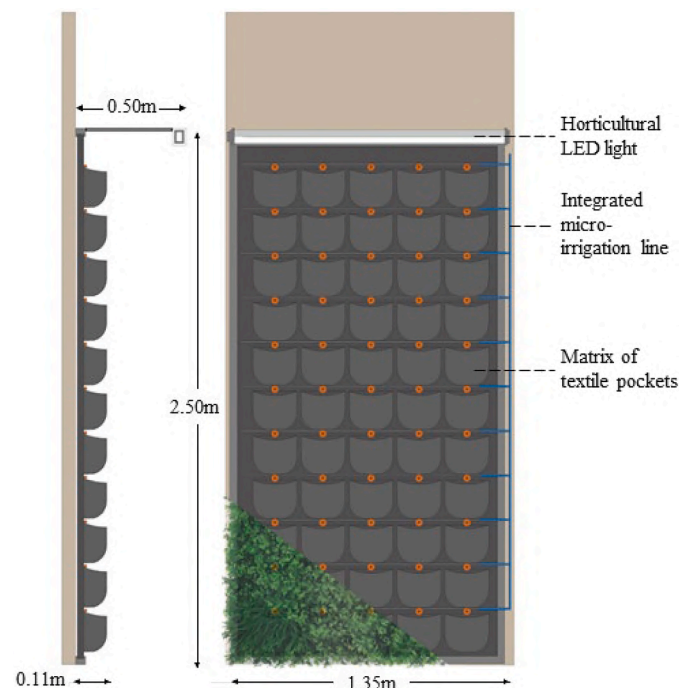


Fig. 1. Side and front schematic views of the selected Living Wall system with horticultural lighting installed on an overhead supporting bracket.

¹ An example is the Fytotextile® system developed by Terapia Urbana (<https://www.terapiaurbana.com/en/fytotextile-vertical-garden/>)

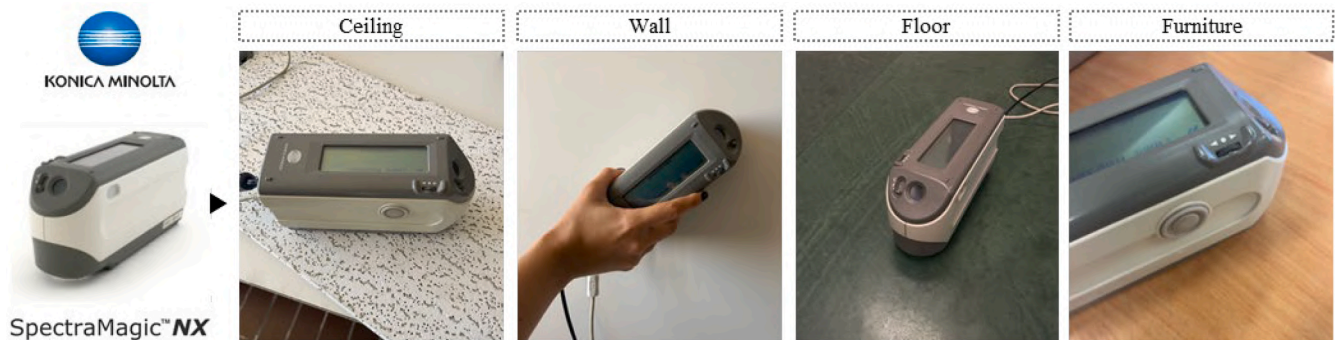


Fig. 2. Measurements of the classroom surface properties using CM-2500d Konica Minolta Spectrophotometer.

In addition, the lighting system ensures visual comfort and preserved illuminance over time through a high maintenance factor equal to 0.8, considering that the university facility management staff adopts planned maintenance interventions, and additional maintenance requests could be directly addressed by teachers in case of any disruption or problem with the classroom lighting system. This factor has been used in simulations, being considered constant in all the assessed scenarios.

The average illuminance, its distribution on the task area and on the immediate surrounding area were measured, in the real classroom (corresponding to scenario B), through a physical monitoring campaign, while for the other two virtual scenarios (LW, LWL), were simulated. In particular, the field measurements were carried out in the real classroom late evening during wintertime and with blinds fully closed to limit the influence of daylight/outdoor light sources. Five task areas were selected as measuring points to represent the lighting levels in different parts of the room, which have different distances to the luminaires. Hence, these points were on a perpendicular line to the windows and alternatively located between two lighting sources and under the edge or in the middle of a lighting source. Before the measurement, the classroom illuminance with artificial lighting off was measured to ensure that the illuminance levels were 0 lux. The measuring device consists of an LP 471 PHOT probe (measurement range: $0.01 - 200 \times 10^3$, accuracy: ± 0.01) connected to a Delta OHM HD32.1 Thermal Microclimate station, and the value for each measurement point is reported in Fig. 3. Values, measured on the reference desk plane, achieved the recommended values of at least 300-500 lx with illuminance on immediate surrounding areas of 200-300 lx, respectively.

Simulation was conducted using ReluxDesktop software, which is an open-source lighting-simulation tool from Relux Informatik AG (Switzerland) [82] that incorporates extensive manufacturer catalogues of luminaires, lamps and sensors. It also allows the modelling of materials, colours and furnishings so that both electric-light and daylight distributions to ensure accurate lighting simulation and calibration of lighting levels based on real-world measurements. In a benchmark study carried out by the IEA Solar Heating and Cooling Programme Task 31, the software results matched analytical reference values in most cases, confirming its reliability for practical design [83]. The Relux 3D model of the selected classroom was built with detailed geometric accuracy, incorporating all architectural elements that influence light distribution: windows, pillars, doors, and workstations (i.e., desks, chairs). Material properties were assigned based on measured reflectance values. The number, location and specification of the lighting system were accurately modelled using manufacturer specifications and field measurements.

The simulations proceeded in two stages. The first involved the calibration of the virtual model representing the real-world classroom, thus without any LW implementation and additional dedicated lighting (scenario B). Illuminance and glare values were calculated and compared with the ones measured on-site. On the reference plane (0.80 m), the calculated illuminance averaged 472 lux across the whole room,

with illuminance on task areas (desks) ranging from 435lux to 546lux. The corresponding Unified Glare Rating was 15, below the reference threshold. As presented in Fig. 4, the maps confirm the accurate translation of physical classroom photometric data (values in italic font) into the Relux model to be adopted for subsequent analyses.

Secondly, LW panels and their dedicated horticultural LED lighting were added to this calibrated model. The simulation in scenario LW_{unshielded} (where LED lighting was unshielded) revealed a significant effect of the dedicated lighting system: the average illuminance distribution was six times higher average illuminance (~ 3000 lux) across the whole room and task. Moreover, the Unified Glare Rating exceeded the standard limit (26). Thus, it was necessary to simulate the presence of an additional L-shape shielding system covering the horticulture LEDs of each living wall panel (scenario LWL), with a vertical inclination of 10° ($< 12^\circ$ as the reference value for the fixture inclination), so as to: 1) keep the horizontal illuminance on the work planes within the standard ranges limiting glare; and 2) still ensure sufficient photon flux for plant photosynthesis, which can support phyto-depuration maximisation.. This solution allows for reaching the proper illuminance distribution on the work planes, ranging from 536 to 650 lux, and a Unified Glare Rating of 16. At the same time, values of PPFD on the LW growing surface were also calculated considering the illuminance distribution on the related vertical plane of the module, and thus deriving ranges for PPFD variation. PPFD (measured in $\mu\text{mol m}^{-2} \text{s}^{-1}$) can be directly calculated depending on the photometric illuminance values (measured in lux) on a given surface [44]. Considering horticultural lighting, the calculation considers the 400 nm – 700 nm wavelength range, which corresponds to the Photosynthetically Active Radiation (PAR), and the number of photons (μmol) that arrive at the illuminated surface per second, divided by the surface area. PPFD characterises the “lighting installation and depends on both the parameters of the luminaire and the position of the luminaire relative to the illuminated area” [44], as also remarked by its unit of measure. Moreover, it can be generally assumed that the conversion from lux to PPFD essentially depends on the light sources, and that, to this end, optical filters with transmittance characteristics matching the standard luminosity function curve are generally incorporated in illuminance and lux meters. In this sense, different online calculators are generally available to provide the conversion factor depending on the typology of light source, which should be multiplied by the surface lux value to derive the related PPFD². In this work, it was conservatively and reliably assumed that the conversion factor was equal to 0.0154, which is a standard value for 4200k colour temperature of a Ceramic Metal Halide light source (see Section 3.1). Therefore, PPFD ranging between 50-100 $\mu\text{mol m}^{-2} \text{s}^{-1}$ was obtained considering illuminance values on the LW from about 3250 to about 6500 lux, obtaining consistent values in respect to the ones reported by literature

² E.g. see <https://www.apogeeinstruments.com/conversion-ppfd-to-lux/>, <https://calculatorshub.net/science/lux-to-ppfd-calculator/>, <https://hortibook.com/tool/Lux-to-PPFD-Calculator.html> (last access: 28/07/2025)

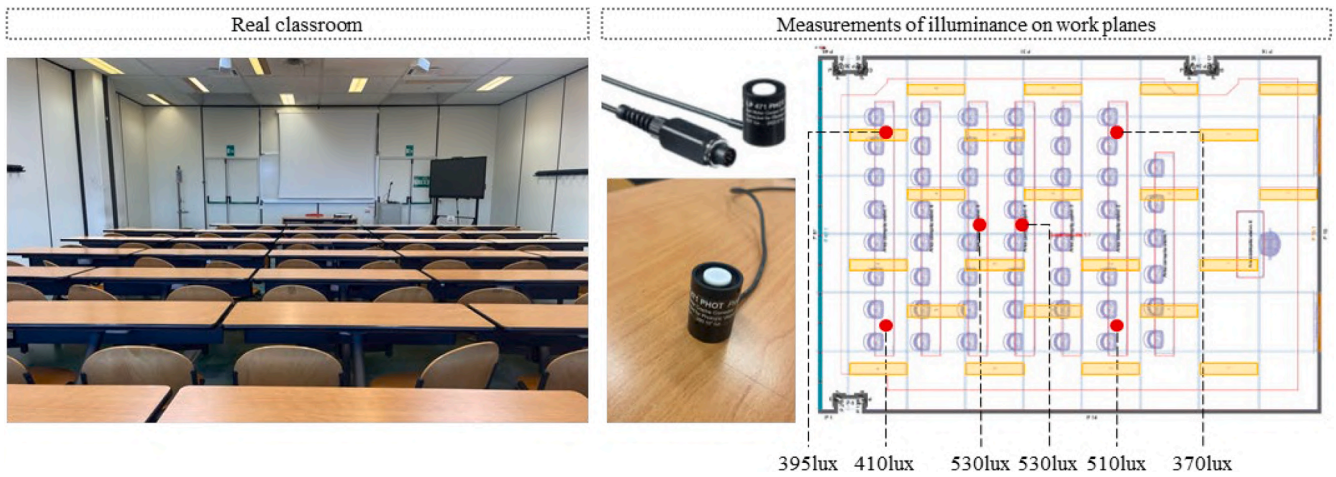


Fig. 3. Configuration of the measurement points (red circles) for the illuminance levels on the work planes in the real classroom (the lights are represented by the shaded yellow boxes).

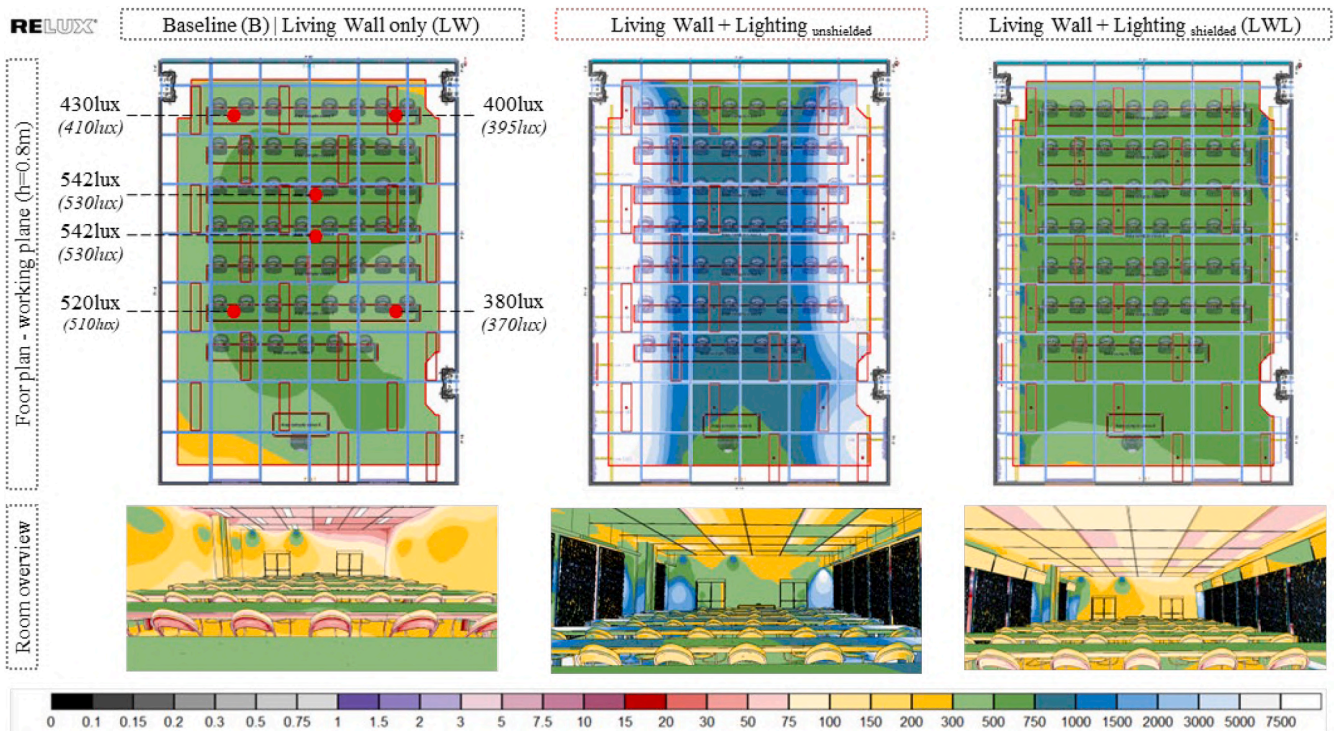


Fig. 4. Results of Relux simulation across the experimental scenarios: B, LW, LWL.



Fig. 5. The three virtual scenarios experienced by participants.

[30] for CO₂ subtraction in real-world settings. Nevertheless, considering standard PPFD ranges [68], it is worth noting that simulations revealed not fully homogeneous conditions on the LW: plants in the highest narrow band of each module (2.20-2.50 m) were exposed to medium-low light levels of 38-42 PPFD; plants set at 1.50-2.20 m received the highest illuminance (102-124 PPFD); the mid-section (0.50-1.50 m) averaged moderate values (46-66 PPFD); a low range of 26-34 PPFD were detected for plants at the bottom (0.5 m).

Finally, scenarios B, LW and LWL, assessed from these simulation results, were then also implemented into three immersive virtual environments experienced by the subjects and virtualised using the Unity engine [84], as shown in Fig. 5. These models were created with the highest level of detail, incorporating real materials and textures into an empty 3D model and properly setting the lighting conditions to be coherent with the real classroom. The first player camera control was in correspondence with the fourth work plane row, so that participants virtually sit in the centre of the classroom in front of a virtual workstation. The position ensured a complete view of both the living walls and the lighting system. Several scripts were coded by using C# in Unity to sequentially and automatically manage experimental sessions, visualise test instructions and task sequences to minimise the interactions with the researcher managing the test [85]. The HTC Corporation VIVE PRO Eye head-mounted display (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) and the SteamVR plugin [86] were adopted to visualise the three models. The HMD was connected to a high-performance computer (Intel(R) Core(TM) i9-9900 K, RAM 64GB) to allow a smooth, immersive virtual experience.

2.3. Assessment methods

2.3.1. Subjective self-reports

The questionnaires used during the test sessions comprised three parts.

First, a general questionnaire was prepared to collect participants' demographics such as age, gender, educational level, eyesight conditions, self-reported sensitivity to luminosity, videogames and VR use.

Building on previous indoor-lighting research studies, an operative-phase questionnaire was organised to investigate six constructs with a seven-point response scale under each virtual scenario exposure (questions reported in Table 1). Participants were asked to first appraise the chromatic quality of the artificial light (Q1) [66,87–89] and the brightness of the room (Q2) [68,87,90–94], and, immediately after, to indicate whether they would prefer a cooler/warmer hue (Q3) [85, 87–89] or a brighter/darker environment (Q4) [90]. Visual comfort was then explored through four statements covering the overall visual comfort (Q5) [95], the luminous field uniformity (Q6) [87,94,96] and the presence of glare (Q7) [36,89] and experienced eye fatigue (Q8) [53, 87,95]. Moreover, three items investigated visual perception about the realism [68] and task suitability [51,87], asking whether the lighting made the virtual classroom appear realistic (Q9) and whether it would be pleasant for working activities (Q10-Q11). Thus, the questionnaire structure allowed to converge on three complementary items: the perception of the lighting system (Q1–Q8) to capture the effects of lighting design on visual comfort; the realism of the virtual scene (Q9) to ensure the reliability and generalizability of results collected in the virtual environments to real contexts; the overall evaluation of the LW design and its integration within the virtual environment (Q10–Q11), allowing comparisons between Baseline, LW, and LWL scenarios in terms of perceived liveability and workability.

Lastly, a post-experimental questionnaire about sense of presence and immersivity and cybersickness disorders developed in previous VR-based research activities [88] was included to assess to verify the ecological validity of the developed virtual environment. In particular, four indicators from the Igroup-Presence Questionnaire (IPQ) were investigated on a seven-point Likert («strongly agree» to «strongly

Table 1
Questionnaire for lighting and visual comfort assessment.

Construct	Question	Response scale
Lighting-colour appraisal	Q1 How would you rate the colour of the artificial light?	Very cool / Cool / Slightly cool / Neutral / Slightly warm / Warm / Very warm
Lighting-brightness appraisal	Q2 How do you perceive the lighting level of the environment?	Very dark / Dark / Slightly dark / Neutral / Slightly bright / Bright / Very bright (glare)
Lighting-colour preference	Q3 At this moment, would you prefer the colour of the artificial light to be...	Much cooler / Cooler / Slightly cooler / No change / Slightly warmer / Warmer / Much warmer
Lighting-brightness preference	Q4 How would you prefer the overall lighting level of the environment to be?	Much darker / Darker / Slightly darker / Neutral / Slightly brighter / Brighter / Much brighter
Visual comfort	Q5 How do you feel in this environment from a visual standpoint?	Comfortable / Slightly uncomfortable / Uncomfortable / Very uncomfortable / Extremely uncomfortable
	Q6 The light is distributed uniformly.	7-point Likert Scale: Strongly Disagree – Strongly Agree
	Q7 The lighting condition causes me eye fatigue.	
	Q8 The lighting condition causes glare.	
	Q9 The lighting makes the office look realistic.	
Visual perception	Q10 The lighting in this environment would be pleasant for working	
	Q11 The overall environment configuration would be pleasant for working	

disagree»): Graphical Satisfaction (GS), Spatial Presence (SP), Involvement (INV), and Experienced Realism (REAL). The Virtual Reality Sickness Questionnaire was adopted to measure six possible disorders (general discomfort, fatigue, eye strain, difficulty in focusing, headache, vertigo) on a five-point scale («not at all» to «a lot»).

2.3.2. Eye-tracking and physiological parameters

In all three experimental scenes, eye-tracking raw data were recorded from the headset-integrated eye tracker and iMotion software (v. 10.1) [97]. These variables are widely adopted to infer cognitive load:

- Blink rate tends to fall in case of higher cognitive demand, because involuntary eyelid closures are reduced to maximise visual intake during attention-intensive activity [98–100].
- Peak pupil diameter enlarges in response to higher mental effort and emotional arousal, making pupillary dilation a robust indicator of cognitive load [98,99,101–103];
- Fixations count denotes how often the gaze focuses on an interest point [102,104]. In particular, it was assumed that more frequent fixations represent greater processing requirements and stronger engagement with the scene [98,99,105];
- Fixation duration represents the time allocated to extract information at each gaze point. Prolonged fixations have been associated with higher cognitive mental processing, as well as with greater visual interest [98,99,105];
- Saccades count is the rapid eye movements between fixation points, which typically rise in case of high information-processing load, reflecting reduced efficiency in selecting relevant cues [99];

During immersion in the virtual scenarios, three physiological channels were continuously recorded with the EmbracePlus wearable device (Fig. 6a) and the Empatica Health Monitoring Platform [99]:

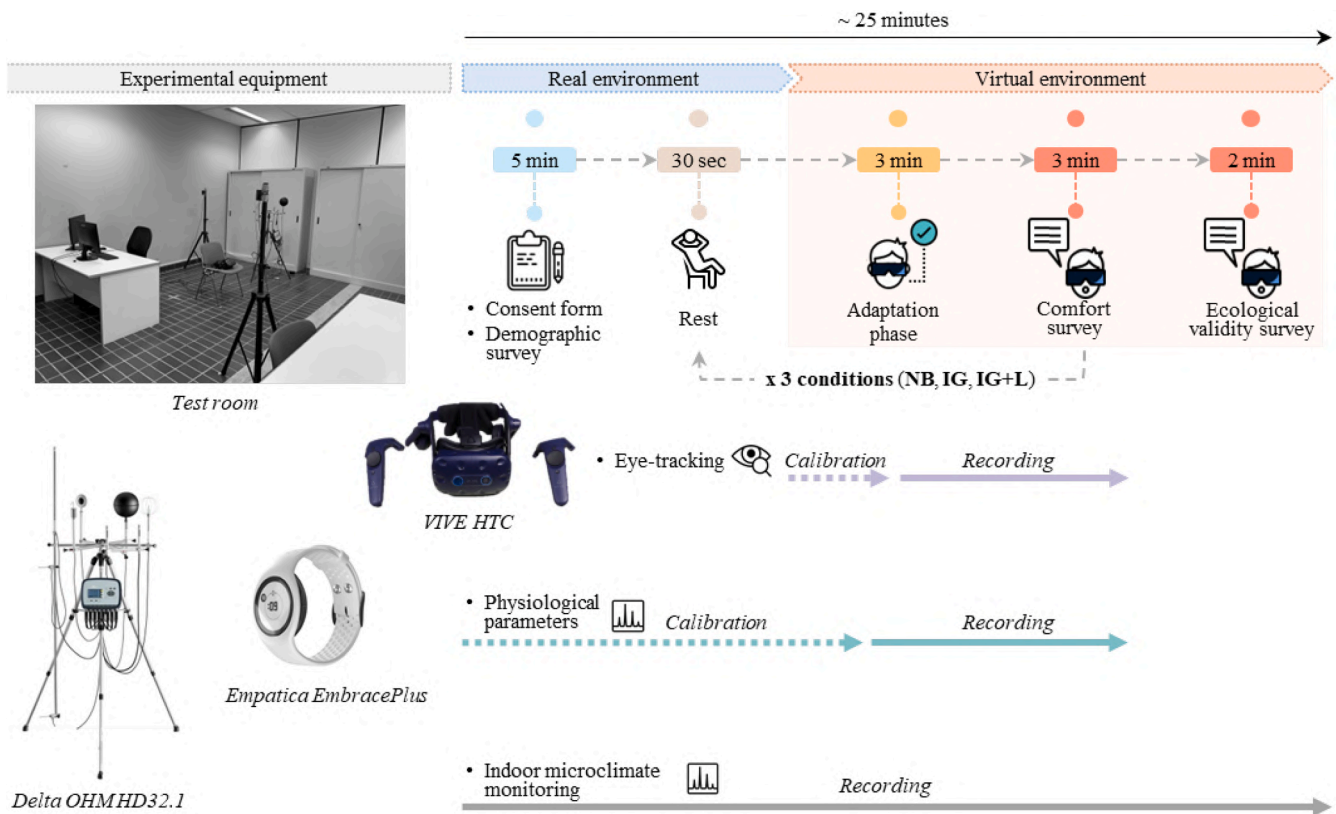


Fig. 6. (a) Experimental equipment; (b) Experimental schedule.

- Electrodermal activity (EDA), sampled over a 0.01–100 μS range, reflects eccrine sweat-gland output under sympathetic control [106]. It is widely used as an index of psychophysiological arousal, with higher amplitudes associated with heightened stress status [107, 108].
- Pulse rate (PR), measured between 24 and 240 bpm with a static-condition accuracy of ± 3 bpm, represents the number of arterial pulsations per minute and varies with autonomic shifts at the sinoatrial node [109]. It is one of the most objective markers of psychological stress, slowing under parasympathetic dominance (i.e., a relaxed status) and accelerating with sympathetic activation [106, 110].
- Skin temperature (ST) is acquired across a 0–50°C span with $\pm 0.1^\circ\text{C}$ precision in the 30–45°C band. Because peripheral vasoconstriction accompanies sympathetic arousal, stress-induced declines in ST can be detected, whereas vasodilation in calm states yields higher ST values [108,111].

2.3.3. Study protocol

Data were collected over 1 week, and tests were carried out in a test room under controlled indoor conditions, which were monitored in real-time through a Delta OHM HD32.1 Thermal Microclimate station (Fig. 6a), located next to the participants' workstation. Throughout the sessions, the indoor environment was kept stable, with an average air temperature of $24.99 \pm 0.05^\circ\text{C}$, a mean relative humidity of $37.86 \pm 0.15\%$, an average air velocity of 0.010 ± 0.005 m/s, and a mean radiant temperature of $24.71 \pm 0.10^\circ\text{C}$.

Each experimental session followed a fixed schedule (Fig. 6b), adapted from [88], and comprised three phases, as follows:

1. *Pre-experimental phase*: after receiving the instruction and consent form, participants completed the demographic questionnaire, remaining in the real test room for 5 min, allowing the stabilisation of the physiological signals. They then wore the head-mounted

display and followed the eye-tracking calibration procedure. A brief 30-second transition introduced the virtual environment. From that moment, the headset remained in place for the rest of the experiment, so the entire test session was conducted within the immersive virtual environment.

2. *Adaptation phase*: participants explored the scene freely for 3 min while physiological data were recorded. This interval was necessary to minimise the psychological novelty effects of the IVE exposure and allow immersivity and visual accommodation to the proposed illuminance scenarios.
3. *Operative phase*: participants completed the visual-comfort questionnaire (paragraph 2.3.1), being involved in this activity for about 3 min.
4. *Post-experimental phase*: a second set of questions was answered to assess the ecological validity of the virtual environment, requiring about 2 min.

The EmbracePlus device was worn upon arrival and while completing the pre-experimental questionnaire. This procedure was necessary to filter out the initial orienting response, so the analysis focused exclusively on the physiological data collected during the operative phase, beginning after the brief adaptation period to each virtual scenario [60,112].

The adaptation and comfort survey phases were repeated for all three virtual scenarios without removing the headset. Thus, the total IVE-exposure comprised three identical 6 min blocks, preceded by 30 seconds of rest with eyes closed between each condition. Each set of questions was presented on a virtual computer monitor, participants answered aloud, and research staff collected the responses. The complete integration of questions inside the virtual model ensures an effective immersive experience and reliable data collection [88].

Since immersive virtual experiences can lead to motion sickness, all participants were informed that they could leave the test session in case of discomfort at any moment. However, none of the 41 participants

withdrew from the experimental session.

The experimental protocol was approved by the Research Ethics Committee of the Università Politecnica delle Marche (No. 0216363, 01/12/2022).

2.3.4. Data analysis

The data analysis was carried out in 2 phases, as reported in Table 2.

In the first phase, the level of presence and immersivity and cybersickness disorders induced by the exposure to virtual environment was analysed with descriptive statistics and compared with previous literature in the field.

In the second phase, the effect of the different combined lighting and greenery conditions (B, LW, LWL) on the subjects' perceptual response, eye-tracking metrics and physiological parameters was calculated, using statistical comparison techniques. Since the questionnaire ratings are ordinal data, the Friedman rank sum test was applied to evaluate the within-group differences as a non-parametric alternative to the repeated-measures ANOVA. The null hypothesis states that there is no effect, no change, or no difference between the indoor layouts: if the computed H-value falls within the critical region (chi-square = ±5.99 for df = 2, α = 0.05) and the p-value is higher than 0.05, the authors conclude participants' response was not influenced by the tested environment.

Conversely, data on a ratio scale, such as eye-tracking and physiological metrics, were first tested for normality with the Shapiro-Wilk test and then analysed with parametric and non-parametric tests according to the normality results of the distribution. Data found to be normally distributed were analysed through a repeated-measures ANOVA, otherwise with the Friedman test. As for the Friedman test, the ANOVA

Table 2
Data analysis workflow.

Phase	Analysis and data used	Statistical treatment	Expected results
Phase 1: <i>Ecological Validity of the Immersive Virtual Environment</i>	Analysis of the level of sense of presence and immersivity, and cybersickness disorders	Descriptive analysis of data distribution Qualitative comparison with previous literature investigating the sense of presence and immersivity indicators in virtual office or school models with indoor greenery Shapiro-Wilk normality test and repeated-measure Friedman or ANOVA test with post hoc test (if necessary), as a function of visual scenarios (B, LW and LWL)	A sufficient level of sense of presence and immersivity Low level of cybersickness disorders
Phase 2: <i>Analysis of perceptual response, eye-tracking and psychological metrics</i>	Phase 2a. Analysis of perceptual response: artificial light colour and brightness appraisal, preference, visual comfort, uniformity, presence of glare and eye fatigue, realism and task suitability Phase 2b. Analysis of psychological response: eye-tracking metrics, heart rate, electrodermal activity, skin temperature parameters	Shapiro-Wilk normality test and repeated-measure Friedman or ANOVA test with post hoc test (if necessary), as a function of visual scenarios (B, LW and LWL)	Limited differences in perceptual metrics based on classroom lighting conditions. Absence of differences in physiological stress responses thanks to the accurate design of the living wall system.

null hypothesis states that there is no difference between the tested conditions: if the computed F-score falls within the critical region (F-ratio = 3.25 for df_{numerator} = 2, df_{denominator} = 38, α = 0.05) and the p-value is higher than 0.05, the authors conclude participants' response was not influenced by the simulated condition. In case statistically significant differences were found between conditions, a post-hoc test [111] was performed to compare all the pairs with Bonferroni's correction to account for planned multiple comparisons [113]. The effect size (i.e., the percentage of variance) is also reported considering Kendall's W value for the Friedman's test [114] which uses the following interpretation guidelines: 0.00 - 0.10 for a negligible effect, 0.11 - 0.30 for a small effect, 0.31 - 0.50 for a moderate effect and ≥ 0.51 for a large effect. The significance level was set equal to .05 (5 %) for all tests, and the analysis and data representation were performed through RStudio software [115].

2.4. Participants recruitment

A total of 41 participants (54 % female, 46 % male, average age 27.98 ± 7.91) were recruited during their normal class or working time at the Engineering Faculty at Università Politecnica delle Marche.

An a priori power analysis was carried out in G*Power v. 3.1.9.7 [116] for a two-tailed Wilcoxon signed-rank test. A first calculation indicated that 35 participants would be sufficient to achieve the conventional minimum statistical power of 0.80, considering a medium within-subjects effect size and a significance level of 0.05. However, to reduce the risk of Type II error and provide a "safety margin" in case of any missing recorded data, 41 volunteers were recruited for this study, increasing the estimated power to 0.86.

The main demographic characteristics of the recruited sample are presented in Table 3. All participants with vision impairments wore corrective lenses during the test sessions.

Concerning self-reported sensitivity to luminosity, participants rated their sensitivity to brightness on a 5-point scale, ranging from «not sensitive at all» to «very sensitive»: 5 % reported no sensitivity, 7 % were slightly sensitive, 30 % were indifferent, 51 % were sensitive, and 7 % considered themselves very sensitive.

Table 3
Characteristics of study participants.

	Sample distribution
Gender	
Female	54 %
Male	46 %
Age	
18-25	42 %
26-30	46 %
31-39	5 %
> 40	7 %
Educational level	
Non-graduated	39 %
Graduated	54 %
PhD, post-graduate school	7 %
Eyesight problems	
None	39 %
Myopia	32 %
Myopia + Astigmatism	15 %
Astigmatism	12 %
Presbyopia	2 %
Previous experience with VR	
Never	24 %
Once	34 %
More than once	42 %
Videogames usage	
Never	49 %
Rarely	34 %
Frequently	15 %
Everyday	2 %

3. Results

3.1. Phase 1: Ecological validity of the immersive virtual environment

The results of the cybersickness questionnaire (Fig. 7) confirmed that the virtual experience produced very little physical discomfort since this study adopted a previously developed experimental protocol [88], which considers the need to limit the VE exposure time below 25/30 min. Indeed, *vertigo* and *headache* were practically absent for the majority of participants, with 97 % of the sample selecting «not at all» and «barely». *General discomfort* and *fatigue* were also limited, with 93 % of participants reporting no discomfort or fatigue beyond the «barely» rating. Visual-related symptoms were elicited more frequently but were still modest. 83 % of participants declared no or little *eyestrain*, and a further 17 % felt it «slightly» to «mildly». The most noticeable symptom was *difficulty in focusing*, which was «slightly» to «mildly» acknowledged by 25 % of participants.

Fig. 8 summarises the Igroup-Presence Questionnaire results with median values. Graphical Satisfaction (GS) was rated very positively: 93 % of participants ticked response categories from «slightly agree» up to «totally agree». Ratings of Spatial Presence (SP) were comparable strong: across the three indicators (SP1, SP2, SP3), at least 95 % agreed to feel present and immersed in the virtual office rather than merely viewing a picture. Scores of Experienced Realism were also favourable, with at least 95 % of participants agreeing that object proportions were correct (REAL1), interaction seemed possible (REAL2), and the overall model appeared realistic (REAL3). A more polarised response pattern was detected for the Involvement construct. Although the majority of participants (76 %) declared to be not aware of the surrounding world while they were immersed in the virtual scenarios, nearly 12 % of the sample reported the opposite.

Based on the latest systematic review on the use of IVEs to assess Biophilic Design strategies [6], the most recent papers that assessed the Ecological Validity in office or school models were selected for comparison with the present study. Only the studies that provided ratings for each indicator were considered, while studies reporting an overall score for each participant were excluded because it was not possible to trace back the results of IPQ indicators. In addition, as previously done by the authors [88], the average values of each indicator were converted to a five-point Likert scale ranging from 1 to 5 to improve comparability. As presented in Table 4, the ratings of the present study demonstrated a

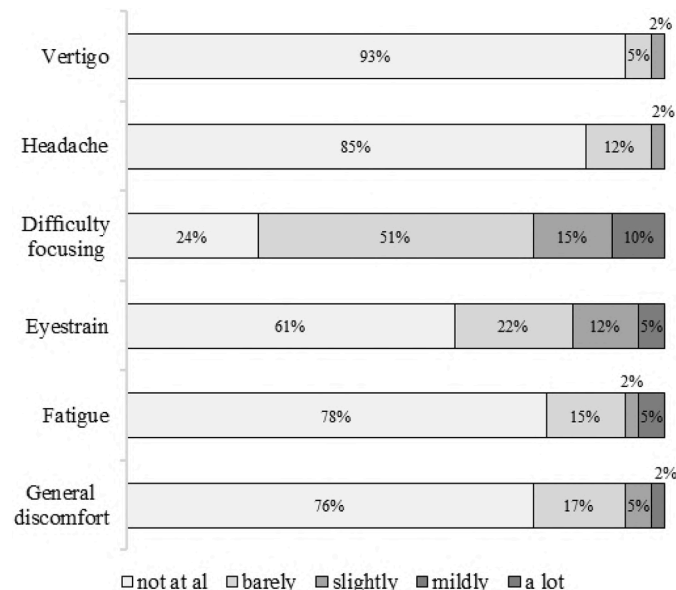


Fig. 7. Cybersickness ratings.

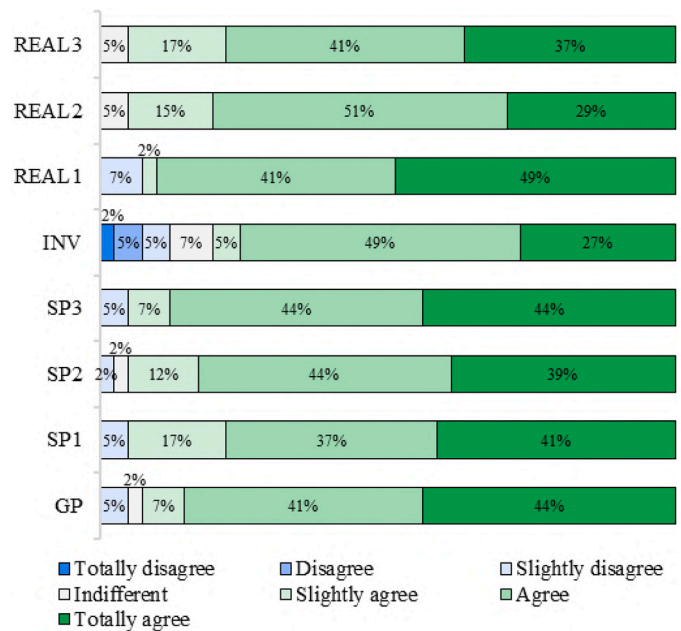


Fig. 8. Analysis of the sense of presence and immersivity indicators.

Table 4

Comparison of IPQ scores (A “*” highlights the indicators higher than the present study).

Reference	Year	GS	SP	INV	REAL
This study	2025	4.41	4.40	4.01	4.38
Latini et al. [47]	2024	4.40	4.29	4.05*	4.45*
Mostajeran et al. [111]	2023	-	4.53*	-	-
Yeom et al. [52]	2022	-	4.04	3.85	3.50
Tawil et al. [112]	2021	3.93	3.44	3.27	2.68
Hong et al. [113]	2019	3.65	3.39	3.23	2.73

very high level of user experience quality and compare favourably to the existing literature, except for a few slightly higher indicators marked with asterisks.

3.2. Phase 2: Analysis of perceptual response, eye-tracking and psychological metrics

3.2.1. Perceptual assessment of different lighting settings

Boxplot distribution (Figs. 9 and Fig. 10) and the results of the one-way Friedman’s test (Table 5) show a certain number of variations among the three groups of responses to each classroom condition.

No statistically significant differences emerged for colour appraisal (Q1) and preference (Q3), confirming that the three scenes were perceived as comparable in chromatic tone to a neutral lighting condition for at least half of the participants (B 63 %, LW 78 %, LWL 56 %). This results in a general satisfaction with the hue provided, with 51-68 % of people claiming no changes and a small part (27-32 %) expressing the desire for a warmer light.

As expected, the perceptual constructs associated with brightness showed a reliable effect depending on the simulated scenario, with statistically significant differences in both Friedman results and post-hoc comparisons. Indeed, the living-wall scene with targeted horticultural LEDs (LWL) was rated 30 % significantly brighter (Q2, $\chi^2(2)=17.54$, $p<0.05$) than both the baseline classroom (B, $p<0.05$) and the classroom with only living-wall (LW, $p<0.05$). LW and B scenarios were mainly rated as neutral and slightly bright by 50-61 % of participants, respectively and did not differ significantly since they shared the same illuminance conditions ($p=0.869$). As a result, the brightness preferences (Q4, $\chi^2(2)=16.26$, $p<0.05$) were significantly different. In fact, 29 %

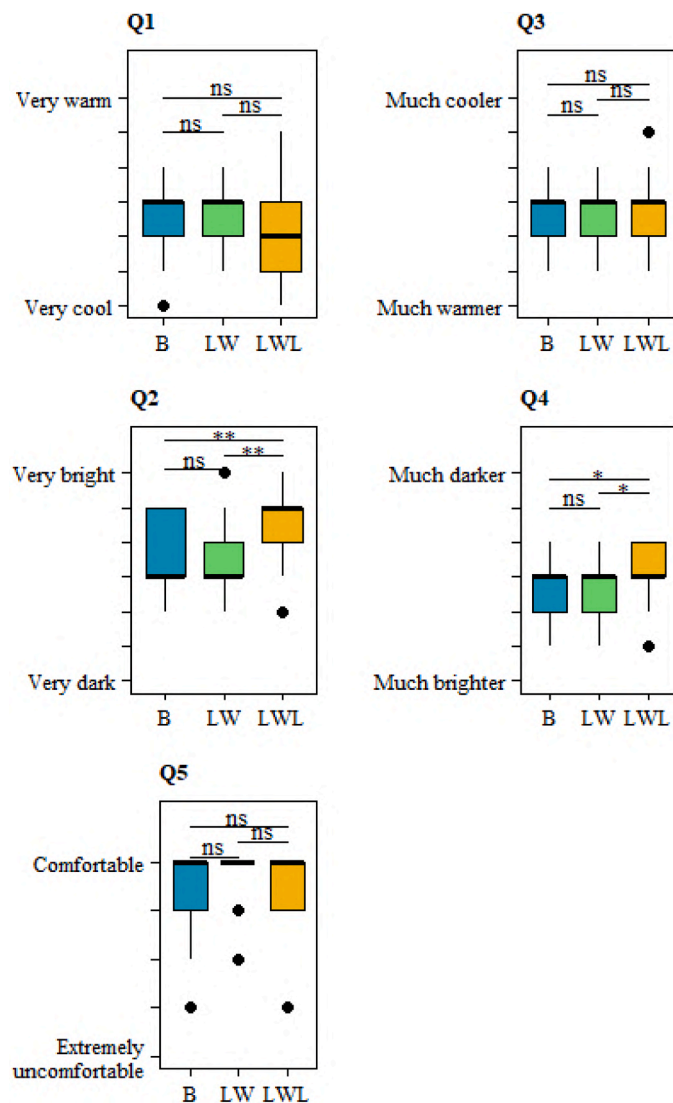


Fig. 9. Boxplot of responses to questionnaire for lighting and visual comfort assessment: Part 1. Inside the boxplots, the line is the median value. ns.: non significant, * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

participants wished the LWL scenarios to be slightly darker compared with LW ($p < 0.05$) and B ($p < 0.05$), whereas 34 % of the sample would have them want at least slightly brighter.

Despite that, the visual comfort ratings showed statistically significant differences between the simulated scenarios (Q5, $\chi^2(2) = 8.25$, $p < 0.05$), yet the associated effect size was negligible (0.10), and, thus, the pairwise comparison was not computed. However, across all scenarios, the majority of ratings fell in the positive part of the scale with median values located around the «comfortable» score: LW condition was rated as the most comfortable by 85 % of participants, which is 15 % higher than B (71 %) and 24 % higher than the LWL (61 %).

Considering light distribution uniformity (Q6) and eye fatigue associated with lighting condition (Q7), the response pattern is comparable across the indoor conditions, and no statistical differences emerged (p -value < 0.05). Indeed, the majority of participants perceived the lighting as equally uniform («agree» and «totally agree», 66 % in B and GW, and 59 % in LWL), confirming also the results of the illuminance measurements and simulations (see paragraph 2.2). Generally, percentages of participants who reported no eye fatigue ranged between 66 % and 80 %, whereas the LWL condition elicited 7 % more fatigue complaints than the B and LW scenarios.

Ratings of glare perception (Q8) significantly differed across the

simulated conditions ($\chi^2(2)=18.46$, $p < 0.05$): LWL induced 25 % more glare than the neutral baseline (LWL $>$ B, $p_{adj} < 0.05$), while 85 % of participants did not perceive glare in the other two conditions which score were comparable.

The different lighting conditions also significantly influenced the realism (Q9, $\chi^2(2)=21.66$, $p < 0.05$). Between 90-93 % of participants equally perceived the LW and B scenarios as being 30 % more realistic than the horticulturally LED scenario ($p_{adj} < 0.05$).

The Friedman analysis confirmed that all three lighting configurations were perceived as equally suitable for working activities (Q10), with non-significant differences. In particular, the living wall condition gained the highest appraisal by 85 % of participants, followed by the baseline classroom (B, 78 %) and living wall condition with horticultural LEDs (LWL, 68 %), which also received an explicit disagreement from 24 % of participants.

Lastly, the three environmental configurations were rated as equally pleasant for working with no statistical differences (Q11, $p > 0.05$). However, numerically considering the share of «slightly agree, agree, totally agree», the scene with the living wall alone again showed the highest acceptance (LW, 85 %), 12 % higher than the LWL scenario and 14 % than the B scenario. Explicit disagreement was higher for B compared to LWL, 24 % and 17 % respectively, maybe due to the absence of indoor greenery.

3.2.2. Physiological responses to different lighting settings

Fig. 11 summarises the physiological metrics recorded across the three simulated environments. Mean values of Electro-Dermal Activity (EDA), Pulse Rate (PR), and Skin Temperature (ST) were computed over the central 3 min of each stimulus presentation to ensure stable physiological responses. Subsequent analyses compared these averaged indices across the experimental scenarios. Statistical analyses (Table 6) indicate no significant physiological differences among B, LW and LWL for the parameters investigated. Specifically, EDA exhibited a non-normal distribution across all scenarios ($p < 0.001$, Shapiro-Wilk tests), with the Friedman test confirming no statistically significant differences ($\chi^2(2)=3.23$, $p=0.199$). Mean EDA values ranged from 0.351 μ S (B) to 0.449 μ S (LWL), indicating similarly low physiological stress levels in all scenarios. Similarly, PR and ST were normally distributed ($p > 0.05$ for all scenarios), and ANOVA tests revealed no significant scenario-related variations (PR: $F=0.09$, $p=0.914$; ST: $F=0.49$, $p=0.612$). Pulse rate remained stable across conditions with an identical mean value (83 bpm), and minimal variation from 11.88 to 14.57 bpm. Skin temperature also demonstrated consistency, with an average of 31°C in all scenarios and very low variance, between 1.20 and 1.36°C.

Differences in eye-tracking metrics between NB, LW, and LWL were analysed during the reading task execution, which was computed as the time taken by the subject to complete the visual comfort questionnaire during the operative phase (see Section 2.3.3, Fig. 12). Blink rate and pupil diameter data showed a non-normal distribution ($p < 0.01$), and the Friedman tests revealed no significant differences between scenarios ($p > 0.05$). The same result occurred considering fixation and saccade metrics, which were normally distributed ($p > 0.05$) and produced non-significant ANOVA results ($p > 0.05$). It was of interest to visualize eye-tracking records by using eye movement heatmaps which adopt a colour gradient from light green to red to represent the degree of accumulation of fixation and duration, [74]. Green colours consider the bottom quartile in visual attention, while warmer colours indicating a higher visual attention, moving towards the upper quartile in red areas. Heatmaps presented in Fig. 13 confirm the quantitative and statistical results showing a uniform gaze movement for all participants during task performance, independently from the simulated scenarios. These overall results confirm that no psychophysiological stress was induced by any of the lighting conditions tested.

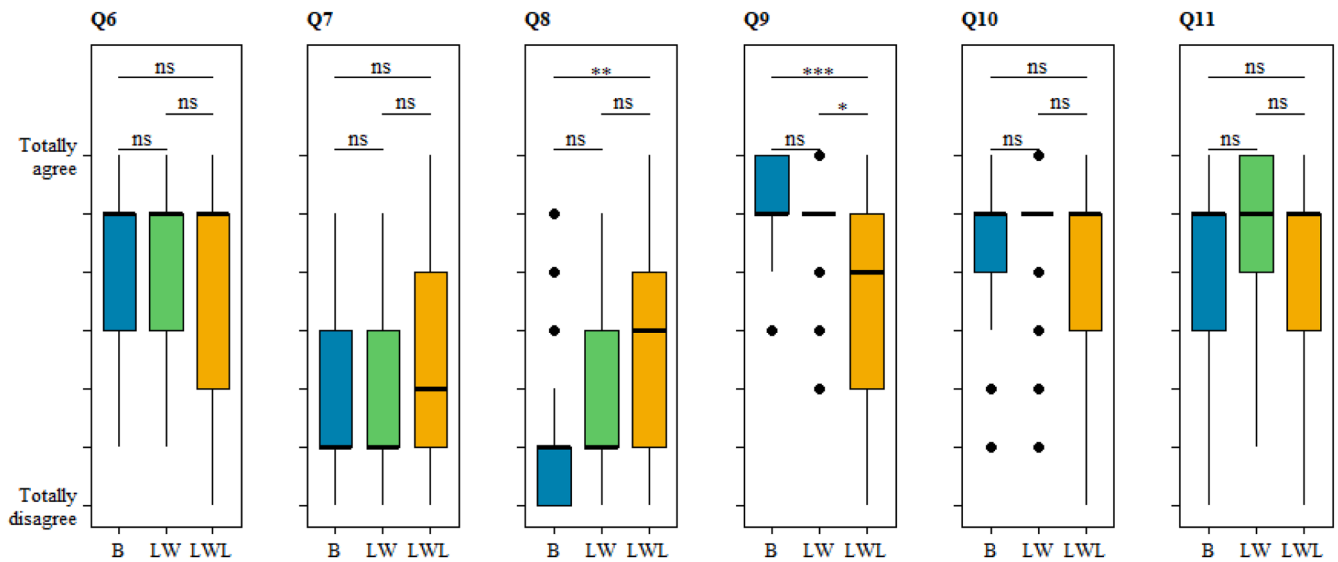


Fig. 10. Boxplot of responses to questionnaire for lighting and visual comfort assessment: Part 2. Inside the boxplots, the line is the median value. ns.: non significant, * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

Table 5

The table presents the Friedman test statistic, the p-values, the generalised eta-squared values (η^2) and the post-hoc comparison results.

Construct	Question	Scenario	Friedman test (Chi-squared)	p-value	Kendall's W value;	Pairwise comparison	Pairwise comparison results p-value _{adj}		
Lighting-colour appraisal	Q1	B	3.84	0.146					
		LW							
		LWL							
Lighting-brightness appraisal	Q2	B	17.54	0.0002	0.214	LW - LWL	0.009		
		LW						LW - B	0.869
		LWL						LWL - B	0.009
Lighting-colour preference	Q3	B	1.25	0.534					
		LW							
		LWL							
Lighting-brightness preference	Q4	B	16.26	0.0003	0.198	LW - LWL	0.019		
		LW						LW - B	0.700
		LWL						LWL - B	0.046
Visual comfort	Q5	B	8.25	0.016	0.10				
		LW							
		LWL							
	Q6	B	2.52	0.283					
		LW							
		LWL							
	Q7	B	3.49	0.175					
		LW							
		LWL							
	Q8	B	18.46	0.00009	0.225	LW - LWL	0.062		
		LW						LW - B	0.349
		LWL						LWL - B	0.004
Visual perception	Q9	B	21.66	0.00002	0.264	LW - LWL	0.034		
		LW						LW - B	0.205
		LWL						LWL - B	0.001
	Q10	B	3.64	0.162					
		LW							
		LWL							
	Q11	B	5.69	0.058					
		LW							
		LWL							

4. Discussion

4.1. Key findings and advances in literature

In phase 1, the high level of presence and graphical quality, realism and spatial immersion were detected, and the very limited occurrence of cybersickness symptoms demonstrated the Ecological Validity of the virtual scenarios. The excellent visual and ergonomic tolerability

underline that highly realistic classroom scenarios were simulated, allowing researchers to explore alternative configurations while collecting reliable perceptual and physiological data long during the pre-design phase. This result encourages the application of VR assessment for LWs, confirming outcomes of previous works, as well as the proper protocol design [16,21,59].

In phase 2, the present study investigated perceptual and physiological implications for Living-Wall design, mainly focusing on whether

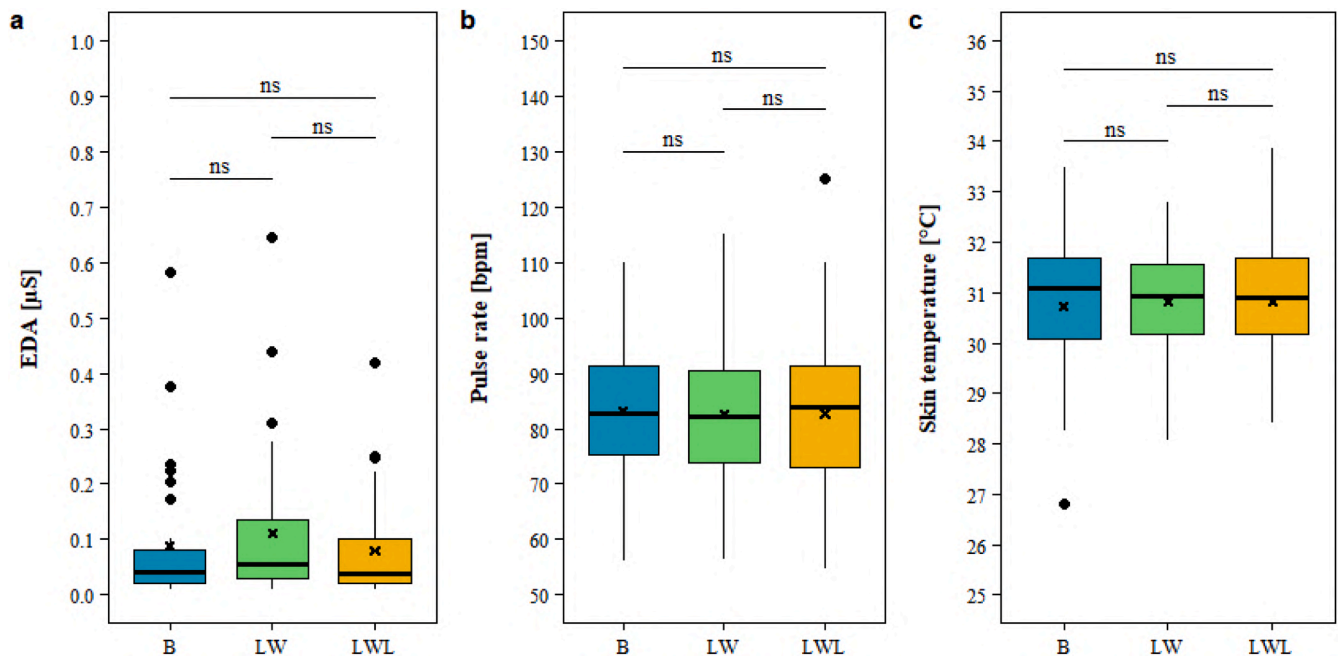


Fig. 11. Boxplots of physiological metrics recorded across the three simulated scenarios (B, LW, LWL). Inside the boxplots, the line is the median value, while the cross indicates the mean. ns.: non significant differences.

Table 6

The table presents the Friedman or ANOVA test statistic and the p-values based on the result of the Shapiro-Wilk analysis on physiological and eye-tracking parameters.

Parameter	Scenario	Shapiro test (W statistics, p-value)	Type of distribution	Friedman test (Chi-squared, p-value)	ANOVA test (F-ratio, p-value)
Electro-dermal activity (EDA)	B	0.43, $p = 8.45e-11$	Not Normal	3.23, $p = 0.199$	
	LW	0.37, $p = 2.25e-11$			
	LWL	0.41, $p = 5.47e-11$			
Pulse rate (PR)	B	0.99, $p = 0.94$	Normal		0.09, $p = 0.914$
	LW	0.98, $p = 0.86$			
	LWL	0.97, $p = 0.47$			
Skin temperature (ST)	B	0.95, $p = 0.07$	Normal		0.49, $p = 0.612$
	LW	0.96, $p = 0.18$			
	LWL	0.98, $p = 0.88$			
Blink rate	B	0.88, $p = 0.56e-04$	Not Normal	0.50, $p = 0.78$	
	LW	0.78, $p = 0.94e-06$			
	LWL	0.81, $p = 2.6e-05$			
Peak pupil diameter (left)	B	0.88, $p = 0.001$	Not Normal	1.17, $p = 0.56$	
	LW	0.85, $p = 0.0002$			
	LWL	0.91, $p = 0.008$			
Peak pupil diameter (right)	B	0.91, $p = 0.008$	Not Normal	0.72, $p = 0.70$	
	LW	0.84, $p = 0.0001$			
	LWL	0.92, $p = 0.01$			
Fixation count	B	0.97, $p = 0.48$	Normal		0.23, $p = 0.80$
	LW	0.99, $p = 0.91$			
	LWL	0.98, $p = 0.79$			
Fixation duration	B	0.98, $p = 0.82$	Normal		0.01, $p = 0.99$
	LW	0.98, $p = 0.88$			
	LWL	0.96, $p = 0.21$			
Saccades count	B	0.95, $p = 0.094$	Normal		0.02, $p = 0.98$
	LW	0.94, $p = 0.06$			
	LWL	0.97, $p = 0.59$			

proper dedicated lighting configurations alter users' visual experience. On the perceptual side, the implementation of a living wall (LW scenario) in the classroom, without a dedicated lighting system, was considered the most comfortable (85 % of participants) and realistic scenario (90 %), with no disadvantages in glare or eye fatigue. In fact, the lighting fixtures are the same of the baseline scenario (B scenario), which could also be considered typical of many working spaces, since it is constituted of fluorescent lights, placed recessed in the modular room ceiling. As expected, when a dedicated horticultural LED system (LWL scenario) is added to meet general greenery requirements, perceptions

shift. In particular, the room was perceived as 30 % more brighter, with slightly lower realism (60 %) and 25 % more glare than either the baseline or the LW scenario, and nearly a third of users would have preferred a lower illuminance (29 %). Anyway, the overall sense of uniformity was not compromised, and additional eye fatigue was not detected in comparison with other scenes. Additionally, lighting colour appraisal remained stable across scenes, lighting conditions were generally comfortable, and all configurations were considered suitable for working activities. These kinds of results, hence, seem to confirm the outputs of lighting simulations carried out according to the EN 12464-1

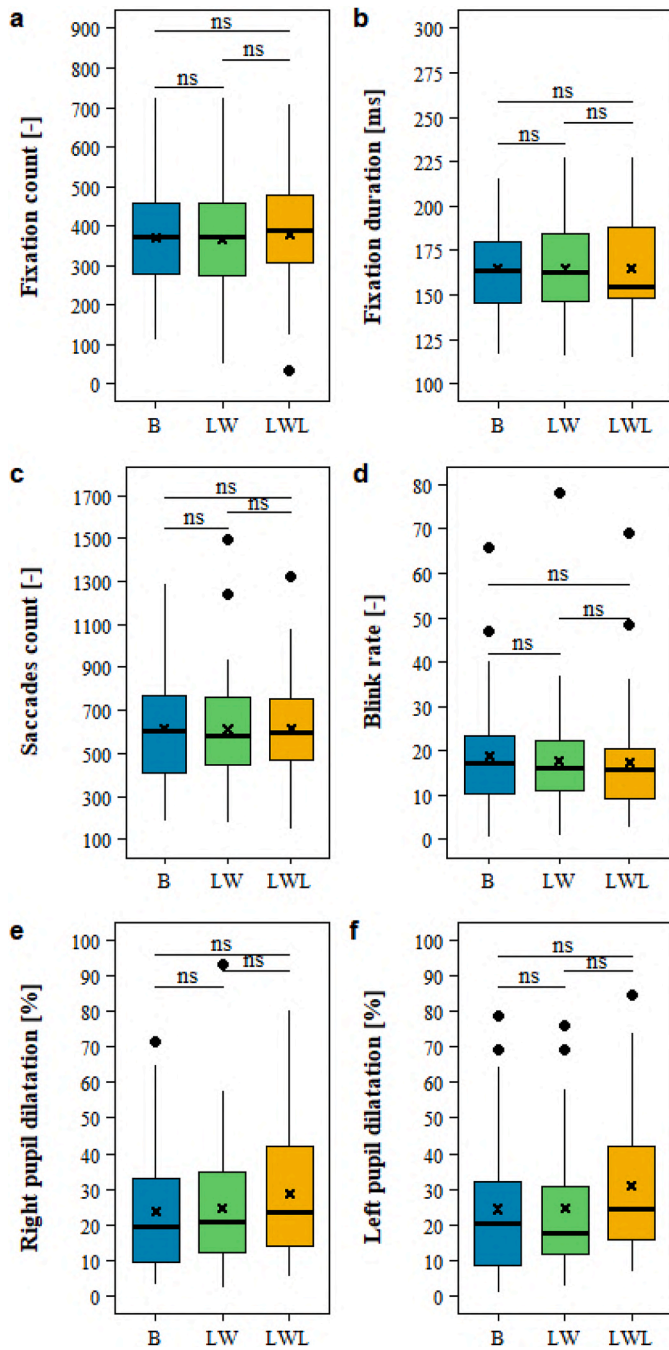


Fig. 12. Boxplots of eye-tracking metrics recorded across the three simulated scenarios (B, LW, LWL). Inside the boxplots, the line is the median value, while the cross indicates the mean. ns.: non significant.

rules by ReluxDesktop software (see Section 2.2).

Physiological and eye-tracking responses were consistent across the three scenarios, indicating that none of them induced significant physiological stress or measurable variations in visual attention, respectively. As for the outcomes of perpetual issues analysis, this result mainly highlights that the modular panel integrated with dedicated lighting system (which was virtually modelled in the LWL scenario) was effectively designed to prevent potential physiological symptoms, such as fatigue, eye strain and headache [48,49] and stress, which could arise from excessively illuminance levels [3,50] if not adequately shielded.

This work expands earlier research on VR-based pre-design evaluation by addressing two literature fields that have so far investigated separately: studies focusing on biophilic design [16,59–64] which not

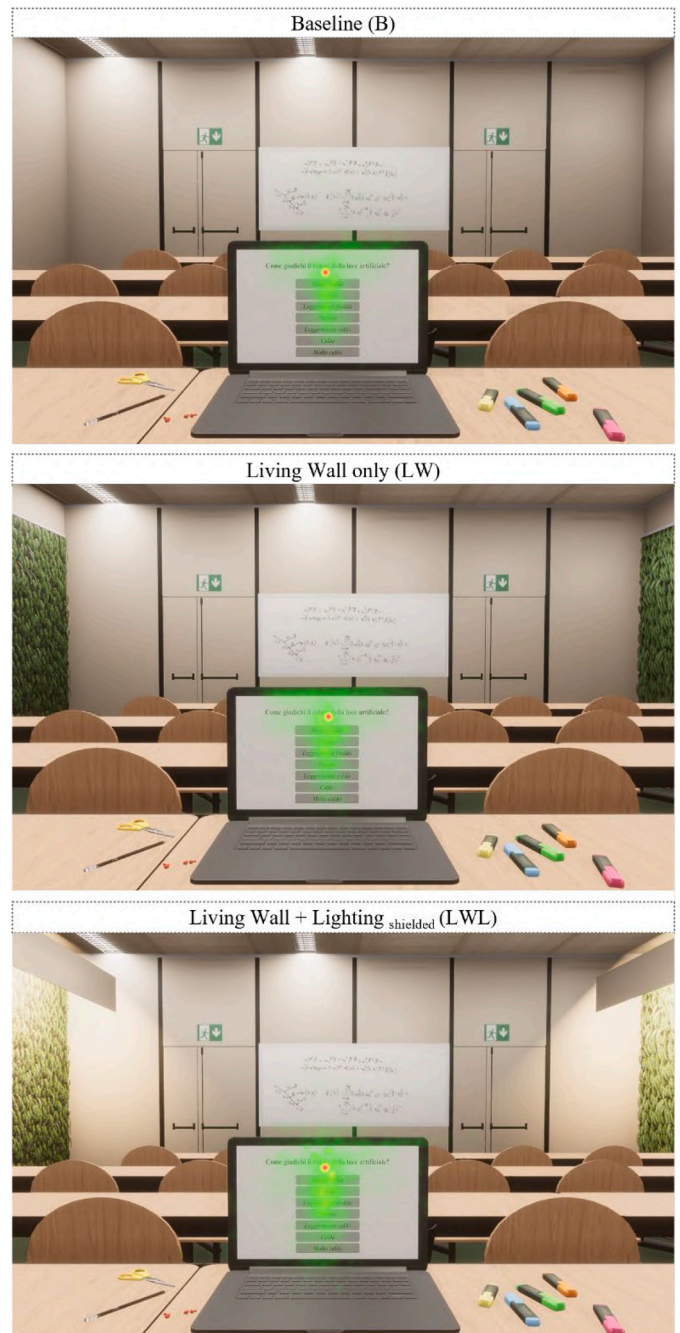


Fig. 13. Heatmaps for B, LW, LWL scenarios during the experimental tests. The coloured areas indicate how many respondents looked at something, and how long each of the individual respondents looked at it (green as bottom quartile and red as upper quartile in attention indicators; not coloured areas represent those areas in which attention indicators are beyond the upper quartile, essentially being too scattered and not relevant in statistical distribution terms).

considered the effects of the technical requirements necessary for the long-term plant liveability; studies centred on indoor lighting conditions [60,67]. Unlike these independent approaches, the present study introduces an innovative use of immersive virtual prototyping, providing robust support for the design of Indoor Living Walls and proper integration of lighting that ensure both plant health and occupant well-being. Such a step forward, however, requires a structured framework that has so far been absent in the literature. To this end, this work advances the literature by developing an integrated, user-centred approach to comprehensively combine immersive virtual prototyping,

lighting and greenery design, with human-centred evaluations. Results demonstrated the effectiveness of this combined approach in collecting reliable data on building occupants' perceptual and physiological responses depending on indoor environmental conditions before real word application.

4.2. Implications for stakeholders

These outcomes highlight a trade-off linked to living wall design in indoor environments to support designers and practitioners: illuminance levels optimised for plant liveability can disrupt human comfort unless secondary measures such as shielding systems are introduced. In fact, the LWL scenario demonstrated that greenery cannot be integrated with standard lighting systems, since they lack in supplying an adequate illuminance level (and thus PPFD) to the growing surface of the LWs. Dedicated solutions can increase these conditions, thanks to the implementation of horticultural lighting systems at the level of each LW panel. Nevertheless, adequate shading should be supplied to the lighting system, especially in case the illuminance value should be additionally increased, moving towards values of $200 \mu\text{mol m}^{-2} \text{s}^{-1}$, since they could additionally guarantee further CO₂ absorption performance by the LW plants [30]. The critical interference among these LWs lighting systems and the surrounding working areas (and reference planes for illuminance measurements) increases with the reduction of distances among them, thus affecting the balance between these requirements in enclosed environments, such as small classrooms.

Overall, this study shows that coupling simulation and virtual modelling could surely support the balance design between the vitality and longevity of greenery, the aesthetic appeal and environmental benefits over time, while ensuring occupant comfort and a physiologically neutral environment.

In particular, findings underline VR effectiveness and potential as a low-risk, high-fidelity prototyping tool for LW design in indoor environmental settings, considering the possible layout of modular systems in real-world settings before their effective implementation in the considered living spaces. Nevertheless, this work also points out how this design process can be possible if virtual environments are effectively coupled with a rigorous, rational design process followed by a comprehensive experimental methodology to generate case-specific, tailored scenarios.

These technical considerations provide useful guidelines for promoting the diffusion of indoor LW through practical design recommendations. Indeed, interior designers and architects can use these findings to inform proper lighting design that meets greenery requirements while accounting for the highest occupants' comfort level and perception. As a necessary steps, an appropriate maintenance protocol should also be implemented, including irrigation schedules and regular calibration of the lighting system, to ensure plant vitality and longevity. This is essential not only for the aesthetic value of the greenery itself but also to maintain effective CO₂ absorption and pollutant reduction, maximizing the environmental benefits of the Living Wall system. Lastly, for policymakers, although Living Wall systems represent a considerable investment, tailored incentive measures could reduce financial barriers facilitating their integration in indoor environments, ensuring that the environmental, and well-being benefits are realized in practice.

4.3. Limitations and future research directions

Although this work promises, the authors are aware of relevant limitations and thus of the need for future work perspectives.

Firstly, this case study was a university classroom, and, thus, the participants' sample consisted mainly of young university students who may be more familiar with screen-based media and less sensitive to VR tools. Recruiting participants with a wider age range and simulating other workplace case studies, thanks to VR flexibility, would allow for

generalising the perceptual and physiological findings beyond the university classroom.

Second, stimulus exposure lasted only a few minutes per scene, which allows for capturing the immediate users' reactions: more prolonged sessions could be scheduled to reveal any delayed fatigue or attentional changes.

Third, daylight was deliberately excluded from this case study. The aim was to isolate the electric lighting system, because the LW modular prototype had to guarantee sufficient illuminance for the living wall also during the winter season, when lower daylighting reaches classrooms while lessons are in progress. Even so, future studies should consider daylight variability and the integration of automatic dimming algorithms.

Fourth, future research should further delve into the impact of supplementary elements useful for Living Wall design, such as plant species, layout variations, greenery quantities, and additional lighting indicators, including different correlated colour temperatures. This will contribute to an even more comprehensive understanding of the integrated effects of LW and lighting design, providing guidance for optimizing a fully integrated and comprehensive users-centred design approach.

In addition, the definition of the LW prototype and its lighting design can be completed by predictive CO₂-absorption models to quantify removal efficiency and optimise the system real-world phytoremediation potential, depending on the activities carried out in the living environment. In this perspective, existing models could be combined with the virtual and simulation-based ones provided by this work [24,46], also using agent-based models as reference tools because of their capability to represent the combination of different interactions among the simulated components (e.g. greenery; environmental conditions; building plants, including HVAC; occupants, their activity schedules, and their actions on building components, including windows and lighting systems [26]). Different models related to lighting system assessment could be used in this context, too, but using the same rationale as this work. This workflow can be hence incorporated in participatory design processes exploiting VR (and, in more general terms, extended reality) [20].

Finally, the authors also acknowledge that dedicated horticultural lighting systems, needed to guarantee the vitality and longevity of greenery, represent additional indoor heat gains and require very high power. Thus, future studies should also consider the electrical load with HVAC and energy requirements to support a living wall without compromising indoor thermal comfort. In addition, cognitive-performance tasks could be introduced to test whether different brightness or glare scenarios influence working performance.

5. Conclusion

The present research activity in a university classroom demonstrates that the prototyping of living walls, increasingly introduced indoors, could be supported by the assessment of users' perceptual and physiological issues using virtual modelling and dedicated simulation tools. This kind of approach could guarantee greenery health, while maximising phyto-remediation potential, but also preserve occupant visual comfort. Indeed, the results of phase 1 confirmed the ecological validity of the virtual scenarios, with high presence, realism, spatial immersion, and minimal cybersickness, demonstrating that highly realistic classroom environments can reliably support long-term collection of perceptual and physiological data during the pre-design phase. Perceptual results (phase 2) showed that the LW scenario without dedicated lighting was perceived as the most comfortable and realistic, with no glare or eye fatigue. Adding horticultural LEDs (LWL scenario) increased perceived brightness and glare and slightly reduced realism, although overall uniformity, comfort, and suitability for work remained high. Physiological and eye-tracking measures were consistent across scenarios, indicating that none induced stress or changes in visual

attention. These findings confirm that the modular panel with integrated horticultural lighting was effectively designed to avoid potential fatigue, eye strain, or stress.

The distinctive contribution of this study lies in its multi-step, user-centred methodology that integrates living wall requirements with users' perceptual and physiological responses using Immersive Virtual Environments, mainly focusing on lighting issues as remarkable ones in working and studying environments, and as measurable elements through the coupling of simulation and IVR-based solutions. By first calibrating a real classroom through on-site photometric measurements and then reproducing it along with two Living-Wall alternative scenarios, in a high-fidelity Immersive Virtual Environment, it was possible to effectively compare users' perceptual and physiological responses under rigorously controlled but realistically complex conditions. The combination of field measurements, lighting simulation, virtual prototyping and immersive experiences goes beyond typical lighting or biophilic design studies: it delivers a repeatable workflow for testing Living Walls indoors before any physical and costly installation is undertaken. Consequently, the present research activity demonstrates how immersive, data-driven environments can answer real built-environment questions with a high level of ecological validity and user involvement that conventional design tools can achieve more difficult and more expensive.

CRediT authorship contribution statement

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

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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