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Investigating the impact of greenery elements in office environments on cognitive performance, visual attention and distraction: An eye-tracking pilot-study in virtual reality

Arianna Latini, Ludovica Marcelli, Elisa Di Giuseppe [*], Marco D'Orazio

Department of Construction, Civil Engineering and Architecture (DICEA), Università Politecnica Delle Marche, Ancona, Italy

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ABSTRACT

The human-nature connection is one of the main aspects determining supportive and comfortable office environments. In this context, the application of eye-tracking-equipped Virtual Reality (VR) devices to support an evaluation on the effect of greenery elements indoors on individuals' efficiency and engagement is limited. A new approach to investigate visual attention, distraction, cognitive load and performance in this field is carried out via a pilot-study comparing three virtual office layouts (Indoor Green, Outdoor Green and Non-Biophilic). 63 participants completed cognitive tasks and surveys while measuring gaze behaviour. Sense of presence, immersivity and cybersickness results supported the ecological validity of VR. Visual attention was positively influenced by the proximity of users to the greenery element, while visual distraction from tasks was negatively influenced by the dimension of the greenery. In the presence of greenery elements, lower cognitive loads and more efficient information searching, resulting in improved performance, were also highlighted.

1. Introduction

According to the World Health Organization, 19% of the factors influencing individuals' health, well-being and productivity are directly related to the characteristics of the built environment (European Agency for Safety and Health at Work, 2023). In recent years, work efficiency has been recognised as a crucial factor in employee performance, having a significant impact on business operating costs (World Green Building Council, 2016). This is particularly significant since humans spend more than half of their day-time in office environments every week (Gao et al., 2017). As a result, due to the importance of indoor environment design on work efficiency, it is expected that actions to improve the quality of working environments will be rewarded by a positive impact on users' concentration, comfort and work efficiency underpinned by individuals' cognitive performance (ASHRAE Standard, 2019; Miyake et al., 2000; Diamond, 2013).

The World Green Building Council framework (WorldGBC and Health, 2020) for healthy and green offices identified biophilia and views of nature from workspaces as one of the eight elements contributing to a healthy office, corresponding to several physical attributes (e.g., indoor air quality and ventilation, thermal comfort, daylighting and lighting, noise and acoustics, interior layout, look and feel, location). Researchers and designers have been widely interested in the potential of incorporating the strategy of Biophilic Design (BD) in office environments. Numerous studies have demonstrated the benefits of biophilic elements in promoting positive mood and emotions, cognitive functioning, stress reduction and learning (Browning and Cooper, 2015; Ulrich et al., 1991). Recently, Green Building Rating Standards have increasingly supported Biophilic Design intervention, moving beyond an energy efficiency focus. One of the categories (i.e., landscape, ventilation, interactive facility, mitigation measure, vehicle usage, sensorial design) to interpret biophilic strategy relies on sensorial design, focusing on visual and non-visual connections with nature to foster human-nature connection (Jiang et al., 2020). This encompasses, for example, the optimisation of window views of the natural landscape, the provision of indoor potted plants or indoor green walls, the access to daylight and natural sound design (Browning et al., 2014). There is a need for continuous policy support to improve the sensorial design. Therefore, a comprehensive understanding of biophilic benefits via extensive research strategies is required to facilitate the incorporation of biophilic criteria into building standards.

Given that vision is the primary sense through which building

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[*] Corresponding author. Department of Construction, Civil Engineering and Architecture, Università Politecnica delle Marche, Via Brecce Bianche, Ancona, 60131, Italy.

E-mail address: e.digiuseppe@staff.univpm.it (E. Di Giuseppe).

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occupants perceive and interpret their surrounding environments (Ko et al., 2020), researchers focused their attention towards the visual connection with nature, such as the presence of nature elements in space and the view of nature from windows). While existing literature has extensively examined the restorative effects of greenery interventions (e.g., Ref (Chang and Chen, 2005; Largo-Wight et al., 2011; Alvarsson et al., 2010; Ratcliffe et al., 2013; Ratcliffe et al., 2016; Marselle et al., 2016)), fewer studies have focused on the effect of visual connection with nature on users' cognitive performance (Raanaas et al., 2011).

Some of them have indicated that introducing indoor plants into workplaces can lead to improvements in self-reported productivity and attention levels (Lohr et al., 1996; Khan et al., 2005), while others have demonstrated a higher accuracy in task execution after the introduction of plants in office settings (Raanaas et al., 2011; Nieuwenhuis et al., 2014; Shibata and Suzuki, 2002, 2004; Hähn et al., 2021). However, despite the promising findings regarding the promising impact of nature on cognitive performance, partially contrasting results were detected by Larsen (LarsenL et al., 1999) and Ayuso (Ayuso Sanchez et al., 2018) reporting a negative effect or no improvements, respectively, on the performance in the presence of plants in offices. The inconsistency in results across studies focusing on the visual domain may be attributed to the adoption of different experimental methodologies, such as different types of tasks performed, exposure time, and sample size.

One of the most critical research gaps identified in evaluating the effect of green elements is that studies focusing on the visual connection with nature were carried out in real settings, (e.g., test rooms or laboratories) integrated with real green elements indoors. This approach usually results in time-consuming and costly research activities.

In recent years, there has been a growing interest in the adoption of Virtual Reality (VR) to support evidence-based building designs (Kalantari and Neo, 2020). VR enables researchers to overcome the practical research constraints that limit the understanding of how specific design factors influence individuals. This technology offers significant advantages as a low-cost and flexible solution to simulate and manipulate visual dimensions, creating alternative environments and rapidly repeating tests while providing users with a real-scale spatial experience and researchers with real-time feedback collection (Latini et al., 2021, 2023a, 2023b). The visual simulation provided by Immersive Virtual Environments (IVEs) provides a higher immersion and presence compared to other modalities, such as photos on monitors or real green elements integrated into physical labs or real context (e.g. (Aristizabal et al., 2021; Choi et al., 2016),). However, the potential impact of Biophilic Design interventions using VR is not fully undertaken.

Indeed, few authors have used VR to investigate the influence of nature on individuals in office environments. Existing studies have focused on the assessment of the impacts of greenery elements, investigating the human-nature connection in terms of «Visual Connection with Nature » occurring indoors (e.g., nature elements in space) (Lei et al., 2021; Yeom et al., 2021; Yin et al., 2018, 2019, 2020; Emamjomeh et al., 2020; Sedghikhanshir et al., 2022; Kim and Gero, 2022; Li et al., 2022; Haryndia and Ayu, 2020), «Prospect» (e.g., natural view from windows) (Yin et al., 2019, 2020; Kim and Gero, 2022; Yeom et al., 2020a) and «Material Connection with Nature» (Yin et al., 2019; Kim and Gero, 2022), with limited efforts in combining these patterns (Yin et al., 2019, 2020; Kim and Gero, 2022).

Such studies in IVE primarily focused on the users' stress and anxiety levels reduction in the presence of nature (Yeom et al., 2021; Yin et al., 2019, 2020; Sedghikhanshir et al., 2022), assessed self-emotions (Emamjomeh et al., 2020; Haryndia and Ayu, 2020; Yeom et al., 2020a) and physiological responses (Yeom et al., 2021; Sedghikhanshir et al., 2022; Kim and Gero, 2022; Yin et al., 2018; Li et al., 2022; Haryndia and Ayu, 2020), thermal state (Sedghikhanshir et al., 2022), single (Emamjomeh et al., 2020) or multiple cognitive tests (Lei et al., 2021; Yin et al., 2018). Thus, the literature analysis highlighted a limited exploration of the potential benefits of nature on cognitive performance, indicating the need for more objective and comprehensive data. Moreover, in evaluating users' cognitive performance, it is of relevant interest to understand the impact of the integration of green elements via biophilic design on attention and concentration during task execution.

In this context, psychophysiological measures, such as eye movements, can provide an objective and unbiased understanding of individual mental workload and visual engagement/disengagement to complement data from traditional approaches, like surveys. Eye-movements have a crucial role in cognitive processes by directing individuals' visual attention to the specific parts of a stimulus processed by the brain (Sharafi et al., 2015). Consequently, eye-trackers are applied to monitor users' visual attention by recording eye-movement data when they engage with a stimulus while performing a task. According to Sharafi et al. (2015) the relationship between eye movements and comprehension is double-fold: after stimuli onset, individuals try to interpret it (immediacy assumption); people focus attention on a stimulus until its comprehension (eye–mind assumption). With the advancements in measurement and device access, the use of gaze behaviour to assess cognitive processes and mental workload has become more widespread (Sharafi et al., 2015; Das et al., 2020). The analysis of eye behaviour can provide valuable insight into users' cognitive functions and affective states in response to stimuli (Sharafi et al., 2015; Skaramagkas et al., 2023).

In the field of VR field, eye-tracking technology integrated into head-mounted displays is adopted to get insights on processing tasks and allocation of attention in simulated environments (Sharafi et al., 2015; Broadbent et al., 2023; Eloy et al., 2023). VR devices equipped with eye-tracking offer the opportunity to continuously monitor workload-related eye behaviour without interfering with the participant's immersive experience and actions. Therefore, it is a valuable tool for a preliminary comprehension of evidence-based human-centric design through VR.

To the best of the authors' knowledge, only a limited number of studies have adopted eye-tracking technology to gain insight into cognitive functions (Lei et al., 2021; Yin et al., 2019) in immersive environments integrated with indoor greenery. A lack of literature exists on users' emotional attachment and distraction induced by specific virtual green elements, as well as comparison with other greenery interventions (i.e., natural view) emerged, even if these are crucial points to understand the effectiveness of design strategies. In addition, more research is needed to develop better eye-tracking data interpretation methods to measure work-efficiency outcomes (Berhe et al., 2023).

Based upon the limited existing literature and the identified research gaps, this research activity moves beyond mere examination of cognitive performance. It proposes a novel approach to investigate the potential and relationship of various visual Biophilic Design interventions on individuals' visual attention, distraction and cognitive load, employing eye-tracking metrics in association with multiple cognitive task performance. A between-subject comparative assessment among three virtual office layouts (Indoor Green- IG, Outdoor Green – OG and Non-Biophilic - NB). Specifically, this paper intends to answer the following research questions: (RQ1) Does the visual connection with nature influence participants' visual attention, interest and distraction from task execution?; (RQ2) Is there a relationship between eye-tracking metrics and cognitive tasks in response to the visual connection with nature?

These questions will be addressed by objectively assessing the difference between the three visual scenarios in terms of cognitive test results and eye-tracking metrics. In section 2, the whole methodology of this study is illustrated in detail. The results of ecological validity are analysed and discussed in section 3.1, while the outcomes of the experiments related to the first and second research questions are reported and discussed in sections 3.2 - 4.1 and sections 3.3 - 4.2, respectively.

2. Methods

The pilot-study was carried out at the Department of Construction, Civil Engineering and Architecture (DICEA) at Università Politecnica delle Marche (Ancona, Italy). Volunteer participants were recruited to perform three cognitive tests and to answer questionnaires in an immersive virtual office scenario integrated or not with green elements, while their eye-tracking data have been recorded. Winter indoor climate conditions were kept constant throughout the experimental sessions with an average indoor air temperature equal to 23.42 °C (sd: 0.32) detected with 60 s time-steps (temperature range: from −4° to +100°, accuracy ±0.01 °C).

2.1. *Virtual experimental conditions*

Three indoor visual conditions (see Fig. 1) were created using the same four-occupancy virtual office space: the NB served as the baseline office room scenario, while IG and OG conditions were developed by integrating greenery elements within the office room.

The NB condition represented the basic scenario of a common office room equipped with complete workstations and furniture (i.e., chairs, bookcases) to simulate a real office environment with the highest levels of detail.

IG condition consisted of the same virtual model enhanced with a living wall and potted plants throughout the office according to the most frequently used indoor greenery interventions and the «Visual Connection with Nature » proposed by Terrapin Bright Green LCC (Browning et al., 2014) as « A view to elements of nature, living systems and natural processes». The greenery quantities exceeded the minimum requirement of the WELL Standard (International WELL Building Instituite, 2020), which proposes 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, to support occupant well-being and restorative spaces by providing a connection to nature. The actual values of the model provided a plant wall covering a wall area equal to 60% of the floor area and potted plants covering 4% of the floor area.

For OG, natural views of trees to the windows aligned with the «Prospects » definition («An unimpeded view over a distance, for surveillance and planning») of the Nature of the Space pattern (Browning et al., 2014). The sitting position of participants within the model was adjusted with a total view rating from the desk (View Factor) equal to 5, corresponding to a lateral view angle of 53° and a vertical view angle of 73° (threshold 50–90°) (Commission, 2003).

These visual conditions were created starting from 3D models and virtualised through the Unity game engine (Unity, 2021) (Version, 2018.4.14f1). Eye tracking data were recorded using iMotion (IMotions, 2022) (Version 9.3), which was adopted also for the post-processing of data. The HTC Corporation VIVE PRO Eye head-mounted display (1440 x 1600 resolution image per eye, a pixel density of 615 PPI, a field of view of 110° per eye, an adjustable interpupillary distance from 60.7 to 73.5 mm) and the SteamVR plugin (SteamVR Plugin, 2021) were adopted to visualise the models.

2.2. *Data collection*

For each experimental condition, the authors collected both objective and subjective data from participants, namely, objective cognitive task performance, eye-tracking metrics, and subjective questionnaire data.

2.2.1. *Cognitive functions*

Participants performed three tasks for the cognitive functions assessment (Latini et al., 2023b), to be correlated with eye-tracking metrics for the mental load assessment: both the Magnitude-Parity test and OSPAN test were displayed as videos composed of a sequence of timed slides, while the Stroop test was presented as an image on the virtual computer monitor.

In particular, the Magnitude-Parity (MP) test was developed to measure the ability to flexibly switch from one activity to another and keep attention («task switching» (Wendt et al., 2017)). Some black-inked digits from "1" to "9" were displayed in the middle of white background slides (200 ms each). Preceding the digits, a red or blue represented the parity and the magnitude stimulus, respectively. After the magnitude stimulus, participants were instructed to express whether the displayed number was smaller or larger than "5" or whether was odd or even after the parity stimulus. There was a total of sixteen numbers to classify.

The OSPAN test, adopted to measure working memory ability (Unsworth et al., 2005), consists of a sequence of slides. Firstly, a simple math operation was displayed for 3 s to be solved by the mind. Secondly, a possible solution to the previous equation was displayed (3sec) and subjects were instructed to tell whether it was true or false. Finally, a letter to be memorised was displayed for 800ms. This sequence was repeated five times with different math equations and letters, concluding with participants recalling the correct order of letters presented.

To measure individuals' ability to control attention («inhibition» (Stroop, 1935)), the Stroop test presents 32 coloured words in red, green, blue, pink and orange ink on a black background. Participants were instructed to name the colour ink of the work as fast as possible, with the authors recording the speed of processing.

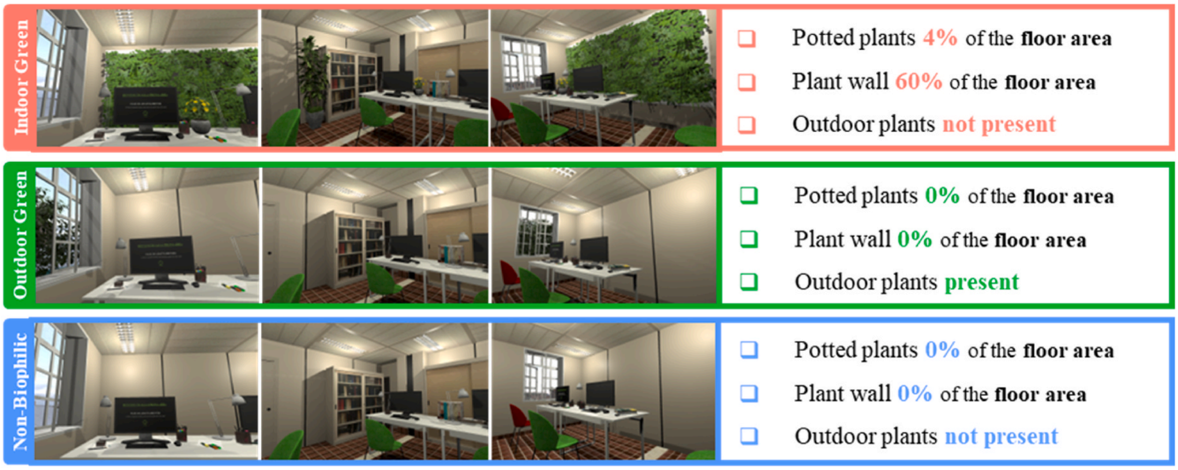


Fig. 1. The Visual Factor Levels: Indoor Green, Outdoor Green and Non-Biophilic scenarios with greenery percentages. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.2.2. Eye-tracking metrics

In the three experimental conditions, participants' raw eye-tracking data (i.e., blink, pupil diameter, fixations and saccades metrics) were collected with an eye-tracking system embedded in the VR headset. To measure mental workload across different tasks, several commonly adopted metrics include.

- **Number of blinks**: it is an involuntary metric whose frequency reduces as cognitive load increases (Jyotsna and Amudha, 2018; Ye et al., 2022). Indeed, during attention-demanding tasks to extract and process critical task-relevant, eye blinks tend to be inhibited to maximise stimulus perception (Chen et al., 2011; Narthur and Kramer, 1990).
- **Pupillary dilation** is another effective indicator of cognitive load as pupils tend to dilate in response to mental demands and emotional arousal (Jyotsna and Amudha, 2018; Ye et al., 2022; Chen et al., 2011; Nenna et al., 2023; Ktistakis et al., 2022; De Greef et al., 2009; Marshall, 2000; Mahanama et al., 2022).
- **Number of fixations/Fixation count:** a fixation is a short period during which an individual gaze remains relatively stable and focused on a specific point of interest to process visual information (Skaramagkas et al., 2023). The number of fixations entails several meanings depending on the content and the task performed which might involve different levels of attention, mental processing and comprehension, for example. More fixations are associated with higher cognitive load (Das et al., 2020; Ke et al., 2023) and engagement in the scene (Kim and Lee, 2021).
- Similarly, the **fixation duration** is linked to the time for information processing: a longer fixation duration indicates a higher mental load in extracting information during reading task (Jyotsna and Amudha, 2018), visual search task (Chen et al., 2011) (Ke et al., 2023) and working memory (Ke et al., 2023) and visual interest toward the scene (Kim and Lee, 2021).
- The **number of saccades** (rapid movements of the eyes as they shift from one point of interest to another) increases in the presence of higher cognitive load in information processing and task performance as the ability to shift gaze effectively to relevant information decreases (Chen et al., 2011; Ke et al., 2023).

It was of interest to couple quantitative eye-tracking data (e.g., blinks, pupil dilation, fixation and saccade) with the visualization of eye-tracking records by using eye movement heatmaps. The **heatmaps** adopt a colour gradient from light green to red the represent the degree of accumulation of fixation and duration, with warmer colours indicating a higher visual attention (Joseph and Murugesh, 2020). Thus, they provide information about visual attention to patterns displayed during task performance (Ke et al., 2023; Kim et al., 2022).

2.2.3. Questionnaires

Participants completed the following questionnaires.

- a pre-experimental survey on basic demographics including gender, age, eyesight problems, educational level and daily habits related to previous experience with VR;
- a post-experimental survey aimed at analysing the effectiveness of the virtual environment evaluating the sense of presence and immersivity within the virtual model using four indicators (Alvarsson et al., 2010): Graphical Satisfaction (GS), Spatial Presence (SP), Involvement (INV), and Experienced Realism (REAL), on a seven-point Likert («strongly agree » to « strongly disagree»). Additionally, participants completed the Virtual Reality Sickness Questionnaire (VRSQ) adapted by Kim et al. (2018) to measure six disorders (general discomfort, fatigue, eye strain, difficulty in focusing, headache, vertigo) on a five-point scale («not at all » to «a lot»).

2.3. Experimental protocol

As presented in Fig. 2, each test session lasted about 20 min, to reduce overall fatigue and exposure to the virtual environment. At the beginning of each test session, participants were briefed about the test to be performed and signed a consent form. During the pre-experimental phase in the real office environment where the experiment take place, participants completed a pre-experimental questionnaire to check the eligibility criteria. Once they wore the head-mounted display, they performed a 5-point calibration of the eye-tracking system, rested with their eyes closed for 30 s and then adapted to the virtual scene. Participants were told to freely explore the indoor scenario for 3 min while sitting in front of the virtual monitor, to reduce psychological fluctuations and facilitate immersion (Latini et al., 2023b). During the proper experiment operative phase (3 min), participants performed the cognitive tests in a random order to counterbalance the order effect and time-related factors (e.g., MP- Stroop-OSPAN, Stroop-MP-OSPAN) (Latini et al., 2023b) (Section 2.3.1) preceded by the related instructions. At the end of the experiment, they answered the post-experimental survey. The experimental protocol was approved by the Research Ethics Committee of the Università Politecnica delle Marche (No. 0216363, December 01, 2022), before the pilot study.

2.4. Participants

This pilot-study included 63 participants (male: 39, female: 24, age range: 19–42, mean age: 24 ± 4.69 years) who were randomly divided into three groups, each consisting of 21 participants, to perform the experimental activity. The sample size was determined using a-priori ANOVA power analysis through the G*Power software [90] considering an effect size $f = 0.35$, $\alpha = 0.05$. The sample size yielded a statistical Power equal to 67%. The group was mostly composed of university students (57%). Participants were recruited on a voluntary basis according to the following eligibility criteria: subjects had to be a minimum of 18 years old, without significant cardiovascular or neurological conditions, and any visual severe impairments such as colour blindness or strabismus that could invalidate the eye-tracking measures. 67% of the sample had common eyesight problems such as astigmatism, myopia, and hyperopia, but all of them wore corrective lenses during the tests. Additionally, 46% of participants had no prior experience with VR technology. Table 1 shows the characteristics of participants within each experimental condition: Indoor Green, Outdoor Green and Non-Biophilic.

2.5. Data processing

The data obtained from cognitive tasks and eye-tracking measures were extracted and analysed for each participant according to the following procedure.

For the instructions of each test, the time taken to read the slides was recorded. The errors in the classification of the digits even/odd and greater/lower than "5" were considered for the Magnitude-Parity test. Concerning the OSPAN test, the analysis involved calculating the number of errors in the true/false string, the correct order of the letters memorised and the OSPAN score, computed as the sum of the number of the right true/false and the letters correctly memorised. Those cognitive metrics were used as indexes for inhibition, task-switching and working memory capacity. Additionally, for the Stroop test, the number of errors in colour naming, and the time taken to complete the test in seconds were computed.

Considering the eye-tracking data, firstly the authors selected the visual stimuli to define the Areas of Interest (AOI), including the plant wall and potted plants for the IG configuration, and trees for the OG scenario. The computer monitor was also planned as a stimulus considering the slide that showed the letters in the OSPAN test, the entire screen during instruction presentations, and during the Stroop

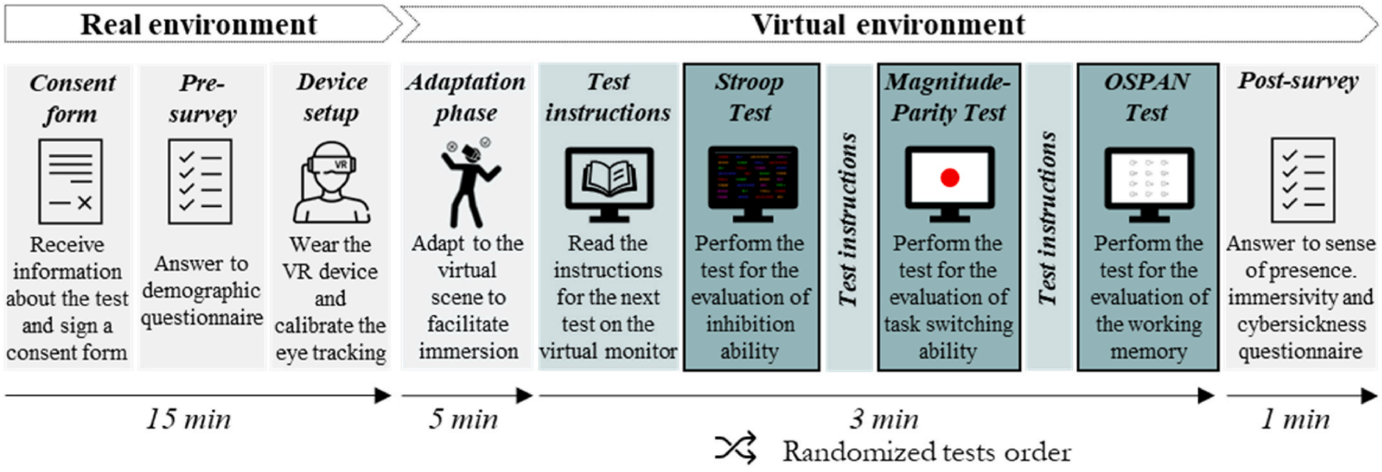


Fig. 2. The experimental protocol of the pilot study.

Table 1
Basic demographic characteristics of overall participants and across the three experimental visual scenarios.

	Overall	IG	OG	NB
Gender				
Female	38%	57%	33%	24%
Male	62%	43%	67%	76%
Age				
19–25	75%	52%	76%	95%
26–30	17%	33%	14%	5%
31–39	6%	14%	5%	–
40–45	2%	–	5%	–
Educational level				
Graduated	35%	38%	48%	19%
Non graduated	57%	48%	43%	81%
PhD, post-graduate school	8%	14%	10%	–
Eyesight problems				
None	33%	33%	48%	19%
Myopia	37%	29%	29%	52%
Myopia, Astigmatism	19%	24%	19%	14%
Astigmatism	8%	10%	5%	10%
Hyperopia	3%	5%	–	5%
Previous experience with VR				
Never	46%	38%	43%	57%
Once	27%	29%	29%	24%
More than once	27%	33%	29%	19%

and the Magitude-Parity tests. Instances of gaze outside those predefined boundary areas were categorised as « eyes-off-task».

Every participant's video recording was exhaustively scanned to identify segments where the selected visual stimuli (landmarks) were within the field of view. The gaze mapping algorithm allowed to map eye-tracking data recorded in the dynamic environments (e.g., adaptation phase, task executions), onto a static reference image of the environment.

As a result, the iMotion software could derive the stimuli-related gaze behaviour within the selected static AOIs based on fixations which were defined as a point-of-gaze that remained on a location for a minimum of 60 ms and classified using the I-VT Fixation filter (Komogortsev et al., 2010). The velocity value is computed for each eye position sample and compared to a threshold of 30°/sec. Samples with velocities below the threshold were marked as fixation, otherwise, as a saccade. Extracted metrics included: fixation count (number of fixations detected inside the AOI), fixation duration (sum of all fixation durations inside the AOI expressed in ms), saccade count (number of saccades with start and end points detected inside the AOI), gaze time (amount of time that respondents have spent looking at a particular AOI). These raw metrics were adopted for the eye-tracking analysis of cognitive performance and post-processed for the adaptation phase assessment. Participants' attention to greenery was calculated as a percentage, following the approach suggested by Bernardini et al. 2021. Specifically, gaze time and fixation count were used to compute A(o,t) and A(o,f), respectively. Time to First Fixation (TTFF) and First Fixation Duration (FFD) were also calculated to evaluate visual interest. TTFF indicates the amount of time that it takes a respondent to look at a specific AOI, while FFD provides data about how long that first fixation lasted. Thus, they give information about how AOIs were prioritized and how much they initially attracted attention: if a participant has a short TTFF and a long FFD, the area is in all likelihood very eye-catching.

In addition, blink rate and pupil dilatation were computed based on the ranges where the landmarks were within the participants' field of view during cognitive task execution and instruction reading. The latter was also calculated during the adaptation phase for the green elements.

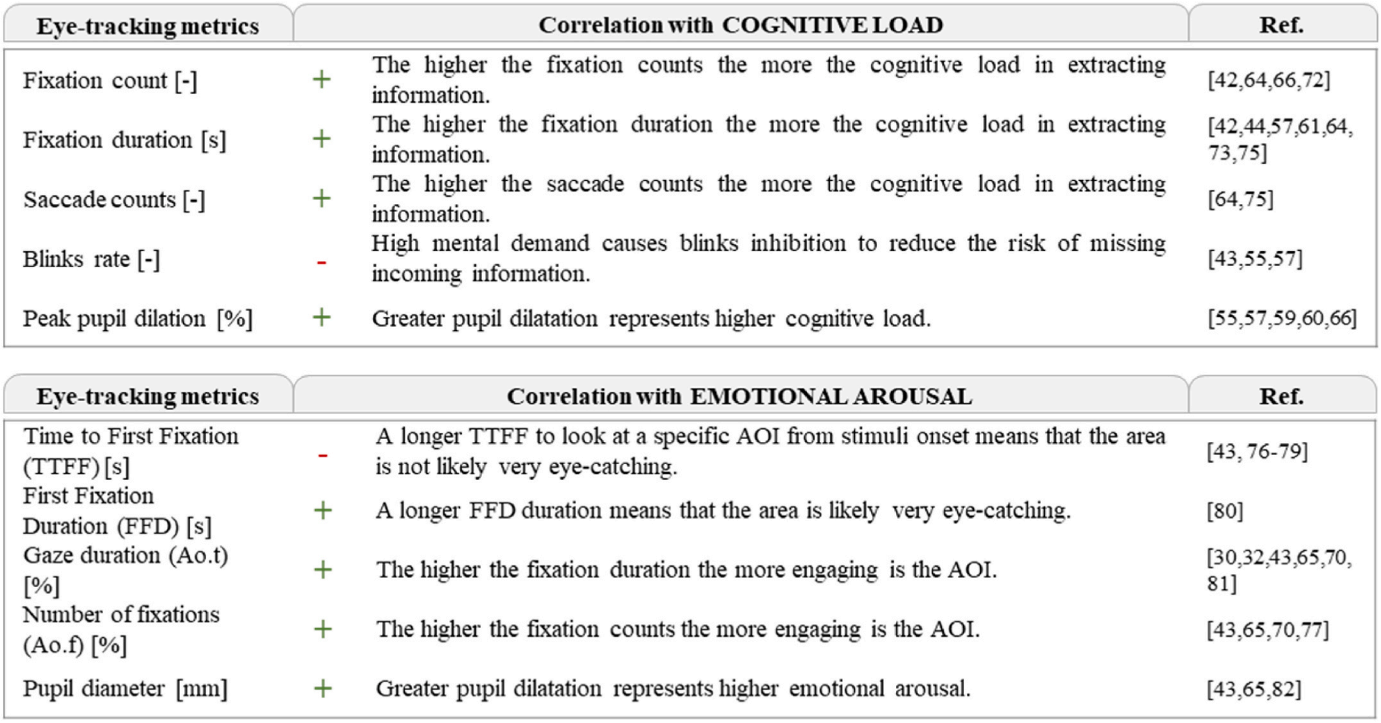
The blink rate was operationally defined as the blink rate per minute, with blinks detected as eye closures lasting between 20 ms and 500 ms. Any eye closure duration outside this range was considered a technical issue of the eye tracker. The minimal duration needed between two blinks to be considered as separated was 70 ms, as recommended by the iMotion guide for optimal results with a 90Hz eye tracker, which records one data sample every 11,1 ms. Pupil dilation was provided in raw data format, presenting a continuous stream of left and right pupil size estimates along with the corresponding timestamp relative to task duration. Pupil peak dilation was computed as the maximum percentage change in pupil diameter. The percentage change in pupil diameter for each data point was computed using the equation provided by Lemercier et al. (2014). Cognitive tests were presented on screens of variable luminance (i.e., black background for Stroop test, white background for MP and Ospan test). Therefore, the baseline was established as the pupil size at the beginning of each task to minimise the impact of light on pupil size variations.

Fig. 3 suggested a workflow for interpreting each eye-tracking metric depending on the correlation with cognitive load and emotional arousal.

2.6. Data analysis

To evaluate how the eye-tracking metrics and cognitive functions differed between the virtual experimental conditions, several statistical methods were applied to the collected sample data using the statistical software R (R Studio, 2021).

Data were first tested for normality with the Shapiro-Wilk test and then analysed with parametric and non-parametric tests according to the normality of the distribution. Since data are found not to be normally distributed, the Kruskal-Wallis test was used as a non-parametric alternative to the independent-measures ANOVA, to investigate the presence



Eye-tracking metrics		Correlation with COGNITIVE LOAD	Ref.
Fixation count [-]	+	The higher the fixation counts the more the cognitive load in extracting information.	[42,64,66,72]
Fixation duration [s]	+	The higher the fixation duration the more the cognitive load in extracting information.	[42,44,57,61,64, 73,75]
Saccade counts [-]	+	The higher the saccade counts the more the cognitive load in extracting information.	[64,75]
Blinks rate [-]	-	High mental demand causes blinks inhibition to reduce the risk of missing incoming information.	[43,55,57]
Peak pupil dilation [%]	+	Greater pupil dilatation represents higher cognitive load.	[55,57,59,60,66]

Eye-tracking metrics		Correlation with EMOTIONAL AROUSAL	Ref.
Time to First Fixation (TTFF) [s]	-	A longer TTFF to look at a specific AOI from stimuli onset means that the area is not likely very eye-catching.	[43, 76-79]
First Fixation Duration (FFD) [s]	+	A longer FFD duration means that the area is likely very eye-catching.	[80]
Gaze duration (Ao.t) [%]	+	The higher the fixation duration the more engaging is the AOI.	[30,32,43,65,70, 81]
Number of fixations (Ao.f) [%]	+	The higher the fixation counts the more engaging is the AOI.	[43,65,70,77]
Pupil diameter [mm]	+	Greater pupil dilatation represents higher emotional arousal.	[43,65,82]

Fig. 3. Workflow for interpreting the correlation between eye-tracking metrics and cognitive load/emotional arousal. Positive correlation is marked in green colour, and negative correlation in orange. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

of differences in cognitive task results (e.g., time to completion, the number of errors) and eye tracking features (e.g., blink rate, peak pupil diameter, fixations count, fixation duration and saccades count) between the three visual conditions (NB, IG, OG). The null hypothesis states that there is no effect, no change, or no difference between the indoor layouts: if the computed H-value falls within the critical region (chi-square = ±5.99 for df = 2, $\alpha = 0.05$) and the p-value is higher than 0.05, the authors could conclude that participants' productivity was not influenced by the tested environment. In case statistically significant differences were found between conditions, a post-hoc Dunn Kruskal-Wallis test was performed to compare all the pairs. Lastly, Kendall Tau correlation analysis was adopted to investigate the relationship between eye-tracking metrics and cognitive task results.

A significance level of 0.05 (5%) was adopted for all tests. Moreover, descriptive statistics (mean, standard deviation) were computed for the eye-tracking metrics and cognitive test results.

3. Results

The following paragraphs present, at first, the ecological validity of the immersive virtual environment to ensure that the model can adequately represent real settings.

Then to answer RQ1, the first aim was to investigate whether and which greenery elements (i.e., potted plants, green wall, outdoor three), could influence most visual attention during the adaptation phase and distraction from task execution. Then, after determining the presence of differences between green elements in terms of aggregated gaze behaviour, it was of interest to carry out a statistical analysis on the results of cognitive tests and eye-tracking metrics for each subject across the investigated scenarios. Indeed, the second aim was to detect any possible relationship between eye-tracking metrics and cognitive tasks in response to the visual connection with nature (RQ2) and then to investigate which condition (IG, OG, NB) could potentially increase most individuals' work-efficiency based on the results of cognitive tests and gaze behaviour.

3.1. *Ecological validity*

For the ecological validity assessment, ratings of the sense of presence and immersivity were analysed and compared to previous literature (Latini et al., 2023a; Tawil et al., 2021; Yeom et al., 2020b; Hong et al., 2019; Chamilothori et al., 2019; Abd-Alhamid et al., 2019) according to Latini et al. suggestions (Latini et al., 2023b). As presented in Fig. 4, mean scores exceed a moderate level (i.e. 4, «I agree») for all four indicators. In particular, a high level of experienced realism (REAL) was obtained, the participants felt involved (INV) and present (SP) within the virtual model, and appreciated the graphics (GS), with mean values of 4.36, 4.17, 4.29, and 4.45, respectively, all surpassing the references. Similar scores to those of Latini et al. (2023a) for REAL and GS were detected (4.47 and 4.58, respectively). As a result, the authors concluded that the participants experienced an effective sense of presence and immersivity within the IVE.

According to the VRSQ results, no subject reported « vertigo» (100% scores assigned to « not at all»). Other symptoms such as « general discomfort», «fatigue», and «headaches» were negligible, with between 92% and 100% of the subjects scoring « not at all» and «slightly». Slight « eyestrain», and «difficulty in focusing» were reported by 19% and 34% of subjects respectively, consistent with the sickness symptoms analysis from previous studies (Latini et al., 2023a).

Thus, no significant cybersickness disorders were experienced by the subjects since the experimental strategy of the present research was based on a previously developed experimental protocol (Latini et al., 2023b), which considers the need to limit the VE exposure time below 25/30 min.

Finally, the authors confirmed the ecological validity of the model which allowed to consider that the created IVE offers a valuable tool to investigate the potential of greenery elements in this research domain.

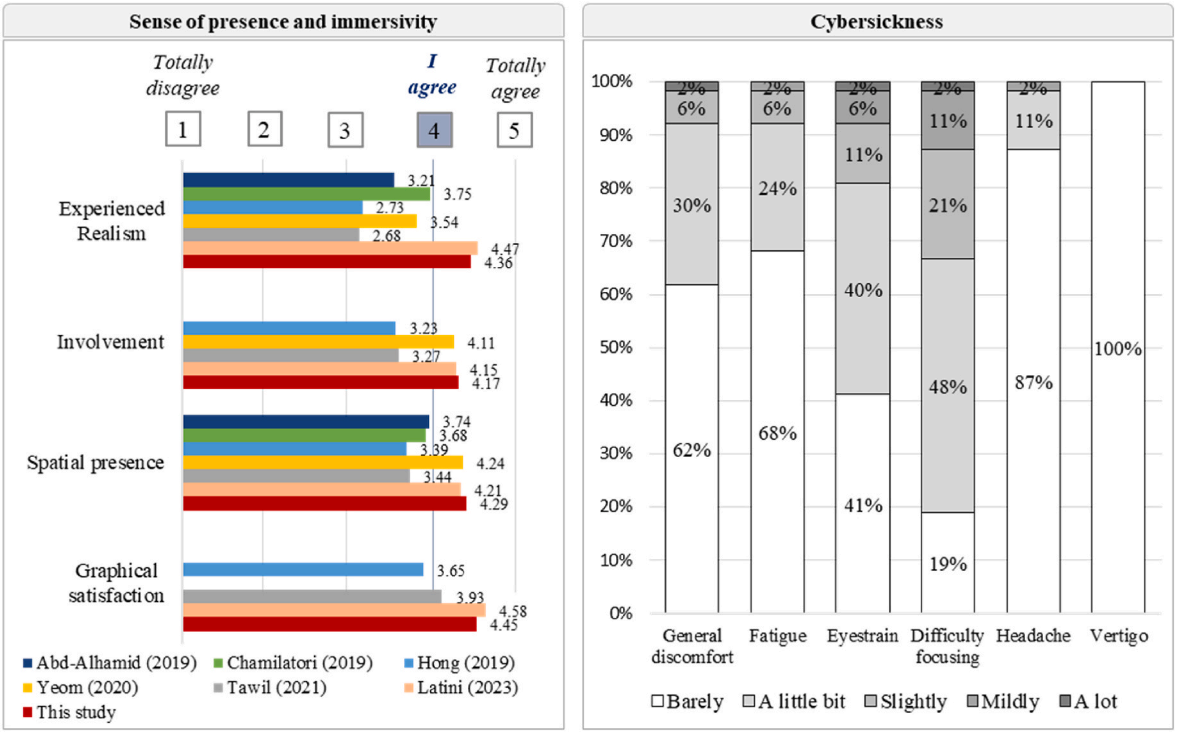


Fig. 4. Results of the sense of presence and immersivity and cybersickness surveys. The reference studies are: Latini et al. (Latini et al., 2023a), Tawil et al. (Tawil et al., 2021), Yeom et al. (Yeom et al., 2020b), Hong et al. (Hong et al., 2019), Chamilatori et al. (Chamilothori et al., 2019), Abd-Alhamid et al. (Abd-Alhamid et al., 2019).

3.2. *RQ1. Does the visual connection with nature influence participants' visual attention and distraction from task execution?*

3.2.1. *Visual attention in the indoor and outdoor greenery*

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

Fig. 5 shows the participants' attention to each greenery elements in terms of A(o,t) and A(o,f). Results (Table 2) showed that the flowered plant on the desk had the highest gaze time (A(o,t) = 100%), followed by the tree (A(o,t) = 68%), which means that it was observed for a longer time with respect to the other greeneries. Conversely, the outdoor tree had the highest number of fixations (A(o,f) = 100%), followed by the flowered plant (A(o,f) = 60%), indicating that it was the most engaging green element. Indeed, both the flowered plant and the outdoor tree were the nearest greenery to the participants with a higher visual interaction potential. During the adaptation phase participants could freely get closer to the flowered plant and turn to the left to look at the tree out of the window. However, they were not given the opportunity to get up to explore the green wall or the plant on the floor which were located farther away.

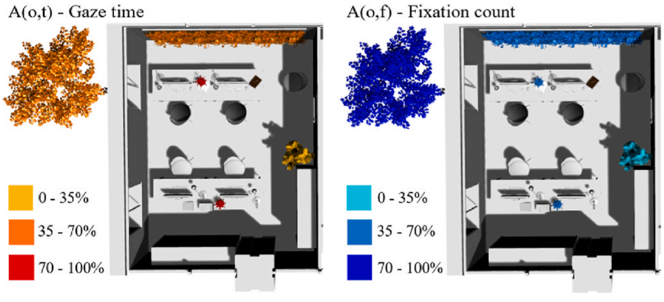


Fig. 5. Participants' attention, in terms of attention time A(o,t) (a) and fixation counts A(o,f) (b).

Table 2
Eye tracking indices across the three biophilic patterns integrated in the virtual model.

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

Time to First Fixation (TTFF) and First Fixation Duration (FFD) were also computed to understand how greeneries were prioritized and how much they initially attracted attention. As presented in Table 2, the flowered plant had the shortest TTFF (7.38s), indicating it was observed before the other greenery elements, followed by the green wall (15.70s), the outdoor tree (15.74s) and lastly the potted plant on the floor (45.12s). This result can be attributed to the spatial location of the greeneries and the proximity to the participants who were sitting in front of the virtual monitor. For instance, the plant on the floor required participants to turn around for a full view, resulting in a higher TTFF, to catch any details and identify it.

The flowered plant scored also the longest FFD (0.63s) due to its position on the desk withing the office environment. Conversely, the green wall and the outdoor tree had the shortest FFD time (0.19s and 0.21s), maybe due to their dimensions, making them easier to identify with less attention needed. These results suggest that the flowered plant resulted to be very eye-catching among the three green objects (shortest TTFF, longest FFD).

Then, the average pupil diameter was extracted within the TTFF of each AOI, with the flowered plant serving as the baseline reference resulting in the most eye-catching object. However, the authors noted only a 3% larger pupil diameter for the flowered plant than the green wall, and just 1% larger than the potted plant on the floor and the outdoor tree. These not significant differences suggest a consistent emotional experience among participants to all green elements.

3.2.2. Visual distraction from the cognitive task

The visual distraction potentially induced by greenery was assessed by considering the instances of “eye-off-task.” defined as participants looking away from the intended target (AOI) (Liang and Lee, 2010; Yuen et al., 2021), identified as the virtual monitor during the execution of the three cognitive tasks.

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

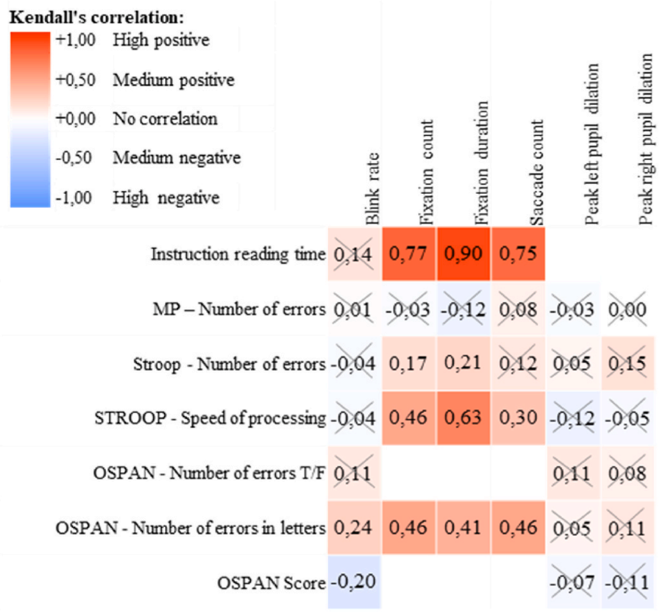
The results (Table 3) suggested that during all tests, between 43% and 62% of subjects were distracted in the presence of indoor greenery (IG) and between 14% and 52% in the presence of outdoor greenery (OG). Otherwise, in the absence of greenery (NB), a lower percentage of subjects looked away from the virtual monitor, ranging between 10% and 38%. Moreover, in the IG condition, the number of off-monitor-fixations was higher with subjects looking outside the computer monitor for a longer time in comparison with OG and NB across all three cognitive tests. In comparison to the indoor green condition, participants in the outdoor green scenario scored fewer fixation and shorter gaze times.

To assess which greenery elements within the IG condition elicited the most visual distraction from task execution, the authors analysed participants’ fixation count and gaze time on the flowered plant and the green wall during the execution of cognitive tests. The findings revealed that eleven out of the twenty-five subjects (44% of the sample) looked away from the virtual monitor to look at the greeneries at least once. Specifically, five of them focused on both the flowered plant and the green wall, while six concentrated solely on the green wall. Hence, it appeared that the green wall elicited a greater visual distraction ($A_{o,t} = 100\%$, $A_{o,f} = 100\%$) during the operative phase. The reduced fixation and gaze time concerning the flowered plant ($A_{o,t} = 26\%$, $A_{o,f} = 21\%$) may be attributed to its less prominent spatial location compared to the green wall.

3.3. RQ2. Is there a relationship between eye-tracking metrics and cognitive tasks in response to the visual connection with nature?

3.3.1. Correlation between cognitive tests and eye-tracking metrics

Kendall’s Tau correlation coefficient was computed to explore the relationship between eye movement metrics and cognitive function measures. Fig. 6 presents the correlation plot useful to investigate coefficients and p-values associated with those metrics. Noteworthy correlations were detected, with negative correlations presented in blue squares and positive ones in a red scale.



Kendall's correlation:
+1,00 High positive
+0,50 Medium positive
+0,00 No correlation
-0,50 Medium negative
-1,00 High negative

	Blink rate	Fixation count	Fixation duration	Saccade count	Peak left pupil dilation	Peak right pupil dilation
Instruction reading time	~~0,14~~	0,77	0,90	0,75		
MP – Number of errors	~~0,01~~	~~-0,03~~	~~-0,12~~	~~0,08~~	~~-0,03~~	~~0,00~~
Stroop - Number of errors	~~-0,04~~	0,17	0,21	~~0,12~~	~~0,05~~	~~0,15~~
STROOP - Speed of processing	~~-0,04~~	0,46	0,63	0,30	~~-0,12~~	~~-0,05~~
OSPAN - Number of errors T/F	~~0,11~~				~~0,11~~	~~0,08~~
OSPAN - Number of errors in letters	0,24	0,46	0,41	0,46	~~0,05~~	~~0,11~~
OSPAN Score	-0,20				~~-0,07~~	~~-0,11~~

Fig. 6. Kendall’s Tau correlation matrix between eye tracking features and performance features in the cognitive tests: non-significant coefficient and p-values >0.05 are indicated with a cross.

- Fixation count demonstrated a positive correlation with instruction reading time ($\tau = 0.77$), time to complete the Stroop test ($\tau = 0.46$), and number of errors in letters during the OSPAN test (positive, $\tau = 0.46$).
- Fixation duration exhibited a significant positive correlation with instruction reading time ($\tau = 0.90$), time to complete the Stroop test ($\tau = 0.63$), and number of errors in letters during the OSPAN test ($\tau = 0.41$).
- Saccade count showed significant positive correlations with instruction reading time ($\tau = 0.75$), time to complete the Stroop test ($\tau = 0.30$), and number of errors in letters during the OSPAN test ($\tau = 0.46$) and Stroop test errors (positive, $\tau = 0.21$).
- Despite that, no significant correlations were detected with blinks and pupil dilatation.

Concerning the relationship between the eye-tracking metrics and errors detected in the Magnitude & Parity test and Stroop test, no significant correlations were identified (p-value >0.05).

3.3.2. Results of cognitive tests and eye-tracking metrics in response to the visual connection with nature

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

Significant differences were observed considering the total instruction reading time ($\chi^2(2) = 28.22$, $p < 0.05$) across the three visual conditions, with lower reading time in Indoor Green (39.30 ± 33.51s) than in Non-Biophilic (98.15 ± 26.64s) and Outdoor Green (81.94 ± 29.94s). The pairwise comparison (Fig. 7a) revealed a significantly

Table 3
Eye-tracking metrics across the three scenarios: Indoor Green (IG), Outdoor Green (OG) and Non-Biophilic (NB).

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

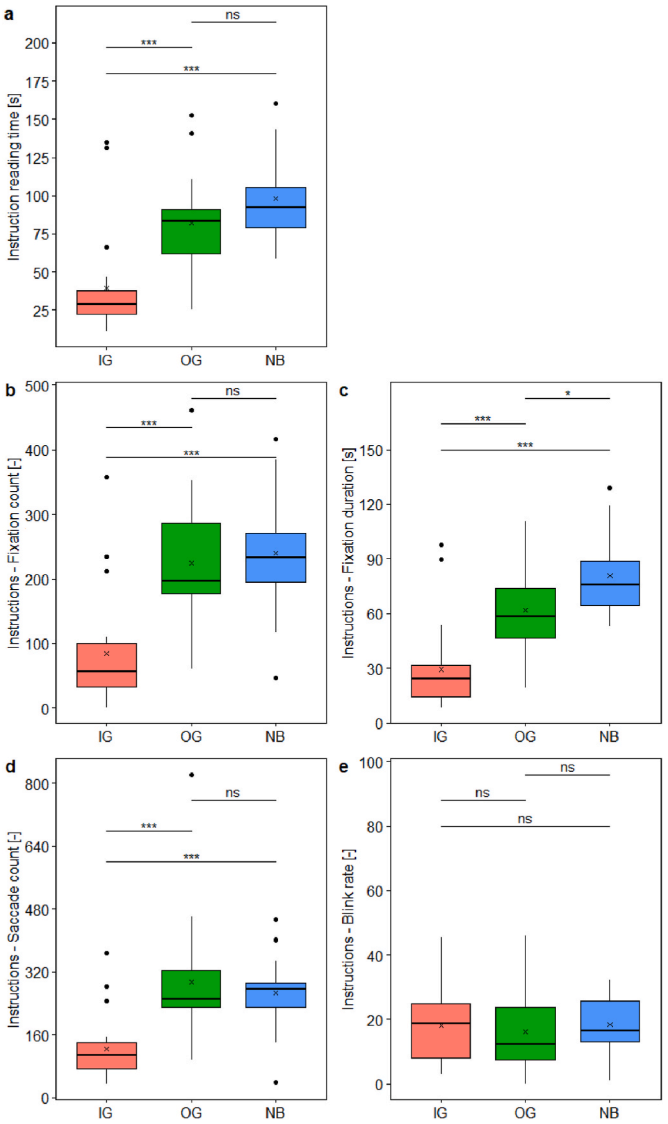


Fig. 7. Instruction tasks: boxplot of the results of reading time and eye-tracking features in the IG, OG and NB conditions.

lower reading time with indoor greenery than in outdoor greenery ($p < 0.05$, 60%) and no-greenery at all ($p < 0.05$, 17%) conditions. The magnitude of the effect highlighted (cf. Table 4) that visual factors had a moderate effect on instruction reading time. Eye-tracking metrics further confirmed that the mental load was lower in the indoor green condition in comparison with OG and NB (cf. Table 5). Except for the blink rate ($p > 0.05$, Fig. 7e), participants in IG showed significantly lower eye-tracking metrics ($p < 0.05$, Fig. 7b,c,d). In comparison with NB and OG, participants showed lower fixation count (58% and 55%, respectively), fixation duration (64% and 53%, respectively) and saccade counts (53% and 58%, respectively) when in the presence of indoor greenery elements. Conversely, OG and NB did not differ significantly in terms of eye-tracking metrics.

Considering the errors in the classification of the digits in the Magnitude - Parity test, the results of the statistical analysis indicated the absence of significant differences between the three visual conditions ($\chi^2(2) = 2.05$, $p = 0.36$). despite that, a slight number of errors occurred for OG (0.24 ± 0.54) and IG (0.62 ± 1.36) in comparison with NB (1.05 ± 1.75) (see Fig. 8a). On average, while participants exhibited higher scores in indoor green (41%) and outdoor green environments (77%) compared to non-biophilic settings, these improvements were not statistically significant. Even if the increased accuracy seemed relevant in the presence of greenery elements, this result aligns with the trend observed in the (indoor) VR-based BD literature on cognitive assessments (Lei et al., 2021; Yin et al., 2018).

Concerning eye-tracking metrics, no statistically significant differences were detected between the three conditions, except for the number of saccades ($\chi^2(2) = 7.98$, $p < 0.05$). Thus, this metric seemed not suitable for assessing mental load due to the nature of the Magnitude & Parity test. As expressed in section 2.3.1, digits and dots were presented in the middle of the screen, thus, this test did not require as not much eye movement to complete the task, as shown in the heatmap (Fig. 11). Indeed, the gaze behaviour remained consistent across the IG, OG and NB conditions and it was stable in the centre of the virtual monitor.

In the analysis of the OSPAN test, a significant effect of the visual condition (χ^2 (2) = 13.93, $p < 0.05$, $\eta^2 = 0.20$) was found on errors in the true-false string. Post-hoc for the pairwise comparisons (Fig. 9a) indicated that participants were more accurate in Indoor Green (0.05 ± 0.22) than in Outdoor Green (0.19 ± 0.51) and Non-Biophilic (0.57 ± 0.60) scenarios (75% and 92% respectively). However, the presence of indoor and outdoor greenery did not elicit relevant differences for this task. While there were no differences in the number of errors in the letters memorised and in the OSPAN score, the comparison of the mean values of the number of errors (Table 4) revealed that participants made fewer errors and achieved a higher OSPAN score in the IG condition (0.90 ± 1.45, 9.05 ± 1.43) in comparison with OG (0.17 ± 0.48, 8.29 ± 2.12) and NB (0.24 ± 0.53, 7.67 ± 2.11). However, the improvement in working memory due to visual biophilic elements is in line with previous studies (Emamjomeh et al., 2020; Yin et al., 2018).

Considering the eye-tracking metrics during the OSPAN test, significant differences were highlighted for the fixation count ($\chi^2(2) = 10.25$, $p < 0.05$), fixation duration ($\chi^2(2) = 13.32$, $p < 0.05$) and saccade count ($\chi^2(2) = 7.78$, $p < 0.05$). Pairwise comparisons revealed significantly lower values for all metrics in the Indoor Green condition compared to Outdoor Green and Non-Biophilic scenarios (between 40% and 70% reduction). This suggests that in the absence of significant differences in the number of letters, subjects experienced a lower mental load to recall the correct order of letters in the IG condition. As a result, they spent more time gazing at the screen and searching for the letters to recall in OG and NB conditions. However, no differences were found between OG and NB. The heatmap (Fig. 11) revealed that participants in the IG focused their attention on the goal-related task (i.e., the correct order of letters memorised). This outcome suggests a more efficient search for the correct information; whereas participants in OG and NB showed attention to the other letters displayed demonstrating a more inefficient gaze behaviour with longer fixations on multiple letters indicating a higher effort in remembering the correct order.

Concerning the Stroop test, significant differences among the scenarios were only detected for the speed of processing ($\chi2$ (2) = 22.82, $p < 0.05$, $\eta^2 = 0.35$) with lower time with indoor greenery (28.21 ± 12.00s) than in outdoor greenery (37.01 ± 6.95s) and no-greenery at all (37.74 ± 9.47s) conditions, as confirmed by the pairwise comparison (Fig. 10b). Participants performed faster in the presence of greenery elements indoors compared with non-biophilic and outdoor natural environments (24% and 28%, respectively). This finding is consistent with existing literature linking greenery to improved cognitive function (e.g. (Lei et al., 2021; Yin et al., 2018)).

Regarding eye-tracking metrics during the Stroop test, significant differences were detected in fixation count ($\chi^2(2) = 20.65$, $p < 0.05$), fixation duration ($\chi^2(2) = 23.60$, $p < 0.05$) and saccade count ($\chi^2(2) = 15.37$, $p < 0.05$). Post-hoc test and pairwise comparisons revealed that the lowest fixation count (Fig. 10c), and duration (Fig. 10d) occurred for IG. In comparison with NB and OG, the presence of greenery elements indoors induced participants to stare at the word fewer times (15% and 50%, respectively) and for a lower time (38% and 50%, respectively), thus completing the task faster. Heatmaps presented in Fig. 11 showed that participants in the indoor green condition exhibited a more effective and efficient gaze movement (i.e., uniform gaze attention looking at

Table 4
The results of the unpaired-sample Kruskal-Wallis test on the instruction reading and the three cognitive tests.

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

the whole set of coloured words), while those in IG and NB displayed less efficient and uniform gaze behaviours.

In general, no differences were found for blink and pupil metrics among the cognitive tasks. This result is in contrast with previous literature (Skaramagkas et al., 2023; Nenna et al., 2023; Kim et al., 2022) but supports the results of the absence of correlation presented in section 3.3.1.

4. Discussion

In this section, the authors discuss the main research questions including the potential visual attention and distraction induced by greenery elements integration in office environments (RQ1), and the related relationship between eye-tracking metrics and cognitive performance during task execution (RQ2).

4.1. RQ1. Does the visual connection with nature influence participants' visual attention and distraction from task execution?

One of the main objectives of this study was to investigate whether the visual connection with nature could influence users' visual attention and distraction from task execution. Consistently with the research question, the participants' visual attention and interest in the presence of indoor and outdoor greenery seemed to be influenced by the spatial location of the greeneries and the distance to the users who were sitting in front of the virtual monitor (i.e., generated a higher number of fixation and gaze time). Indeed, the higher the proximity of participants to the greenery element, the higher the visual interaction potential, and the stronger emotional attachment. In addition, a consistent emotional experience of participants for all the green elements (i.e., no differences in pupil dimension) was detected.

Additionally, participants' visual distraction during the cognitive tasks was induced by the more prominent green element in terms of dimension and spatial location (i.e., the green wall, larger number of distracted subjects, fixation counts, and time spent gazing in relation to the test duration). Despite that, this is in contrast with the cognitive performance metrics which revealed a higher accuracy in the presence of greenery elements. Such a result is of relevant interest because allows to understand that the introduction of green elements has the potential to increase users' interest in the indoor environment even during the task execution while not damaging the related cognitive performance.

This outcome can be analysed in the context of Attention Restoration Theory (ART) (Kaplan, 1995) related to the fact that the nature view captures an individual's attention, allowing the brain regions linked to cognitive load to be restored. In this study, the results of eye-tracking analysis pinpointed that participants briefly shifted their attention to the green elements. This behaviour might be associated with the need for a mental break to allow attention restoration from the cognitive load associated with the tests (i.e., Stroop test, Magnitude-Parity test, OSPAN test).

Table 5
Results of the statistical analysis for the eye-tracking features from each task in the IG, OG and NB conditions.

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

Indeed, literature highlighted that the effects of "irrelevant distractors" can be eliminated in the presence of tasks requiring a high perceptual load (Forster and Lavie, 2008). Hence, in the present study, greenery can be considered as an irrelevant distractor because it was presented in a peripherical location outside of the fixation area required for task completion (i.e., the virtual computer monitor). In addition, due to the fact that it was adopted as an independent variable (i.e., layout variation), its function was not correlated with the typology of cognitive tests administered to the subjects. As a result, the cognitive effort necessary to visually process green elements may be minimal in

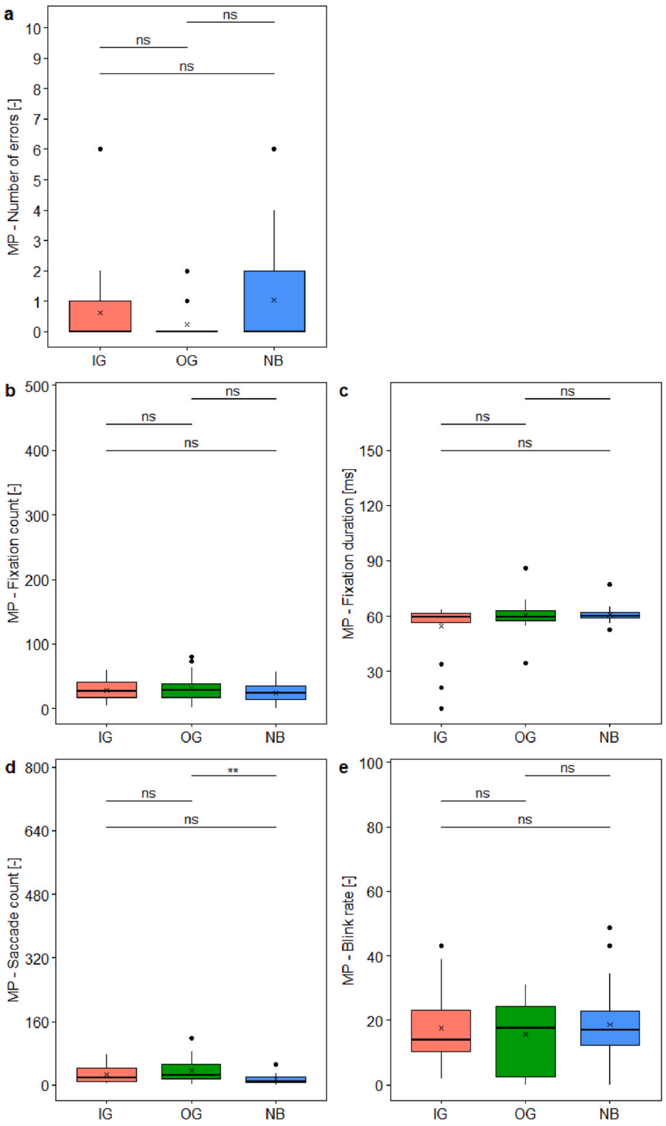


Fig. 8. Magnitude and Parity test: boxplot of the results of the test and eye-tracking features in the IG, OG and NB conditions.

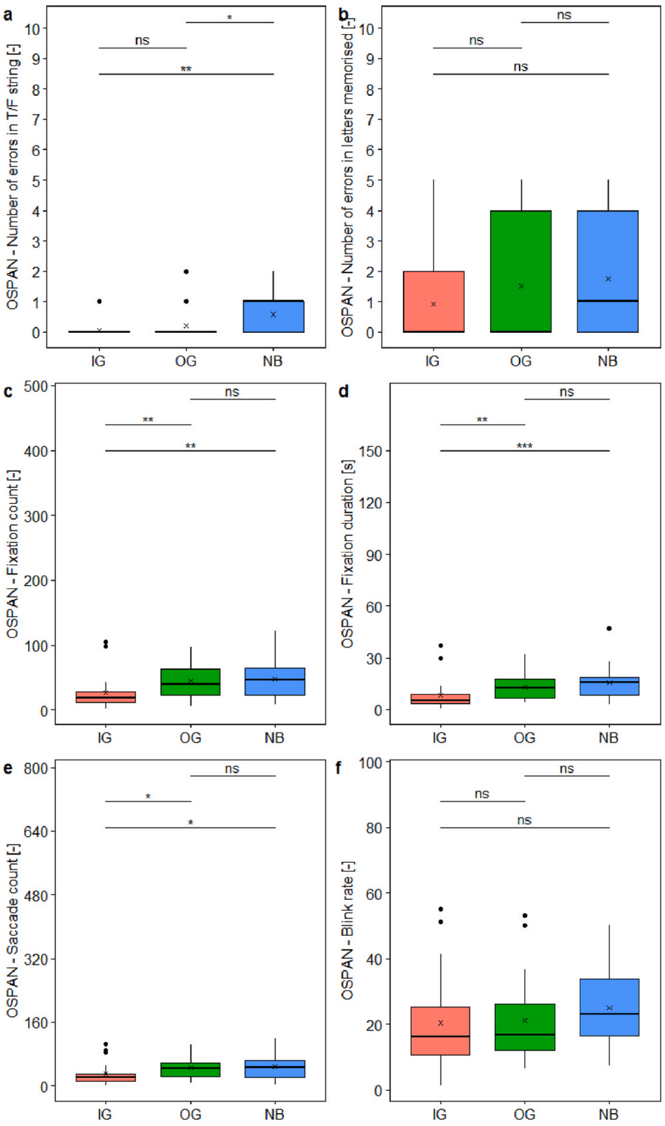


Fig. 9. OSPAN test: boxplot of the results of the test and eye-tracking features in the IG, OG and NB conditions.

comparison with the huge amount of cognitive load required to complete the task thus not affecting the cognitive performance of the participant.

These findings supported the hypothesis that the visual connection with nature can enhance visual attention and interest, potentially preventing fatigue during task completions serving as short breaks (i.e., brief diversion). However, the scarcity of literature in this field makes it challenging to look for comparable and generalizable results.

4.2. RQ2. Is there a relationship between eye-tracking metrics and cognitive tasks in response to the visual connection with nature?

The second objective of the present work was to investigate the potential relationship between eye-tracking metrics and cognitive tasks in response to the visual connection with nature.

To the best of the authors' knowledge, there is a scarcity of literature examining eye-tracking metrics and cognitive task response in the presence of visual connection with nature, complicating the comparison with the present outcomes. Therefore, this research activity was carried out as a first attempt to fill the literature gap and give researchers a landmark in the assessment of Biophilic Design intervention coupling traditional and innovative methods with users' gaze behaviour. To establish this research as a reference point for further research activities, it was essential to analyse and interpret the results verifying that the eye-tracking analysis reflected a common assumption in literature: the more the amount of fixation and duration, the increasing workload (Das et al., 2020; Jyotsna and Amudha, 2018; Chen et al., 2011; Ke et al., 2023) which could be translated into the longer time it takes participants to understand instructions, complete the test and lower accuracy. These findings suggest that cognitive load measured by eye-tracking and performance results could potentially influence each other, as highlighted in previous literature (Das et al., 2020; Ke et al., 2023) and that the fixations and saccades are the strongest determinants of time of completion and accuracy.

In addition, no relationship was detected between pupil dilatation and cognitive performance results despite these metrics play a crucial role in effectively assessing cognitive effort during classification problem-solving (Skaramagkas et al., 2023). These findings diverge from the literature reporting higher pupil size for higher task load (Nenna et al., 2023) and during specific task execution, such as solving complex mathematical problems (Jyotsna and Amudha, 2018), making difficult decisions (Ye et al., 2022), and memorizing playing strategies requiring greater mental effort (Chen et al., 2011). Conversely, the present results are consistent with those reported by Que (World Green

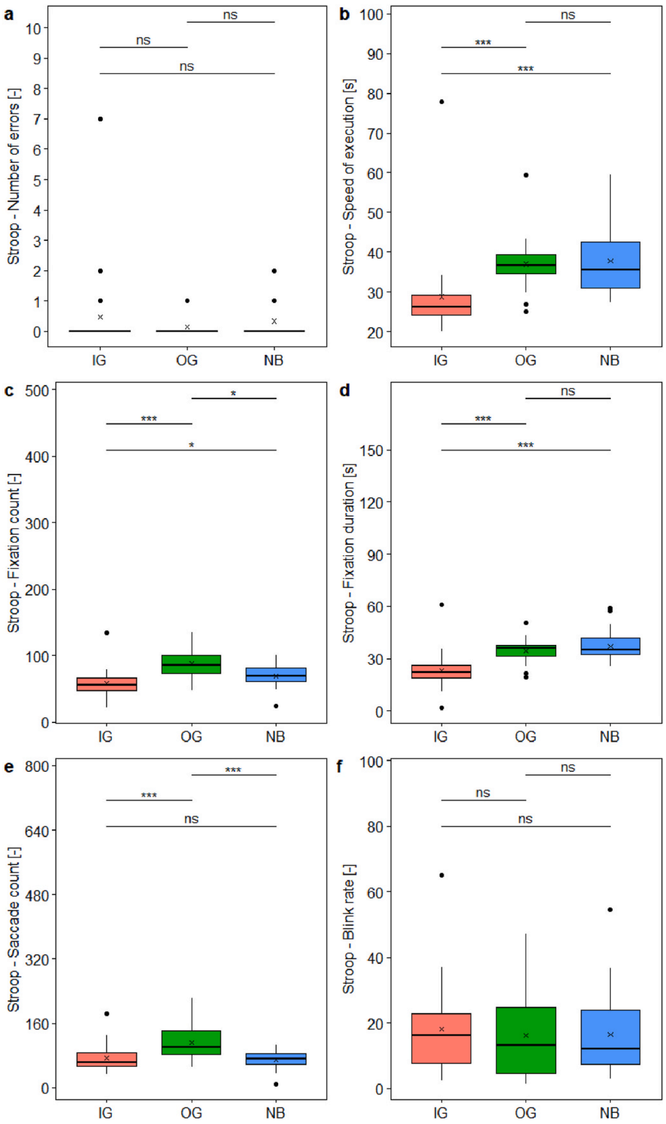


Fig. 10. Stroop test: boxplot of the results of the test and eye-tracking features in the IG, OG and NB conditions.

Building Council, 2016) who similarly did not detect differences in change of pupil size and blink rate. However, Joseph (Joseph and Murugesh, 2020) and Skaramagkas (Skaramagkas et al., 2023) highlighted a drawback of pupil dilation in the large deviation caused by changes in gaze angle and illuminance. As a result, Kim (Kim et al., 2022) suggested the adoption of the number of blinks as an involuntary eye-tracking metric in the assessment of cognitive load (Perkhofer and Lehner, 2019). It is important to note that such references deal with different contexts and stimuli than the one tested in the present research activity (e.g., robotics, acoustical stimuli domain) which limits the comparison of the results with previous literature in Biophilic Design interventions. To the best of the authors' knowledge and based on the results of these studies, the virtual environment did not negatively influence the results of those metrics. Indeed, it is well-known that pupil metrics are sensible to lighting variation (Duchowski et al., 2018) which should be kept constant during experiments in order not to affect the measurements reliability. This is especially difficult in real environment settings where lighting variation may occur for example in the presence of natural lighting coming from operable windows, while in laboratory-based studies the controlled illuminance settings are needed to ensure the participants equal testing conditions. Thanks to the advantages of Virtual Environments, it is possible to keep the lighting condition constant during the whole experiment session and replicate the same scenarios ensuring controlled conditions for each participant thus not generating bias that might limit the validity and generalizability of the results.

Moreover, a possible explanation could be that pupil metrics might not serve as the most reliable indicator of workload in this research context. Indeed, blink and pupil parameters did not appear to adequately capture differences in cognitive task load across the specific tests performed in this study (i.e., Stroop test, OSPAN test, Magnitude and Parity tests). In the presence of those tests, other metrics, such as fixation count, fixation duration and saccade count proved to be more effective and sensitive in capturing variations in participants' gaze behaviour depending on visual stimuli.

A significant improvement in reading time, speed of processing for the inhibition function and fewer errors in the working memory performance seemed to be dependent upon the presence of nature within the working environment. This aligns with existing literature, although previous VR-based studies evaluated the impact of nature exposure with a limited assessment of cognitive responses (Ref. Section 1).

These results corresponded to eye-tracking metrics which analysis confirmed a lower cognitive load and a more efficient search for the correct information in the IG compared to OG and NB scenarios even in the absence of significant differences in performance results. According to the literature, a more efficient search deals with the time participants took to identify the correct information (e.g., the letters to be memorised in the OSPAN test): the lower the time the better the accuracy in searching information. This results in heatmaps more focused in the "zone" with the correct answers. Such interpretation agrees with previous literature showing more effective and efficient gaze movements in looking at information relevant to the goal (Kim et al., 2022) as users can discern and discriminate between relevant and irrelevant information in problem-solving (Ke et al., 2023; Liberman and Dubovi, 2023) which occurred in the presence of indoor greenery in the present activity.

In conclusion, the resulting trend indicates a promising relationship between eye-tracking metrics and cognitive response particularly depending on the visual connection with nature, thus confirming the RQ2.

5. Conclusions

This pilot-study proposed a novel approach to investigate the potential impact and relationship of various visual biophilic design interventions on individuals' visual attention, distraction and cognitive load employing eye-tracking-equipped VR in association with multiple cognitive task performance. The general intent was to bridge the lack of human-centric attention to support evidence-based design in the biophilic research field through VR. The authors investigated differences between three virtual office layouts (Indoor Green, Outdoor Green and Non-Biophilic) integrated or not with green elements in terms of eye-tracking metrics and cognitive performance.

Firstly, the virtual environment successfully promoted a high sense of presence and limited cybersickness disorders among participants. The authors confirmed the ecological validity and effectiveness of VR in carrying out pre-occupancy evaluations of the potential benefits of greenery intervention strategies to support an evidence-based design.

Secondly, the integration of eye tracking and VR allowed to investigate the visual attention and distraction induced by greenery element integration in office environments (RQ1). Participants' visual attention was influenced by the proximity of participants to the greenery element (i.e., the nearer the object the higher the visual attention) while visual distraction from tasks was influenced by the spatial location and dimension of the greenery (i.e., the larger the object the more it potentially distracts the users).

Lastly, the outcome revealed a relationship between eye-tracking metrics and cognitive performance during task execution depending on the visual connection with nature (RQ2). Participants in the presence

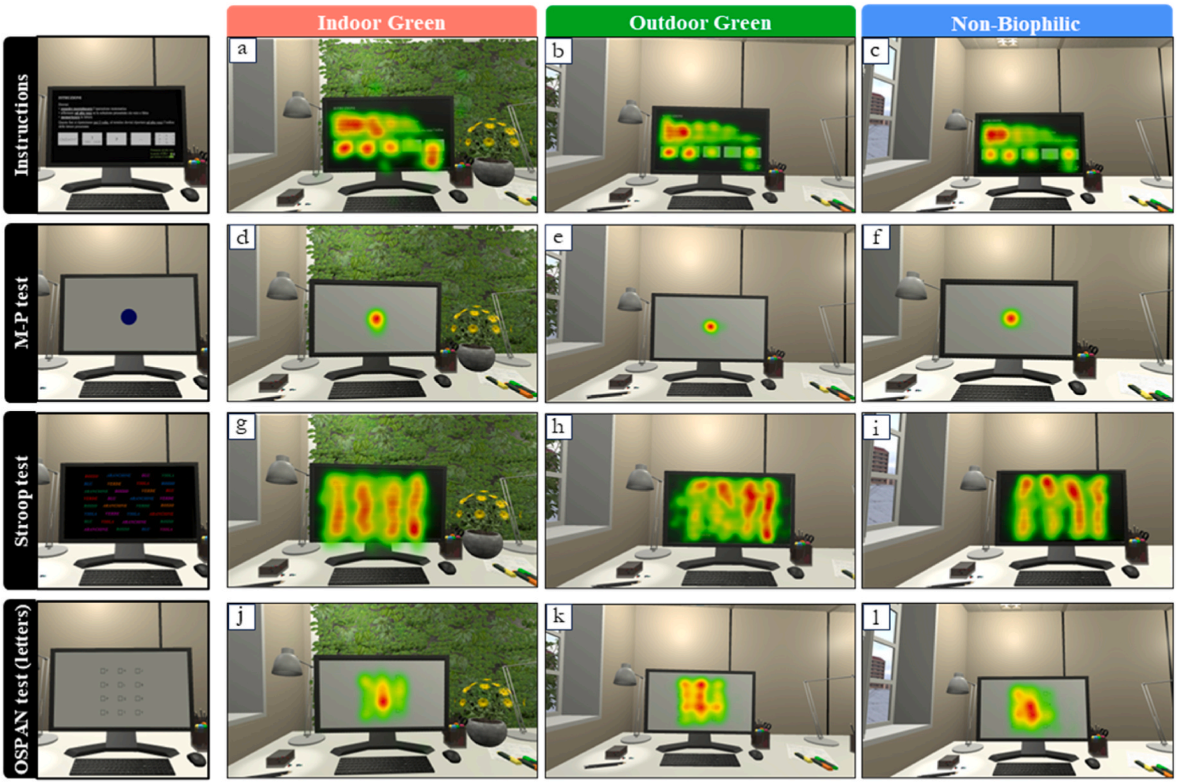


Fig. 11. Heatmaps for IG, NB, and OG conditions during each cognitive test. The coloured areas indicate how many respondents looked at something, and how long each of the individual respondents looked at it.

of indoor greenery seemed to experience a lower level of cognitive load and a more efficient search for the correct information resulting in improved performance (i.e., much less time to read and complete the task, fewer errors).

Despite these findings, this pilot-study acknowledges several limitations. The scarcity of existing literature makes it difficult to look for generalizable results. In addition, the results were gathered based on participants' availability, thus, larger sample sizes with more diversified features (i.e., age, education) should be recruited to increase the accuracy of the results. It would be of interest to see whether different greenery locations and quantities (i.e., heavily planted space versus minimum standards requirements) could diversely impact on visual attention, distraction and cognitive performance. Moreover, it would be beneficial to evaluate any possible cofounding variables related to individuals' differences that may have influenced the results. This could highlight the potential contribution of such differences (e.g., gender, age) to the observed outcomes, thus, improving their comprehension.

These findings have various potential implications at both scientific and professional levels. From a scientific standpoint, this research contributes to the enhancement of literature by highlighting the effect of introducing greenery elements in the office environment on users' cognitive performance, visual attention and distraction. The present activity offers a novel method for better interpreting eye-tracking data to measure cognitive outcomes. Thus, researchers have the chance to detect on an individual level if and how greenery elements and the office layout can improve cognitive performance while reducing task distraction and enhancing visual attention. The findings also show that the eye-tracking technology integrated into IVE offers insight related to how building users visually interact with indoor space. Thus, the collected data can be effective and promising for the assessment and improvement of performance by correctly designing indoor environments. The findings from virtual office environments could be translated into practical design strategies, as follows: the identification of factors leading to cognitive overload could allow designers to modify office spaces, ensure convenient location and minimise unnecessary distraction thus improving work-efficiency; workspace design can be personalized based on visual preference, behaviour and unique needs of different users; the analysis of the most attractive elements could be used to make more accessible and noticeable the important resources. Thus, professionals could adopt innovative and effective solutions suitable to support optimal work efficiency and create more engaging office environments capable of restoring attention.

As a result, the findings on the effectiveness of integrating eye-tracking in VR can be leveraged to adopt a new empirical research approach. The comprehension and quantification of human responses to biophilic environments could be used for preoccupancy evaluation and support and evidence-based design of the built environment.

Professionals are then provided with the possibility of enhancing individuals' cognitive performance through the design of working environments depending on the results of gaze behaviour. Understanding how greenery introduction affects users' attention, cognitive load and performance makes a great contribution to supporting indoor design practice, fostering a deeper human-nature connection and enabling more personalized interventions in indoor built environment design.

CRediT authorship contribution statement

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

References

Abd-Alhamid, F., Kent, M., Bennett, C., Calautit, J., Wu, Y., 2019. Developing an innovative method for visual perception evaluation in a physical-based virtual environment. Build. Environ. 162, 106278 https://doi.org/10.1016/j.buildenv.2019.106278.

Alvarsson, J.J., Wiens, S., Nilsson, M.E., 2010. Stress recovery during exposure to nature sound and environmental noise. Int. J. Environ. Res. Publ. Health 7, 1036–1046. https://doi.org/10.3390/ijerph7031036.

Aristizabal, S., Byun, K., Porter, P., Clements, N., Campanella, C., Li, L., Mullan, A., Ly, S., Senerat, A., Nenadic, I.Z., Browning, W.D., Loftness, V., Bauer, B., 2021. Biophilic office design: Exploring the impact of a multisensory approach on human well-being. J. Environ. Psychol. 77, 101682 https://doi.org/10.1016/j.jenvp.2021.101682.

ASHRAE Standard, 2019. Journal - June 2019 61, 1–85.

Ayuso Sanchez, J., Ikaga, T., Vega Sanchez, S., 2018. Quantitative improvement in workplace performance through biophilic design: a pilot experiment case study. Energy Build. 177, 316–328. https://doi.org/10.1016/j.enbuild.2018.07.065.

Berhe, I., Paul, A., Eelke, M., 2023. Eye tracking in virtual reality : a broad review of applications and challenges. Virtual Real. https://doi.org/10.1007/s10055-022-00738-z.

Bernardini, G., Gregorini, B., Quagliarini, E., D'Orazio, 2021. How do visitors perceive the architectural heritage? Eye-tracking technologies to promote sustainable fruition of an artistic-valued hypogeum. TeMA 7.

Broadbent, D.P., D'Innocenzo, G., Ellmers, T.J., Parsler, J., Szameitat, A.J., Bishop, D.T., 2023. Cognitive load, working memory capacity and driving performance: a preliminary fNIRS and eye tracking study. Transport. Res. F Traffic Psychol. Behav. 92, 121–132. https://doi.org/10.1016/j.trf.2022.11.013.

Browning, B., Cooper, C., 2015. The global impact of biophilic design in the workplace. http://humanspaces.com/resources/reports/.

Browning, W.D., Ryan, C.O., Clancy, J.O., 2014. 14 Patterns ofBiophilic Design: improving health & wellbeing in the built environment. Terrapin Bright Green 1, 1–64.

Chamilothori, K., Wienold, J., Andersen, M., 2019. Adequacy of immersive virtual reality for the perception of daylit spaces: comparison of real and virtual environments. LEUKOS - J. Illum. Eng. Soc. North Am. 15, 203–226. https://doi.org/10.1080/15502724.2017.1404918.

Chang, C.Y., Chen, P.K., 2005. Human response to window views and indoor plants in the workplace. Hortscience 40, 1354–1359. https://doi.org/10.21273/hortsci.40.5.1354.

Chen, S., Epps, J., Ruiz, N., Chen, F., 2011. Eye activity as a measure of human mental effort in HCI. In: Int. Conf. Intell. User Interfaces, IUI. Proc., pp. 315–318. https://doi.org/10.1145/1943403.1943454

Choi, J.Y., Park, S.A., Jung, S.J., Lee, J.Y., Son, K.C., An, Y.J., Lee, S.W., 2016. Physiological and psychological responses of humans to the index of greenness of an interior space. Compl. Ther. Med. 28, 37–43. https://doi.org/10.1016/j.ctim.2016.08.002.

Commission, C.E., 2003. Windows and Offices: a Study of Office Worker Performance and the Indoor Environment.

Das, S., Maiti, J., Krishna, O.B., 2020. Assessing mental workload in virtual reality based EOT crane operations: a multi-measure approach. Int. J. Ind. Ergon. 80, 103017 https://doi.org/10.1016/j.ergon.2020.103017.

De Greef, T., Lafeber, H., Van Oostendorp, H., Lindenberg, J., 2009. Eye movement as indicators of mental workload to trigger adaptive automation. Lect. Notes Comput. Sci. 219–228. https://doi.org/10.1007/978-3-642-02812-0_26.

Diamond, A., 2013. Executive functions. Annu. Rev. Psychol. 64, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750.

Duchowski, A.T., Krejtz, K., Krejtz, I., Biele, C., Niedzielska, A., Kiefer, P., Raubal, M., Giannopoulos, I., 2018. The index of pupillary activity. In: Proc. 2018 CHI Conf. Hum. Factors Comput. Syst. ACM, New York, NY, USA, pp. 1–13. https://doi.org/10.1145/3173574.3173856.

Eloy, S., Andrade, M., Dias, L., Dias, M.S., 2023. The impact of sound in people's behaviour in outdoor settings: a study using virtual reality and eye-tracking. Appl. Ergon. 108, 103957 https://doi.org/10.1016/j.apergo.2022.103957.

Emamjomeh, A., Zhu, Y., Beck, M., 2020. The potential of applying immersive virtual environment to biophilic building design: a pilot study. J. Build. Eng. 32, 101481 https://doi.org/10.1016/j.jobe.2020.101481.

European Agency for Safety and Health at Work, 2023. Occupational safety and health in europe-state and trends 2023 European agency for safety and. Health at Work. https://doi.org/10.2802/26873.

Forster, S., Lavie, N., 2008. Failures to ignore entirely irrelevant distractors: the role of load. J. Exp. Psychol. Appl. 14, 73–83. https://doi.org/10.1037/1076-898X.14.1.73.

Gao, L., Wang, S., Li, J., Li, H., 2017. Application of the extended theory of planned behavior to understand individual's energy saving behavior in workplaces. Resour. Conserv. Recycl. 127, 107–113. https://doi.org/10.1016/j.resconrec.2017.08.030.

Hähn, N., Essah, E., Blanusa, T., 2021. Biophilic design and office planting: a case study of effects on perceived health, well-being and performance metrics in the workplace, Intell. Build. Int. 13, 241–260. https://doi.org/10.1080/17508975.2020.1732859.

Haryndia, D., Ayu, T., 2020. Effects of Biophilic Virtual Reality Interior Design on Positive Emotion of University Students Responses.

Hong, T., Lee, M., Yeom, S., Jeong, K., 2019. Occupant responses on satisfaction with window size in physical and virtual built environments. Build. Environ. 166 https://doi.org/10.1016/j.buildenv.2019.106409.

Imotions, A./S., 2022. iMotions (9.3), Copenhagen, Denmark. https://imotions.com/.

International WELL Building Instituite, 2020. WELL v2. https://v2.wellcertified.com/en/wellv2/overview.

Jiang, B., Song, Y., Li, H.X., Lau, S.S.Y., Lei, Q., 2020. Incorporating biophilic criteria into green building rating tools: case study of Green Mark and LEED. Environ. Impact Assess. Rev. 82 https://doi.org/10.1016/j.eiar.2020.106380.

Joseph, A.W., Murugesh, R., 2020. Potential eye tracking metrics and indicators to measure cognitive load in human-computer interaction research. J. Sci. Res. 64, 168–175. https://doi.org/10.37398/jsr.2020.640137.

Jyotsna, C., Amudha, J., 2018. Eye gaze as an indicator for stress level analysis in students. Int. Conf. Adv. Comput. Commun. Informatics, ICACCI 2018, 1588–1593. https://doi.org/10.1109/ICACCI.2018.8554715 (2018).

Kalantari, S., Neo, J.R.J., 2020. Virtual environments for design research: lessons learned from use of fully immersive virtual reality in interior design research. J. Inter. Des. 45, 27–42. https://doi.org/10.1111/joid.12171.

Kaplan, S., 1995. The restorative benefits of nature: toward an integrative framework. J. Environ. Psychol. 15, 169–182. https://doi.org/10.1016/0272-4944(95)90001-2.

Ke, J., Liao, P., Li, J., Luo, X., 2023. Effect of information load and cognitive style on cognitive load of visualized dashboards for construction-related activities. Autom. Constr. 154 https://doi.org/10.1016/j.autcon.2023.105029.

Khan, A.R., Younis, A., Riaz, A., Abbas, M.M., 2005. Effect of interior plantscaping on indoor academic environment. J. Agric. Res. 43, 235–242.

Kim, N., Gero, J., 2022. Neurophysiological responses to biophilic design: a pilot experiment using VR and eeg biomimetic inspired architectural design view project design neurocognition view project. Des. Comput. Cogn. 1–21.

Kim, N., Lee, H., 2021. Assessing consumer attention and arousal using eye-tracking technology in virtual retail environment. Front. Psychol. 12 https://doi.org/10.3389/fpsyg.2021.665658.

Kim, H.K., Park, J., Choi, Y., Choe, M., 2018. Virtual reality sickness questionnaire (VRSQ): motion sickness measurement index in a virtual reality environment. Appl. Ergon. 69, 66–73. https://doi.org/10.1016/j.apergo.2017.12.016.

Kim, S.Y., Park, H., Kim, H., Kim, J., Seo, K., 2022. Technostress causes cognitive overload in high-stress people: eye tracking analysis in a virtual kiosk test. Inf. Process. Manag. 59, 103093 https://doi.org/10.1016/j.ipm.2022.103093.

Ko, W.H., Schiavon, S., Zhang, H., Graham, L.T., Brager, G., Mauss, I., Lin, Y.W., 2020. The impact of a view from a window on thermal comfort, emotion, and cognitive performance. Build. Environ. 175, 106779 https://doi.org/10.1016/j.buildenv.2020.106779.

Komogortsev, O.V., Gobert, D.V., Jayarathna, S., Koh, D.H., Gowda, S.M., 2010. Standardization of automated analyses of oculomotor fixation and saccadic behaviors. IEEE Trans. Biomed. Eng. 57, 2635–2645. https://doi.org/10.1109/TBME.2010.2057429.

Ktistakis, E., Skaramagkas, V., Manousos, D., Tachos, N.S., Tripoliti, E., Fotiadis, D.I., Tsiknakis, M., 2022. COLET: a dataset for COgnitive workLoad estimation based on eye-tracking. Comput. Methods Programs Biomed. 224, 106989 https://doi.org/10.1016/j.cmpb.2022.106989.

Largo-Wight, E., William Chen, W., Dodd, V., Weiler, R., 2011. Healthy workplaces: the effects of nature contact at work on employee stress and health. Public Health Rep 126, 124–126. https://doi.org/10.1177/00333549111260s116.

LarsenL, E., Adams, J., Deal, B., Kweon, B.S., Tyler, 1999. Plants in the workplace the effects of plant density on productivity, attitudes, and perceptions. Environ. Behav. 30, 261–281 publication/uuid/BD10AA79-D958-43EF-A03B-013230F826C7.

Latini, A., Di Giuseppe, E., D'Orazio, M., Di Perna, C., 2021. Exploring the use of immersive virtual reality to assess occupants' productivity and comfort in workplaces: an experimental study on the role of walls colour. Energy Build. 253, 111508 https://doi.org/10.1016/j.enbuild.2021.111508.

Latini, A., Di Giuseppe, E., D'Orazio, M., 2023a. Immersive virtual vs real office environments: a validation study for productivity, comfort and behavioural research. Build. Environ., 109996 https://doi.org/10.1016/J.BUILDENV.2023.109996.

Latini, A., Di Giuseppe, E., Orazio, M.D., 2023b. Development and application of an experimental framework for the use of virtual reality to assess building users ' productivity. J. Build. Eng. 70, 106280 https://doi.org/10.1016/j.jobe.2023.106280.

Lei, Q., Yuan, C., Lau, S.S.Y., 2021. A quantitative study for indoor workplace biophilic design to improve health and productivity performance. J. Clean. Prod. 324, 129168 https://doi.org/10.1016/j.jclepro.2021.129168.

Lemercier, A., Guillot, G., Courcoux, P., Garrel, C., Baccino, T., Schlich, P., 2014. Pupillometry of taste: methodological guide – from acquisition to data processing - and toolbox for MATLAB, Quant. Methods Psychol 10, 179–195. https://doi.org/10.20982/tqmp.10.2.p179.

Li, Z., Wang, Y., Liu, H., Liu, H., 2022. Physiological and psychological effects of exposure to different types and numbers of biophilic vegetable walls in small spaces. Build. Environ. 225, 109645 https://doi.org/10.1016/j.buildenv.2022.109645.

Liang, Y., Lee, J.D., 2010. Combining cognitive and visual distraction: less than the sum of its parts. Accid. Anal. Prev. 42, 881–890. https://doi.org/10.1016/j.aap.2009.05.001.

Liberman, L., Dubovi, I., 2023. The effect of the modality principle to support learning with virtual reality: an eye-tracking and electrodermal activity study. J. Comput. Assist. Learn. 39, 547–557. https://doi.org/10.1111/jcal.12763.

Lohr, V.I., Pearson-Mims, C.H., Goodwin, G.K., 1996. Interior plants may improve worker productivity and reduce stress in a windowless environment. J. Environ. Hortic. 14, 97–100. https://doi.org/10.24266/0738-2898-14.2.97.

Mahanama, B., Jayawardana, Y., Rengarajan, S., 2022. Eye movement and pupil measures. A Review 3, 1–22. https://doi.org/10.3389/fcomp.2021.733531.

Marselle, M.R., Irvine, K.N., Lorenzo-Arribas, A., Warber, S.L., 2016. Does perceived restorativeness mediate the effects of perceived biodiversity and perceived naturalness on emotional well-being following group walks in nature? J. Environ. Psychol. 46, 217–232. https://doi.org/10.1016/j.jenvp.2016.04.008.

Marshall, S.P., 2000. Method and Apparatus for Eye Tracking and Monitoring Pupil Dilation to Evaluate Cognitive Activity.

Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A., Wager, T.D., 2000. The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: a latent variable analysis. Cogn. Psychol. 41, 49–100. https://doi.org/10.1006/cogp.1999.0734.

Narthur, N., Kramer, F., 1990. Physiological Metrics of Mental Workload: A Review of Recent Progress.

Nenna, F., Zanardi, D., Gamberini, L., 2023. Enhanced interactivity in VR-based telerobotics: an eye-tracking investigation of human performance and workload. Int. J. Hum. Comput. Stud. 177, 103079 https://doi.org/10.1016/j.ijhcs.2023.103079.

Nieuwenhuis, M., Knight, C., Postmes, T., Haslam, S.A., 2014. The relative benefits of green versus lean office space: three field experiments. J. Exp. Psychol. Appl. 20, 199–214. https://doi.org/10.1037/xap0000024.

Perkhofer, L., Lehner, O., 2019. Using Gaze Behavior to Measure Cognitive Load. Springer International Publishing. https://doi.org/10.1007/978-3-030-01087-4_9.

R Studio, 2021. https://www.rstudio.com. (Accessed 31 May 2021).

Raanaas, R.K., Evensen, K.H., Rich, D., Sjøstrøm, G., Patil, G., 2011. Benefits of indoor plants on attention capacity in an office setting. J. Environ. Psychol. 31, 99–105. https://doi.org/10.1016/j.jenvp.2010.11.005.

Ratcliffe, E., Gatersleben, B., Sowden, P.T., 2013. Bird sounds and their contributions to perceived attention restoration and stress recovery. J. Environ. Psychol. 36, 221–228. https://doi.org/10.1016/j.jenvp.2013.08.004.

Ratcliffe, E., Gatersleben, B., Sowden, P.T., 2016. Associations with bird sounds: how do they relate to perceived restorative potential? J. Environ. Psychol. 47, 136–144. https://doi.org/10.1016/j.jenvp.2016.05.009.

Sedghikhanshir, A., Zhu, Y., Chen, Y., Harmon, B., 2022. Exploring the impact of green walls on occupant thermal state in immersive virtual environment. Sustain. Times 14. https://doi.org/10.3390/su14031840.

Sharafi, Z., Soh, Z., Guéhéneuc, Y.G., 2015. A systematic literature review on the usage of eye-tracking in software engineering. Inf. Softw. Technol. 67, 79–107. https://doi.org/10.1016/j.infsof.2015.06.008.

Shibata, S., Suzuki, N., 2002. Effects of the foliage plant on creative task performance and mood. J. Environ. Psychol. 22, 265–272. https://doi.org/10.1006/jevp.232.

Shibata, S., Suzuki, N., 2004. Effects of an indoor plant on creative task performance and mood. Scand. J. Psychol. 45, 373–381. https://doi.org/10.1111/j.1467-9450.2004.00419.x.

Skaramagkas, V., Giannakakis, G., Ktistakis, E., Manousos, D., Karatzanis, I., Tachos, N., Tripoliti, E., Marias, K., Fotiadis, D.I., Tsiknakis, M., 2023. Review of eye tracking metrics involved in emotional and cognitive processes. IEEE Rev. Biomed. Eng. 16, 260–277. https://doi.org/10.1109/RBME.2021.3066072.

SteamVR Plugin, 2021. https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647.

Stroop, J.R., 1935. Studies of interference in serial verbal reactions. J. Exp. Psychol. 18, 643–662. https://doi.org/10.1037/h0054651.

Tawil, N., Sztuka, I.M., Pohlmann, K., Sudimac, S., Kühn, S., 2021. The living space: psychological well-being and mental health in response to interiors presented in virtual reality. Int. J. Environ. Res. Publ. Health 18. https://doi.org/10.3390/ijerph182312510.

Ulrich, R.S., Simonst, R.F., Lositot, B.D., Fioritot, E., Milest, M.A., Zelsont, M., 1991. Stress Recovery during Exposure to Natural and Urban Environments.

Unity. https://unity.com, 2021.

Unsworth, N., Heitz, R.P., Schrock, J.C., Engle, R.W., 2005. An automated version of the operation span task. Behav. Res. Methods 37, 498–505. https://doi.org/10.3758/BF03192720.

Wendt, M., Klein, S., Strobach, T., 2017. More than attentional tuning - investigating the mechanisms underlying practice gains and preparation in task switching. Front. Psychol. 8, 1–9. https://doi.org/10.3389/fpsyg.2017.00682.

World Green Building Council, 2016. Building the business case: health, wellbeing and productivity in green offices, better places people campaign, 27. http://www.worldgbc.org/sites/default/files/WGBC_BtBC_Dec2016_Digital_Low-MAY24_0.pdf.

WorldGBC, health & wellbeing framework: six principles for a healthy, sustainable built environment. Exec. Rep., 2020 18. https://worldgbc.org/sites/default/files/WorldGBC.Health.%26.Wellbeing.Framework_Exec.Report_FINAL.pdf.

Ye, Y., Shi, Y., Xia, P., Kang, J., Tyagi, O., Mehta, R.K., Du, J., 2022. Cognitive characteristics in firefighter wayfinding Tasks: an Eye-Tracking analysis. Adv. Eng. Informatics. 53, 101668 https://doi.org/10.1016/j.aei.2022.101668.

Yeom, S., Kim, H., Hong, T., Park, H.S., Lee, D.E., 2020a. An integrated psychological score for occupants based on their perception and emotional response according to the windows' outdoor view size. Build. Environ. 180 https://doi.org/10.1016/j.buildenv.2020.107019.

Yeom, S., Kim, H., Hong, T., Lee, M., 2020b. Determining the optimal window size of office buildings considering the workers' task performance and the building's energy consumption. Build. Environ. 177, 106872 https://doi.org/10.1016/j.buildenv.2020.106872.

Yeom, S., Kim, H., Hong, T., 2021. Psychological and physiological effects of a green wall on occupants: a cross-over study in virtual reality. Build. Environ. 204, 108134 https://doi.org/10.1016/j.buildenv.2021.108134.

Yin, J., Zhu, S., MacNaughton, P., Allen, J.G., Spengler, J.D., 2018. Physiological and cognitive performance of exposure to biophilic indoor environment. Build. Environ. 132, 255–262. https://doi.org/10.1016/j.buildenv.2018.01.006.

Yin, J., Arfaei, N., MacNaughton, P., Catalano, P.J., Allen, J.G., Spengler, J.D., 2019. Effects of biophilic interventions in office on stress reaction and cognitive function: a randomized crossover study in virtual reality. Indoor Air 29, 1028–1039. https://doi.org/10.1111/ina.12593.

Yin, J., Yuan, J., Arfaei, N., Catalano, P.J., Allen, J.G., Spengler, J.D., 2020. Effects of biophilic indoor environment on stress and anxiety recovery: a between-subjects experiment in virtual reality. Environ. Int. 136, 105427 https://doi.org/10.1016/j.envint.2019.105427.

Yuen, N.H., Tam, F., Churchill, N.W., Schweizer, T.A., Graham, S.J., 2021. Driving with distraction: measuring brain activity and oculomotor behavior using fMRI and eye-tracking. Front. Hum. Neurosci. 15 https://doi.org/10.3389/fnhum.2021.659040.