Potential of Biophilic Design in Workplaces: A Pilot Study with Eye Tracking in Immersive Virtual Environments

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Abstract. Biophilic Design (BD) approach promotes the integration of Nature Based Systems into the built environment, with a positive impact on human comfort, health, well-being, and cognitive functions. In this pilot study, a virtual model of an office room was integrated with nature's patterns (living wall, potted plants) to create an Immersive Biophilic Environment (IBE). In the IBE, 25 participants performed three cognitive tasks while their eyes movements were detected through an eye tracking technology integrated within the head-mounted display for Virtual Reality (VR). The authors focused on two goals: verifying the ecological validity of the virtual biophilic model and evaluating the potential effect of introducing green elements in terms of visual attention, interest, and distraction. Findings revealed that the IBE created an excellent level of presence and immersivity. The preliminary results show that visual attention could be positively triggered by the proximity of users to the natural element and the possibility of freely exploring the biophilic environment, while visual distraction from operative tasks might be negatively influenced by the spatial location and dimension. Hence, the results of this pilot study support the potentiality of adopting VR in extensive research studies to support a proper biophilic design promoting emotional attachment and work efficiency.

Keywords: Immersive Virtual Environment, Biophilic Design, Eye Tracking.

1 Introduction

Indoor work environments designed only to maximize space efficiency are no longer useful and desirable. As people spend about 60% of their time in office environments every week [1], it would seem reasonable to expect that improving the design of working environments would have a positive impact on their concentration, comfort and work efficiency. In addition, due to the COVID-19 pandemic, employees are reconsidering the functionality and utility of their working spaces, wondering if they correctly answer their needs and foster mental and emotional well-being as well as their home workspaces during smart-working periods. One particular factor, upon which this research focused, is the potential of integrating biophilic design in office environments, due to the well-known benefits in terms of mood, cognitive functioning [2] and stress recovery [3]. The first studies on biophilic design were carried out in real physical contexts, such as test rooms or lab settings integrated with real green elements (e.g., [4,5]), resulting in time and cost-consuming research, depending on the complexity and scale of experiments. Recently, due to technological developments, it is also possible to study biophilic design by conducting tests in Virtual Reality (VR): thanks to its many advantages as a low-cost and flexible technology, it allows researchers to properly manipulate the desired variables (e.g., visual and acoustical dimensions) and rapidly repeat tests [6–8] Only a limited number of studies have explored the potential of Immersive Biophilic Environments (IBEs), mainly focusing on stress and anxiety levels [9–12], self-emotion assessment [13–19] and single [14–18] or multiple cognitive tests [20,21]. In the VR field, several available headsets are integrated with eye trackers adopted for highly diversified applications. In particular, eye tracking is increasingly used to investigate visual, cognitive, and attentional performance during experiments without interfering with the participant's immersive experience. Indeed, eye tracking data reflect cognitive performance, engagement, or disengagement and are adopted to supplement data from traditional approaches, such as questionnaires. To the authors' knowledge, only a few studies adopted the eye tracking technology during the assessment of cognitive functions in biophilic environments [9]. Hence the measurement of people's visual attention to specific virtual green elements and the visual distraction induced during cognitive tests is still understudied, even if it is a crucial point to understand the effectiveness of proposed design strategies. Therefore, this paper presents a pilot study, carried out to increase the empirical understanding on how introducing indoor greenery should be interpreted using physiological measures collected integrating eye tracking in VR (e.g., visual attention, interest, distraction).

2 Materials and methods

25 participants were recruited to perform three productivity tests and to answer questionnaires in an IBE, a virtual office scenario integrated with green elements. All participants were immersed in the same room located inside the Department of Construction, Civil Engineering and Architecture (DICEA) at Università Politecnica delle Marche (Ancona, Italy), with a constant winter indoor air temperature (mean: 23.42 °C, sd: 0.32), relative humidity (mean: 31.57%, sd: 0.82), and air velocity (mean: 0.01 m/s, sd: 0.02), detected with a time-step of 60 seconds (temperature range: -4°..+100°, accuracy ±0.01°C; relative humidity range: 0...100%UR, accuracy ±0.1%UR; air velocity range: 0.1 ... 5m/s, accuracy ± 0.2 m/s).

2.1 Participants

The recruited participants, selected from university students and researchers, presented the following demographic features.

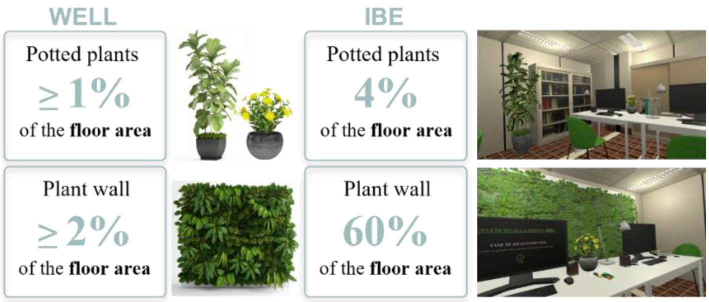
- Gender: 44% (male) and 56% (female).
- Age distribution: 56% from 20 to 25, 32% from 26 to 30, and 12% from 31 to 39, with overall mean and standard deviation equal to 25.44 and 4.91 years, respectively.

- Eyesight problems: 68% of the sample of the pilot study had common eyesight problems, (astigmatism, myopia), but wore corrective lenses during the tests.
- Previous VR experience: About 48% of participants were not familiar with virtual reality, while the other 52% experienced a virtual environment at least once.

2.2 IBE development

The generation of the IBE involved the modification of a previously validated office model (26 mq) [22], consisting on a four-occupancy room with two windows, which represented a basic scenario. Then, according to the "Visual Connection with Nature" patterns [23], a living wall and potted plants were added to the model, thus creating the IBE scenario. The greenery was added exceeding the minimum requirement of the WELL Standard [24] (**Fig. 1**). Unity game engine (Version 2018.4.14f1) was adopted to virtualize the 3D model and add materials, light and cameras. In addition, to gauge participants' visual attention, iMotion software [25] (Version 9.3) was used to record participants' eye tracking. The VR model was visualized through the HTC Corporation VIVE PRO Eye head-mounted display (1440x1600 resolution image per eye) using the SteamVR plugin.

Fig. 1. Biophilic variables for the generation of the IBEs. Percentages represent the covered floor area in the IBEs compared to the minimum percentages defined in the WELL standard.

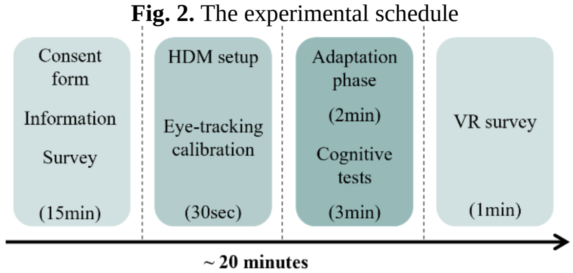


2.3 Experimental procedure

At the beginning of each test session, participants were asked to sign a consent form and received information about the test. Each session consisted of four phases. During the first pre-experimental phase, lasting 15 minutes, participants got used to the climatic indoor conditions and completed a pre-experimental questionnaire to retrieve information about demographics (gender, age, eyesight problems, and previous experience with VR).

Secondly, participants wore the head-mounted display, calibrated the eye tracking, rested with their eyes closed for 30 seconds then adapted to the virtual scene for 2 minutes while sitting in front of the virtual monitor, to reduce psychological fluctuations and facilitate immersion [26]. Thirdly, during the operative phase task (3 minutes), participants performed three cognitive tests to stay focused within the virtual scenario and simulate a traditional working activity: the Magnitude-parity test, for task switching, the OSPAN test, for the evaluation of the working memory, and the Stroop test, for inhibition [26]. Lastly, they answered a post-experimental survey, to test all the relevant constructs that typically ensure the effectiveness of the virtual environment [26]: sense of presence, immersivity and cybersickness disorders assessment. In particular, the sense of presence and immersivity was investigated via four indicators: Graphical Satisfaction (GS), Spatial Presence (SP), Involvement (INV), and Experienced Realism (REAL), on a seven-point Likert scale (from «totally disagree» to «totally agree»). The Virtual Reality Sickness Questionnaire (VRSQ) was used to assess general discomfort, fatigue, eye strain, difficulty in focusing, headache, and vertigo on a five-point scale (from «not at all» to «a lot»). Both the productivity test and questions were displayed on the virtual computer monitor. Responses were given by voice and recorded by the researchers. As presented in **Fig. 2**, each test session lasted about 20 minutes, to reduce overall fatigue and exposure to the virtual environment.

Fig. 2. The experimental schedule



3 Results and discussions

The following paragraphs present the ecological validity of the IBE to ensure that the model can adequately represent real settings, and the assessment of introducing greenery inside office environments in terms of visual attention and interest (point a) and visual distraction (point b). Eye tracking data are analysed through iMotions software [25].

3.1 Ecological validity

The authors analyzed scores data about sense of presence and immersivity and cybersickness ratings, compared to other reference studies according to [26], i.e., Latini et al. [22], Tawil et al. [18], Yeom et al. [27], Hong et al. [28], Chamilatori et al. [29], Abd-Alhamid et al. [30]. As reported in **Table 1**, the mean scores exceed a moderate level (i.e. 4) for all four considered indicators. In particular, a very good experienced realism (REAL) was obtained, the participants felt involved (INV) and present (SP) within the IBE, and appreciate the graphics (GS) of the model, with mean values of 4.45, 4.55, 4.55, and 4.50, respectively. In addition, all the values are higher than the references and similar to [22] (4.47). Hence the authors concluded that the IBE offered the participants an effective sense of presence and immersivity.

Table 1. Comparison of scores on a five-point scale of the four indicators

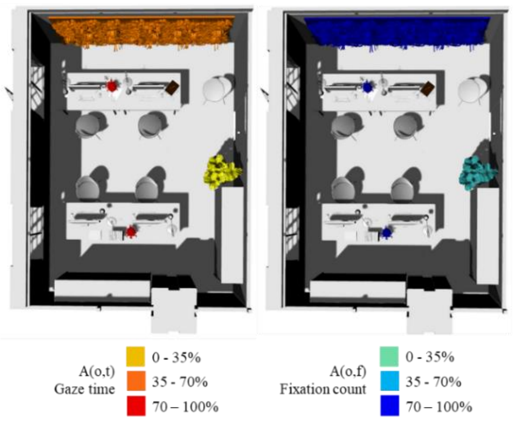
Indicator	This study	[22]	[18]	[27]	[28]	[29]	[30]
GS	4.60	4.58	3.93	-	3.65	-	-
SP	4.55	4.21	3.44	4.24	3.39	3.68	3.74
INV	4.55	4.15	3.27	4.11	3.23	-	-
REAL	4.45*	4.47	2.68	3.54	2.73	3.75	3.21

According to the results of the VRSQ, no subject during the pilot study reported «vertigo», «general discomfort» and «headaches» (100% scores assigned to «not at all»). Symptoms, such as «fatigue», «eyestrain», and «difficulty in focusing» were negligible, since between 92% and 100% of the subjects were assigned a score of «not at all» and «slightly». Thus, these results supported the ecological validity of the pilot study.

3.2 Eye Tracking

Visual attention and interest are widely investigated themes concerning performance outcomes and cognition processes: the higher the fixation duration and counts the more engaging is the scene [31], while greater pupil dilatation represents higher arousal. Firstly, participants' visual attention and interest in biophilic patterns during the adaptation phase (point a) were analyzed. The IBE environment was tagged with Areas of Interest (AOI) to gain the eye tracking metrics on the role played by the plant wall and by potted plants on desk and floor. For each area, the participants' gaze duration A(o,t) and the number of fixation A(o,f) have been calculated according to equations in [32]. **Fig. 3** shows the participants' attention to each of the considered greenery: the higher the percentage the higher the visual attention. The flowered plant was the nearer to the observer, which could also get closer to it within the virtual environment. Otherwise, subjects were not given the possibility to get up to the chair to explore the wall or the plant on the floor. Thus, results show that the potted plant with yellow flowers on the desk was perceived as the most relevant element, followed by the plant wall, thus both had the strongest influence considering visual attention.

Fig. 3. Participants' attention, in terms of attention time A(o,t) (a) and fixation counts A(o,f) (b)



In addition, the average values from participants' aggregated data of Time to First Fixation (TTFF) and First Fixation Duration (FFD) provided the authors with information about how greenery was prioritized and how much it initially attracted attention. As reported in **Table 2**, the flowered plant has the lower TTFF (7.71s), which means that it was observed before other greeneries, followed by the green wall (15.70s) and lastly by the potted plant on the floor (45.12s). The reason for the highest TTFF for the plant on the floor is its location behind the seat of the subject, which could perceived it just by turning around to get a full visualization. In addition, also the FFD of the flowered plant was higher than that of the plant on thr floor (0.87s > 0.31s) and of green wall (0.87s > 0.23s). According to the layout of the IBE, the flowered plant was the nearest green object with a higher visual interaction potential, then resulting in a stronger emotional attachment. On the other side, the plant on the floor was difficult to be visually identified as the farthest greenery, thus it required the participants a higher focus to catch any details. Among all greeneries, the green wall had the shortest FFD time (0.23s), maybe indicating that its dimension, which exceeded the minimum requirement of the WELL Standard [24], was easy to be identified and gained less attention. These results indicate that the flowered plant resulted to be very eye-catching among the three green objects (shortest TTFF, longest FFD).

As pupil dilation is already known to be related to mental workload and emotional arousal [33], the authors computed the average pupil diameter within the TTFF of each AOI. The flowered plant was considered as the baseline reference resulting in the most eye-catching object. However, the authors observed a pupil diameter 3% larger for the flowered plant (3.71 ± 0.55mm) than the green wall (3.59 ± 0.54mm), and the potted plant on the floor (3.60 ± 0.49mm). No significant difference was detected; thus, these results indicate participants' consistent emotional experience for both green wall and floor plant in comparison with the flowered plant.

Then, the visual distraction (point b) potentially induced by the introduction of green elements in the virtual office environment was assessed by considering the "eye-off-monitor". According to other research fields [34,35], it occurs when participants look away from an intended target (e.g., the virtual monitor during the operative phase to look at greenery). In particular, the authors analyzed the fixation count and gaze time of participants looking at the flowered plant and the green wall during the execution of cognitive tests. The plant on the floor was not considered as it was located behind the participants and then not visible during the operative phase. If participants were visually distracted and they shifted their gaze to the biophilic AOIs for at least 1 fixation (which is computed for a dwell time higher than 300ms), their gaze was then identified as eye-off-task. The results indicated that eleven of the twenty-five subjects (44% of the sample) look away from the virtual monitor to look at the greeneries at least once. In particular, 5 of them focused on both the flowered plant and the green wall, while 6 on the green wall only. Hence, the green wall seemed to elicit most participants' visual distraction ($A_{o,t}$ = 100%, $A_{o,f}$ = 100%) during the operative phase. The reason why the flowered plant scored less fixation and gaze time ($A_{o,t}$ = 26%, $A_{o,f}$ = 21%) might be because it was not as prominent as the green wall in spatial location.

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

Eye tracking indices	Biophilic pattern		
	Green wall	**Potted plant with flower**	**Potted plant on the floor**
Adaptation phase			
A (o,t) [%]	35%	100%	33%
A (o,f) [%]	77%	100%	48%
TTFF [s]	15.70	7.71	45.12
FFD [s]	0.23	0.87	0.31
Pupil diameter [mm]	3.59 ± 0.54	3.71 ± 0.55	3.60 ± 0.49
Operative phase			
A (o,t) [%]	100%	26%	-
A (o,f) [%]	100%	21%	-
Subjects no.	11 (5)	5	

4 Conclusions

The results of the present pilot study confirmed the ecological validity of the modelled IBE. Indeed, the comparison of the four indicators (GS, REAL, INV, SP) with previous studies highlighted that an excellent level of presence and immersivity was obtained and that the model did not cause significant cybersickness disorder levels.

The first step toward the evaluation of the positive effect of introducing greenery inside office environments was to understand how people explored the IBE using the sight sense. Thus, the authors measured participants' visual attention and interest in presence of a visual connection with nature and the distraction induced while performing the cognitive tests. In summary, results, even if related to this specific case-study with limited sample size, show that the stronger influence on visual attention was triggered by the proximity of users to the natural element and the possibility of freely exploring the biophilic environment. That is why the plant with flowers on the desk resulted in highest fixation counts, gaze time, FFD, and shortest TTFF, thus resulting was the most eye-catching element. On the contrary, a stronger influence in promoting visual distraction from specific tasks seemed to be caused by the spatial location and dimension of the greenery. The outcomes highlighted that the larger the object the more it potentially distracts the users (green wall > potted plant). Finally, according to pupil dilation, both green wall and floor plant elicited the same emotional experience in participants, slightly highest than the flowered plant. With the understanding of perceptual attention, interest, and visual distraction toward biophilic elements, this work contributes to increasing the empirical understanding on how introducing indoor greenery should be interpreted using physiological measures collected integrating eye tracking and immersive environments.

However, this pilot study is a first attempt to understand the effectiveness of the proposed biophilic design strategies and entails limitations. Firstly, the lack of literature in this field makes it difficult to look for generalizable results and larger sample sizes are required to increase the accuracy of the results. The outcomes of cognitive tests were not assessed but will constitute the subject of future investigations to correlate cognitive performance with emotional data collected by eye tracking tools integrated within the IBE. Moreover, pupil diameter fluctuation could be further investigated by adopting specific indices, such as in [33], and qualitative metrics (e.g., heat map, gaze pathway). Future studies should be designed to assess the effect of different greenery location and quantities (i.e., heavily planted space versus minimum standards requirements) within the indoor office environment to design a less distractive biophilic layout while promoting the highest emotional attachment. Thanks to the many advantages of VR, it would be possible also to design and test other office layout (i.e., cellular office space) and to combine the sight sense with the acoustical and olfactory dimensions of nature, thus creating multi-domain evaluation of well-being.

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