



## OPEN **Biophilic interventions in real and virtual environments reduce stress during cognitively demanding tasks**

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Biophilic design integrates natural elements into indoor environments to mitigate the negative effects of urbanization on human well-being. However, its efficacy in reducing stress during demanding tasks and the extent to which virtual biophilic interventions replicate real-world benefits remain unclear. We investigated whether a small-scale biophilic intervention—a removable, medium-sized living wall (LW) containing plants—reduces stress during performance of a cognitively demanding working memory task and positively influences emotions and environmental judgment. Its effects were compared to those of a virtual simulation. Forty-one participants, assigned to either a real (N = 21) or virtual (N = 20) environment, completed two sessions: one with the LW, one with an object-filled shelf. Heart rate variability, self-reported emotions, and environmental evaluations were collected. The results show higher physiological relaxation during the task and more favorable environmental ratings when exposed to the LW, regardless of the type of environment. Positive emotions were higher only in the real environment, suggesting a stronger emotional impact of real biophilic elements. These findings are of practical relevance for places where managing stress during demanding activities is crucial (offices, schools) or where access to nature is limited (hospitals, confined spaces).

**Keywords** Biophilic design, Stress reduction, Heart rate variability, Physiological arousal, Virtual reality (VR), Cognitive performance

While urbanization is emblematic of human and technological progress, it has also increased the distance from nature, potentially affecting people's well-being. Today, more than half of the world's population resides in urban areas, and projections from the United Nations World Urbanization Prospects<sup>1</sup> estimate that this proportion will rise to 68% by 2050. Living in the city has been associated with stress-related health problems and a higher prevalence of mental disorders, such as depression, anxiety, and schizophrenia<sup>2,3</sup>. In contrast, exposure to nature has been linked to an improvement in psychophysical well-being, due to a decrease in physiological stress and a reduction in anxiety and depression<sup>4,5</sup>. The Biophilia Hypothesis<sup>6</sup> provides a theoretical framework for understanding the mechanisms underlying these beneficial effects. This hypothesis posits that, rooted in their evolutionary history, humans possess an innate affinity with nature and tend to respond positively to elements that belong to or resemble the natural environment.

The growing disconnection from nature underscores the need to reintegrate natural elements into daily environments, especially in urban contexts. Biophilic design<sup>7</sup> addresses this need by incorporating natural elements, such as vegetation, natural light, and materials, into indoor built environments where people spend up to 90% of their time<sup>8</sup>. The benefits of biophilic design have been increasingly supported by scientific evidence. Studies show that it enhances the aesthetic appreciation of indoor environments<sup>9–11</sup>, fosters positive emotional responses<sup>12,13</sup>, alleviates negative mood states<sup>14–16</sup>, and contributes to improving cognitive performance<sup>13,14,17</sup>. Furthermore, introducing elements of biophilic design into indoor spaces has been linked to calming effects on their occupants, including reductions in physiological measures related to stress, such as heart rate, blood pressure, electrodermal activity, and cortisol levels<sup>9</sup>. These findings align with the two primary theories on nature's restorative effects, the Stress Recovery Theory<sup>18</sup> (SRT) and the Attention Restoration Theory<sup>19</sup> (ART), according to which, incorporating nature into everyday environments can reduce stress (SRT) or improve

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cognition (ART). In line with ART, many studies have investigated perceived restorativeness—typically assessed through self-report scales—as a key psychological indicator of an environment’s capacity to support recovery from mental fatigue and stress<sup>20,21</sup>. In the context of SRT, instead, biophilic design studies have mainly focused on the physiological benefits of exposure to nature in an indoor environment during rest or recovery from stress. The first line of research seeks to determine whether biophilic elements can reduce physiological arousal during normal, unstressed conditions, when participants are *at rest*. The second approach aims to determine whether exposure to nature facilitates recovery from stress *after* undergoing a stressful or demanding task<sup>22</sup>.

In this context, less attention has been paid to the effectiveness of biophilic design in mitigating or contrasting stress *during* the performance of challenging, demanding tasks. To the best of our knowledge, only one study has examined stress reduction by a nature-enriched environment during the execution of a cognitively demanding task (i.e., a working memory task). Using EEG indices of mental workload and cognitive stress, i.e., the delta-to-theta (DTR) and delta-to-alpha ratios (DAR), the authors reported no significant effects during the task phase<sup>23</sup>. This paucity of evidence highlights the need for further research to clarify whether biophilic design can effectively mitigate stress in real-time during high-demand cognitive activities. Addressing this gap has significant real-world implications, potentially guiding the design of workplaces, schools, hospitals, and other indoor environments to enhance psychological well-being through the integration of biophilic elements.

Design interventions require careful planning to avoid inefficiency and resource waste. Several studies have shown that biophilic interventions may fail to produce the expected benefits or even have adverse effects. For example, multisensory biophilic stimuli—such as a combination of visual (e.g., indoor plants and digital projections of nature) and auditory (e.g., natural sounds like wind and water) elements—have been found to increase distraction and impair cognitive performance, especially in tasks requiring attentional shifting<sup>17</sup>. Similarly, high green coverage in indoor environments has been associated with higher arousal, mental fatigue, and lower perceived restorativeness<sup>15,24</sup>. These findings emphasize the importance of carefully tailoring biophilic design interventions to the specific context, with a focus on the cognitive and psychological needs of users. In this scenario, virtual reality (VR) offers a cost-effective and flexible tool for simulating and testing biophilic design solutions before implementation. It may also serve as a powerful research tool for scientifically investigating the effects of specific biophilic design elements on people’s well-being, as it allows for the controlled manipulation of experimental stimuli<sup>25</sup>. Beyond its utility in design and research, VR becomes particularly valuable in contexts where direct exposure to real nature is not feasible, such as in healthcare facilities or isolated and confined environments.

While VR holds significant promise in the field of biophilic design, research in this area remains limited. Studies have shown that biophilic virtual environments can improve cognitive function and promote stress recovery<sup>14–16,26–28</sup>. However, only a few studies have directly compared the effects of real-world biophilic design interventions with their virtual counterparts. One study found no significant differences between real and virtual biophilic environments in terms of their effects on negative and positive emotions, blood pressure, electrodermal activity, and short-term working memory, suggesting that virtual exposure may effectively replicate real-world outcomes across psychological, physiological, and cognitive domains<sup>12</sup>. However, another study found comparable effects only at a psychological level, specifically in the reduction of negative mood<sup>14</sup>. These inconsistencies may be partly explained by individual differences in participants’ sense of immersion and presence, as well as mismatches between the virtual environment and real-world contexts (e.g., showing a virtual room with a sunny outdoor view while it is raining outside)<sup>14</sup>. These factors may diminish the perceived realism and level of engagement in the virtual experience, potentially attenuating its effects on physiological and cognitive responses. Given these limitations, it remains unclear to what extent VR biophilic environments can fully replicate the effects of real-world settings. To address these limitations, our study directly compared a physical and a virtual biophilic setting, while controlling for contextual factors and assessing participants’ subjective sense of presence.

## Research objectives and hypotheses

To address these gaps, we conducted a study that primarily focused on two key research questions: does exposure to a living wall—a vertical structure that can be easily implemented indoors—reduce stress during the performance of a demanding task? And if so, are the effects comparable to those of a virtual simulation? For the first question, we predicted that exposure to a living wall, compared to a non-natural condition featuring a shelf with everyday objects, would reduce physiological arousal both at rest and while performing a challenging task. Regarding the second question, we predicted that the effects of a virtual living wall would be analogous to those of its physical counterpart. Furthermore, we expected both real and virtual living walls to enhance psychological well-being by improving emotions and the overall subjective evaluation of the indoor environment. This multidimensional approach enables a more comprehensive understanding of how biophilic exposure impacts human well-being across multiple domains—an aspect often overlooked in existing literature, where studies tend to focus on isolated outcomes (e.g., physiological or emotional responses).

## Methods

### Participants

A total of 41 healthy volunteers were contacted via email and agreed to participate in the study: 21 (11 females, 10 males, age  $M = 38$ ,  $SD = 9.48$  years old) completed the study in a real environment, while 20 completed the study in a virtual one (17 females, 3 males, age  $M = 23.15$ ,  $SD = 2.48$  years old). As the two groups differed in terms of age and biological sex, these demographic variables were included as covariates in all statistical analyses.

The study was approved by the Ethics Committee of the University of Turin (Prot. No. 0202727) and conducted in accordance with relevant guidelines and regulations. The participants took part in the study voluntarily and signed an informed consent form. Exclusion criteria included a history of neurological or psychiatric disorders,

current use of psychoactive or autonomic nervous system-affecting medications, and, for the VR group, also a self-reported susceptibility to cybersickness.

### Study design

This study used a mixed experimental design with between-subjects and within-subjects factors. Participants were assigned to one of two groups based on the type of environment they were going to experience (between-subjects factor): real environment and virtual environment. Each group underwent two sessions, held on different days, during which they were exposed to one of two possible conditions (within-subjects factor): a living wall (LW) condition or a non-living wall (NLW) condition. The sequence of these conditions was counterbalanced across participants to control for order effects.

### Real and virtual environment

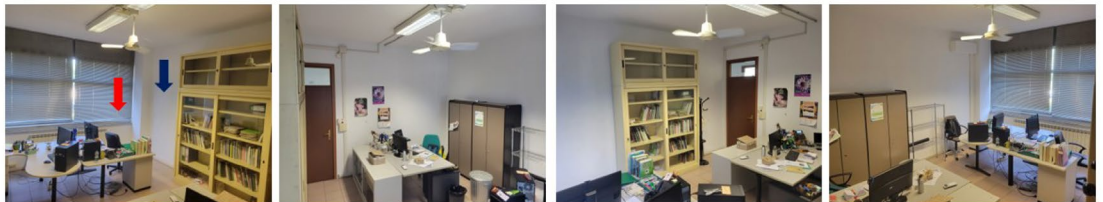
The two experimental sessions in the real environment took place in an office of the Department of Agricultural, Forest, and Food Sciences of the University of Turin. The office was a rectangular-shaped room of  $\sim 15 \text{ m}^2$  with a large window on the wall. Venetian blinds were used to block the natural view and prevent daylight from entering the room. Artificial illumination was employed to ensure consistent lighting conditions across participants. This setup was chosen to exclude potential confounds from natural outdoor views and enable a more accurate comparison with the virtual setting, which remained constant across sessions. This approach prevented possible mismatches between the virtual environment (e.g., a sunny simulated window view) and the real-world contextual cues (e.g., rainy or cloudy weather), ensuring a controlled and coherent experience across conditions. The sessions in the virtual environment were conducted in a university lab of the Department of Psychology of the same university. The virtual environment group experienced a virtual simulation of the real office, modeled using Autodesk 3ds Max 2017 (version 19.0.1072.0; <https://www.autodesk.com/it/products/3ds-max/overview>) and rendered in real-time during the experiment by using Unity software (version 2019.2.1f1). Figure 1 shows images of both real and virtual environments.

### Living wall and non-living wall conditions

In one session, participants in the real environment were seated  $\sim 100 \text{ cm}$  from a medium-sized ( $78 \times 78 \times 10 \text{ cm}$ ) LW placed on one of the office walls (Fig. 1). The LW included 9 cubic structures ( $26 \times 26 \times 10 \text{ cm}$  each) displayed in a  $3 \times 3$  grid. Each cubic structure contained 3 pots with an indoor plant ( $8 \times 8 \times 8 \text{ cm}$  each, for a total of 27 pots). The indoor plants included five different species: *Epipremnum aureum*, *Chlorophytum comosum*, *Nephrolepis exaltata* 'Bostoniensis', *Tradescantia fluminensis* 'Quadricolor', and *Fittonia albivenis* (see Table S1 in the Supplementary Material for a more in-depth description of each plant species). These plant species were selected based on the following criteria: small size, moderate growth habitus, and appreciable ornamental features. The plant disposition followed a perspective pattern, with taller plants in the lateral structures and shorter plants in the central structures. The size of the LW was designed to allow for the survivability of 3 plants in each cubic structure, while ensuring both compactness and visibility in a room of  $\sim 15 \text{ m}^2$ . In the other session, participants were exposed to the NLW, which consisted of a shelf of the same shape and dimensions as the LW, filled with office items that were chosen to recreate the same visual pattern of the plants, and positioned in the same location.

In the virtual environment, both LW and NLW conditions of the real environment were digitally recreated to approximate the real versions, capturing key elements while acknowledging some differences in detail (Fig. 2).

#### A) Real Environment



#### B) Virtual Environment



**Fig. 1.** Real and virtual environments. (A) Photographs of the university office (real environment) taken from four different viewpoints. (B) Screenshots of the virtual environment showing the same four viewpoints. The red arrow in the first image of both the real and virtual environments indicates the participant's position during each session. The blue arrow indicates the wall—real or virtual—where the living wall or non-living wall condition was located.

### Physiological response

Participants' physiological response was continuously measured during each session. An Empatica E4 wristband (Empatica Inc., Cambridge, MA) was used to record blood volume pulse (BVP) at 64 Hz. The device automatically derived inter-beat intervals (IBIs), representing the time between consecutive heartbeats, from the BVP signal. Heart rate variability (HRV), defined as the variation in IBIs, was calculated using Python with the pyhrv module<sup>29</sup>. Frequency-domain HRV indices were extracted, specifically the power of the low-frequency (LF: 0.04–0.15 Hz) and high-frequency (HF: 0.16–0.4 Hz) bands. The normalized HRV index %HF was computed using the formula  $HF/(LF + HF) \times 100$ . This index reflects sympathovagal balance, where higher %HF values indicate greater parasympathetic nervous system (PNS) activity—associated with a relaxation response—and lower values suggest sympathetic nervous system (SNS) predominance, linked to a stress response<sup>30</sup>.

### Cognitive task

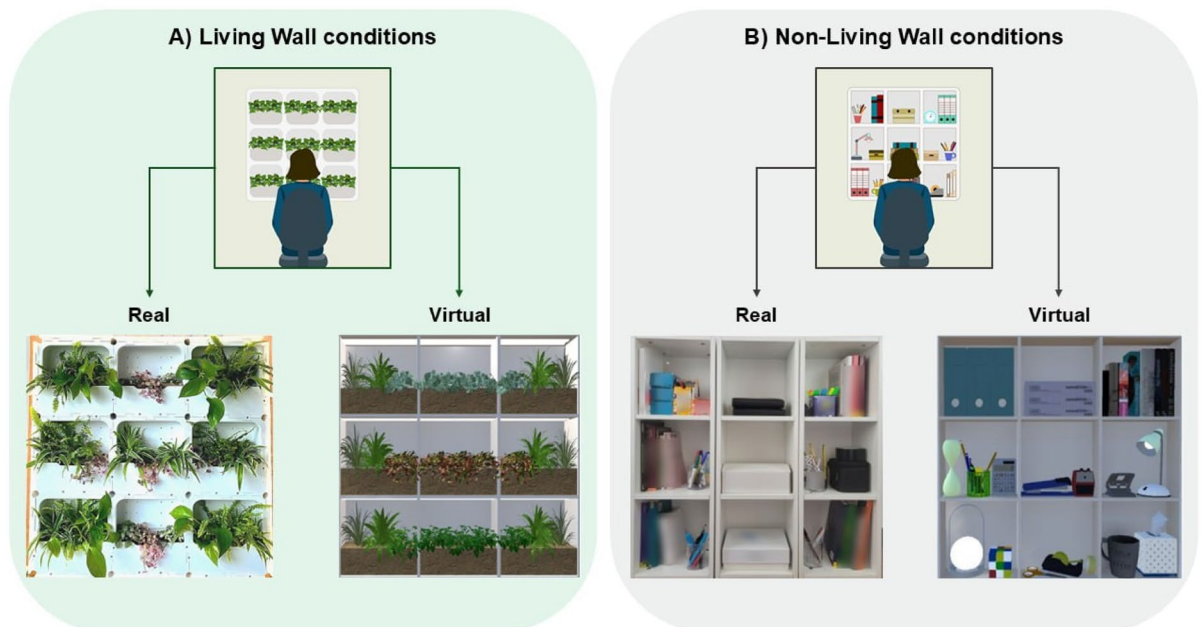
Participants were asked to perform the backward digit span task twice during each session; the specific timing is described in the Experimental procedure section. The task consisted of 14 digit sequences (seven pairs increasing in length from three to nine digits) presented to participants via audio recordings from a laptop. This has allowed control of the potential influence of prosody, which can facilitate memory recall tasks<sup>31</sup>. After each sequence, participants were instructed to verbally recall all the digits in reverse order. Task administration was interrupted if participants incorrectly recalled both sequences of the same length. Each correctly recalled sequence earned 1 point, regardless of its length, with a maximum possible score of 14.

This task was chosen because it is widely recognized as cognitively demanding. Performing it challenges working memory and executive functions—key cognitive processes crucial for managing and organizing information in complex tasks. Importantly, it has also been shown to be sensitive to the positive effects of nature exposure, with several studies reporting performance improvements following contact with natural stimuli<sup>32</sup>.

### Emotional state and environmental evaluation

Participants' emotions were assessed using a questionnaire based on the Circumplex Model of Affect<sup>33</sup>, following the approach used in a study on the emotional effects of natural views in indoor environments<sup>13</sup>. This questionnaire included 24 emotional adjectives, clustered in eight emotion octants: High Arousal (HA), High Arousal Positive (HAP), Positive (P), Low Arousal Positive (LAP), Low Arousal (LA), Low Arousal Negative (LAN), Negative (N), High Arousal Negative (HAN). Each emotion octant represents emotional valence (from positive to negative), arousal (from high-arousal to low-arousal), and their interactions (see Supplementary Material, Fig. S1A). Participants rated how they felt about each adjective on a 5-point Likert scale (from “1” = “not at all” to “5” = “extremely”). Scores for each emotion octant were computed as the median of the ratings of the adjectives within that octant.

The environment evaluation was assessed using an adaptation of the Environmental Assessment Scale<sup>34</sup> (Cronbach's  $\alpha = 0.84$ ) comprising five positive and five negative adjectives that participants rated using a 5-point Likert scale (from “1” = “not at all” to “5” = “extremely”; see Supplementary Material, Fig. S1B).



**Fig. 2.** Real and virtual conditions. (A) Real and virtual living wall (LW) conditions; (B) Real and virtual non-living wall (NLW) conditions.

### VR experience quality control

Participants who experienced the environment in VR also completed the Igroup Presence Questionnaire<sup>35</sup> (IPQ). The IPQ was used to evaluate the level of perceived presence in the virtual environment. It comprises three subscales (spatial presence, involvement, and experienced realism) and a general “sense of being there” item, for a total of 14 items. In the present study, we computed the median score for each participant within each IPQ subscale (Spatial Presence, Involvement, and Experienced Realism), while for the single-item General Presence, the single score was considered. All items were rated on a 5-point Likert scale (range 1–5). Spatial presence refers to the participants’ sense of being physically present within the virtual environment. Involvement assesses the level of engagement and attention that the participants directed toward the virtual environment. Experienced realism captures how realistic and plausible the virtual environment is perceived. Controlling for these aspects allowed us to ensure that any difference in participants’ cognitive performance or psychophysiological state between sessions could be attributed to the experimental conditions per se (LW vs. NLW), rather than to differences in the perceived presence between the two conditions.

### Demographic and lifestyle questionnaire

At the end of each session, all participants completed a questionnaire with two main sections. Demographic information was collected in the first section, where the participants had to state their sex (by choosing between: “male”, “female”, “other: specify”, and “prefer not to answer”), age (by writing their specific age in years), place of origin (by choosing between: “rural”, “suburban”, and “urban” areas) and general health status<sup>36</sup> (by choosing how they perceived their health status on a Likert scale from “1: poor” to “5: excellent”). Lifestyle information was collected in the second section using binary responses (by choosing “0” if the statement did not apply, “1” if the statement applied). In particular, information was gathered on smoking tobacco within the previous 24 h, intensive physical activity and caffeine intake within the last six hours, and the quality of sleep of the night before. Given their influence on physiological state and cognitive performance, these session-specific variables were considered as potential covariates in the analyses.

### Experimental procedure

Upon arrival, participants provided their informed consent, wore the Empatica E4 wristband for continuous physiological monitoring, and completed a brief training session for the backward digit span task.

Each session began with participants sitting quietly for 5 min to establish a physiological baseline, without exposure to either condition (resting baseline). Then, participants completed the backward digit span task to establish the baseline measure of cognitive performance (cognitive baseline).

After these initial baseline phases, participants spent 5 min seated, directly observing either the LW or NLW (resting exposure). Immediately afterward, they completed the backward digit span task a second time while continuing to view LW or NLW (cognitive exposure). At the end of each session, participants completed questionnaires on a laptop, providing demographic information and responses regarding their emotional state and evaluation of the indoor environment.

The same procedure was followed for both the real and virtual environment groups, with the only difference being that participants in the virtual environment group wore the Meta Quest 2 (Meta Platforms Inc., Menlo Park, CA) VR headset after the initial training on the digit span task.

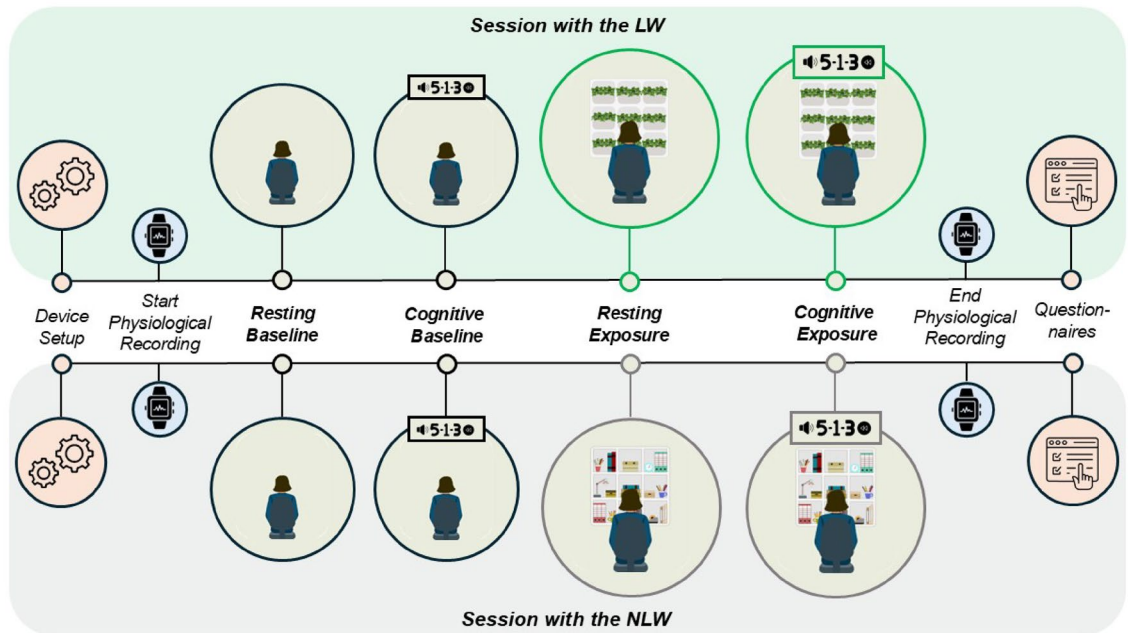
Each session lasted approximately 45 min. For each group, the two conditions (LW and NLW) were counterbalanced across participants, with the second session performed after 7 days. The timeline of both sessions is illustrated in Fig. 3.

### Data analysis

All statistical analyses were performed using R (version 4.3.3) and R studio (version 2024.9.0.37).

To assess the physiological response, linear mixed-effects models were conducted on %HF. As a preliminary step, we tested whether the cognitive task elicited a stress response under baseline conditions (i.e., comparing the resting baseline with the cognitive baseline, before exposure to any conditions). To this end, we performed a linear mixed-effects model to assess the effect of session phase (resting baseline vs. cognitive baseline). We also included environment (real vs. virtual) and session (session with LW vs. with NLW) as fixed factors to account for potential differences between the two groups (each tested in a different environment) and for intra-individual variability across the two sessions, which were conducted on different days. The model was:  $\text{c} \sim \text{lmer}(\text{physiological response} \sim \text{environment} * \text{session} * \text{phase} + (1 | \text{ID}))$ , where Participant ID was included as a random effect to account for repeated measures. In addition, different variables were included as covariates in the model: the order of sessions (defining who began with the LW vs. NLW condition) and demographic variables, such as biological sex (male, female) and age (in years). Since all participants reported not engaging in intensive physical activity before each session, only quality of sleep, caffeine intake, and smoking were added as covariates in the analysis. Then, to evaluate the full physiological response throughout the session, a second linear mixed-effects model was conducted to assess the effect of environment, condition (LW vs. NLW), all session phases (resting baseline, cognitive baseline, resting exposure, cognitive exposure), and their interaction on %HF. The model was:  $\text{c} \sim \text{lmer}(\text{physiological response} \sim \text{environment} * \text{condition} * \text{phase} + (1 | \text{ID}))$ . The same covariates of the previous model were included.

To assess the emotional state and environmental evaluation, cumulative link mixed models were conducted to evaluate the effects of the environment, condition (LW vs. NLW), and their interaction on each emotion octant and environmental evaluation score (both measured as ordinal variables). The model was:  $\text{c} \sim \text{clmm}(\text{score} \sim \text{environment} * \text{condition} + (1 | \text{ID}))$ . Given that familiarity with natural environments may influence subjective responses and the perception of natural stimuli, we included participants’ place of origin, along with demographic variables (age and sex) and order of sessions as covariates to control for their potential effects.



**Fig. 3.** Timeline of the experimental procedure for both sessions with the living wall (LW) and non-living wall (NLW) conditions. The informed consent procedure and training for the cognitive task were completed once, before the first session.

To assess performance on the backward digit span task, a generalized linear mixed-effects model was used to analyze the effects of environment, condition, phase of the session (cognitive baseline, cognitive exposure), and their interaction on the backward digit span score. The model was:  $\text{score} \sim \text{environment} * \text{condition} * \text{phase} + (1 | \text{ID})$ . The same covariates used in the physiological analysis were included.

Post-hoc tests were conducted on the marginal means of each model using the emmeans R package. In the case of multiple comparisons,  $p$ -values were adjusted using the Bonferroni correction.

## Results

Statistical analyses conducted on psychological and physiological data showed significant results, which will be described in the following sections. For the physiological analysis, four participants from the real environment group were excluded because they had missing physiological data. Regarding cognitive performance, statistical analyses did not reveal any significant effect ( $p > 0.05$ ; see Supplementary Material, Table S2 for descriptive statistics).

### Physiological response

Results from the linear mixed-effects model conducted to verify whether the cognitive task elicited a stress response under neutral conditions revealed a significant main effect of *phase* ( $F(3, 243.64) = 2.733, p = 0.04$ ). Post-hoc comparison showed that %HF was significantly lower during the cognitive baseline compared to the resting baseline ( $\beta = -4.86, SE = 2.44, z = -1.99, p = 0.04$ ). This indicates an increase in sympathetic activity during task execution. No significant effects of *environment* and *session*, nor *interactions* with these factors, were found ( $p > 0.05$ ), suggesting that the observed effect was consistent across both environments (real vs. virtual) and sessions (with LW vs. with NLW). These findings support the effectiveness of the cognitive task in eliciting a stress response (see Supplementary Material, Table S3 for descriptive statistics).

After assessing the effectiveness of the cognitive task in inducing a stress response, we analyzed %HF across all four experimental phases. The model revealed a significant *session*  $\times$  *phase* interaction on %HF values ( $F(3, 242.92) = 3.04, p = 0.03$ ), indicating that changes in physiological activity differed across experimental phases depending on the condition (LW vs. NLW). To explore the *condition*  $\times$  *phase* interaction, we first compared each phase of the session with the LW with the corresponding phase in the session with NLW (see timeline in Fig. 3). Specifically, we compared the resting and cognitive baselines of the LW and NLW sessions to verify that participants had the same level of physiological activation prior to exposure. This ensures that changes observed during the exposure phases were not driven by pre-existing differences. This assumption was supported by the results, which showed no significant differences in %HF between the LW and NLW sessions during either the resting or cognitive baseline phases ( $p > 0.05$ ). Then, we compared the resting and cognitive exposure phases across sessions to test our prediction that exposure to the LW, compared to the NLW, would reduce physiological arousal both at rest and during a cognitively demanding task. The results partially confirm our prediction: although no significant difference emerged between the two resting exposure phases ( $p > 0.05$ ), we found that participants' parasympathetic activity was significantly higher when performing the cognitively demanding task in the presence of the LW compared to the NLW ( $\beta = 7.62, SE = 3.28, t(247) = 2.32, p = 0.02$ ; Fig. 4). This

result indicates that exposure to the LW significantly reduced the physiological stress response during task performance compared to the NLW.

To provide a better understanding of the main findings, we examined physiological changes within each session separately, exploring how the physiological response evolved across the different phases (see timeline in Fig. 3). In the session with the LW, parasympathetic activity significantly increased during the resting exposure phase (i.e., 5 min of passive exposure to the LW) compared to the cognitive baseline phase ( $\beta = 8.98$ ,  $SE = 3.22$ ,  $t(242) = -2.78$ ,  $p$ -adjusted = 0.03; Fig. 4), suggesting a recovery in physiological activity following the demanding task. This effect was not observed when comparing the cognitive baseline with the resting exposure in the NLW session ( $p > 0.05$ ). Conversely, in the NLW condition, parasympathetic activity was significantly lower during the cognitive exposure phase (i.e., performing the task while looking at NLW) compared to the resting baseline phase ( $\beta = 8.65$ ,  $SE = 3.22$ ,  $t(242) = 2.68$ ,  $p$ -adjusted = 0.04; Fig. 4), indicating an increased stress response when performing the task in the presence of the NLW. These patterns suggest that, although the LW and NLW exposure phases did not differ significantly in absolute terms, exposure to the LW was associated with a physiological recovery following cognitive effort, while the NLW appeared to sustain or even exacerbate the stress response (see Supplementary Material, Table S3 for descriptive statistics). Interestingly, no *environment*  $\times$  *condition* or *environment*  $\times$  *condition*  $\times$  *phase* interactions were found ( $p > 0.05$ ), supporting our prediction that the positive physiological effects of the living wall occur independently of the type of environment (real vs. virtual).

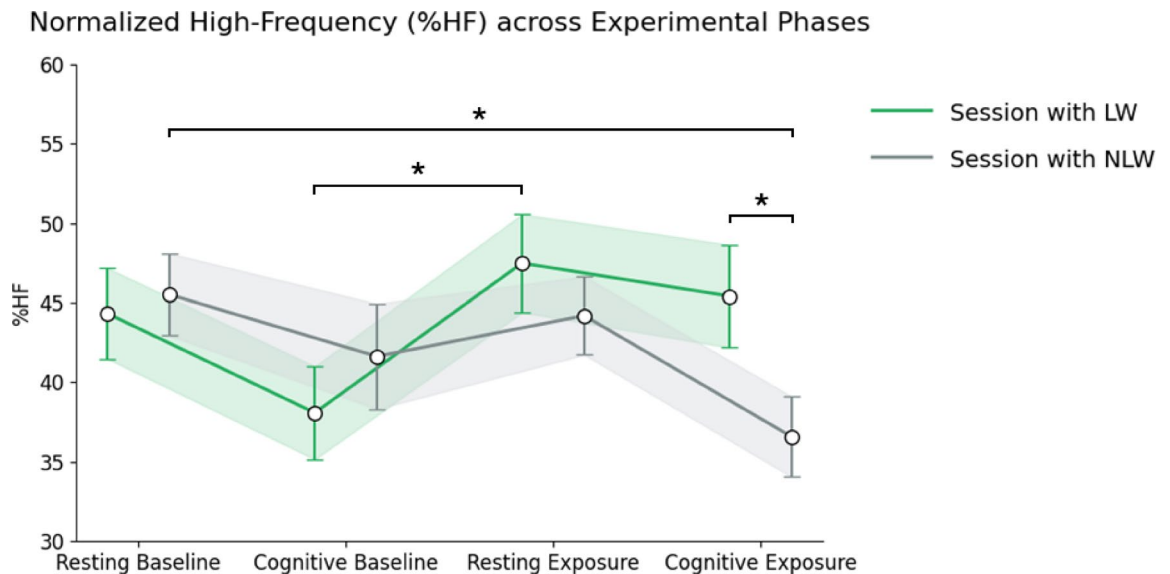
### Emotional state and environmental evaluation

For the emotional state, the model revealed an *environment*  $\times$  *condition* interaction ( $\chi^2(1) = 6.65$ ,  $p = 0.01$ ) only on the positive emotion octant (P) score.

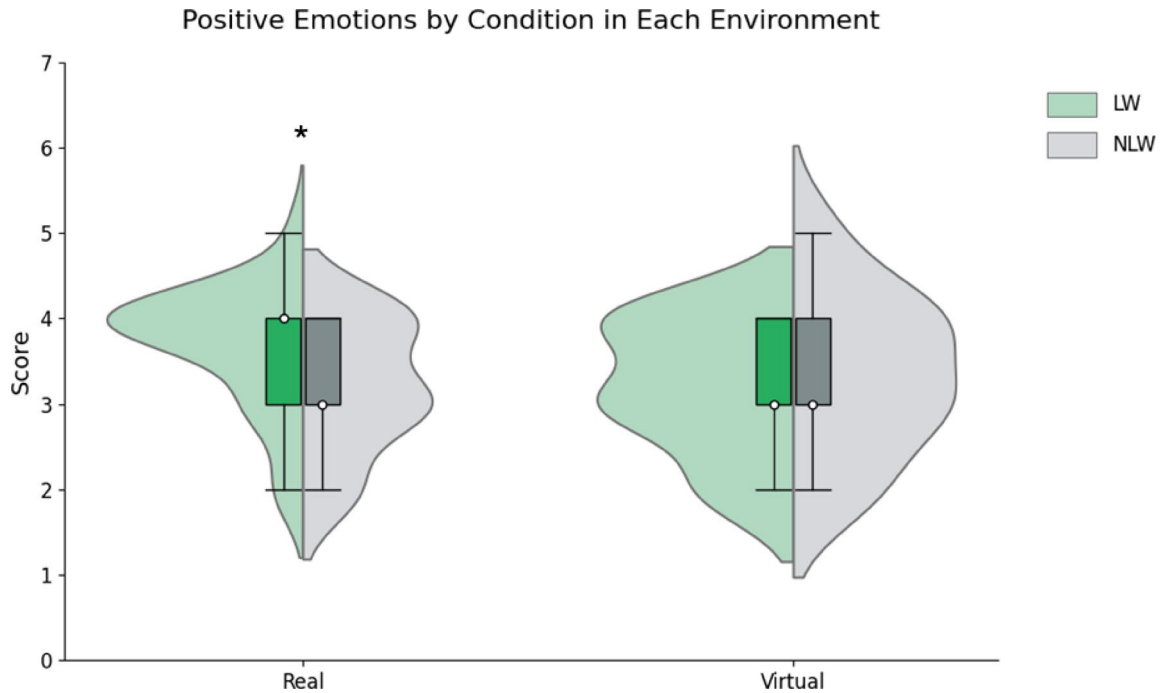
To further explore this interaction, we compared the two conditions (LW vs. NLW) within each environment (real and virtual). Additionally, we compared both the real LW and NLW with their virtual counterparts (real vs. virtual). Results confirmed that positive emotions (P) were significantly higher in the LW condition than in the NLW condition in the real environment ( $\beta = 2.73$ ,  $SE = 1.02$ ,  $z = 2.68$ ,  $p$ -adjusted = 0.04; Fig. 5). No significant differences were found in the other set of comparisons (see Supplementary Material, Table S4 for descriptive statistics). These findings did not confirm our hypothesis that both the real and virtual living walls have a positive influence on emotional responses.

For the environmental evaluation, results showed a main effect of *condition* on several evaluation adjectives independently of the environment (real vs. virtual).

Post hoc analyses comparing the two conditions (LW vs. NLW) revealed that participants evaluated the environment with the LW condition as more pleasant ( $\beta = 1.78$ ,  $SE = 0.54$ ,  $z = 3.26$ ,  $p = 0.001$ ), cheerful ( $\beta = 1.06$ ,  $SE = 0.47$ ,  $z = 2.21$ ,  $p = 0.03$ ), and with more fresh air ( $\beta = 1.23$ ,  $SE = 0.46$ ,  $z = 2.93$ ,  $p = 0.003$ ). On the other hand, participants rated the environment with the NLW as more unpleasant ( $\beta = -1.63$ ,  $SE = 0.58$ ,  $z = -2.79$ ,  $p = 0.005$ ), uncomfortable ( $\beta = -1.98$ ,  $SE = 0.63$ ,  $z = -3.14$ ,  $p = 0.002$ ), and with more stale air ( $\beta = -1.07$ ,  $SE = 0.54$ ,  $z = -2.38$ ,  $p = 0.02$ ; Fig. 6; see Supplementary Material, Table S5 for descriptive statistics). Results from these comparisons



**Fig. 4.** Physiological response. Line graph showing changes in normalized high-frequency (%HF) of heart rate variability (HRV) across the experimental phases (resting baseline, cognitive baseline, resting exposure, and cognitive exposure) of both sessions with the living wall (LW) and non-living wall (NLW) conditions, independently of the environment (real vs. virtual). White circles represent mean %HF values, while error bars and shaded areas around the line indicate the standard error of the mean (SEM). \* $p < 0.05$ , based on post hoc pairwise comparisons of estimated marginal means derived from the linear mixed-effects model. Significance reflects differences in the predicted means, after adjusting for covariates.



**Fig. 5.** Emotional state. Violin plots with embedded box plots showing scores for the positive emotion octant across living wall (LW) and non-living wall (NLW) conditions in both real and virtual environments. The width of each violin reflects the kernel density estimation of the data distribution. Box plots within violins represent the interquartile range, and white circles indicate medians. \*  $p < 0.05$ , based on post hoc pairwise comparisons of estimated marginal means derived from cumulative link mixed models. Significance refers to differences in the ordinal response distribution after adjusting for covariates.

confirmed our prediction that both real and virtual living walls enhanced the subjective evaluation of the indoor environment.

#### VR experience quality control

Wilcoxon signed-rank tests conducted on IPQ scores revealed no significant differences ( $p > 0.05$ ) between the two sessions in any of the three subscales (spatial presence, involvement, and experienced realism), nor in the general “sense of being there” item (with LW and NLW; see Supplementary Material, Table S6 for descriptive statistics). These results suggest that participants experienced a similar sense of presence in the virtual environment in both the LW and NLW sessions.

#### Discussion

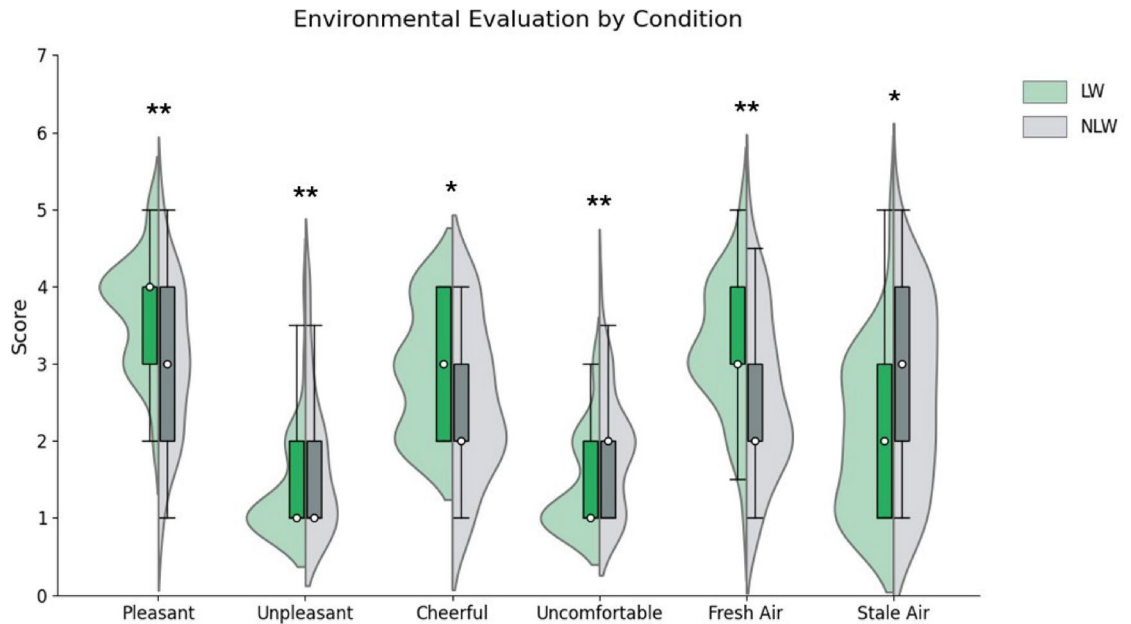
In this study, we investigated whether brief exposure to a real and virtual medium-sized Living Wall (LW) could reduce stress during engagement in a cognitively demanding task, and whether there was comparability between the effects of real and virtual exposure.

Our findings show that exposure to the LW reduces physiological arousal during cognitive performance. Participants exhibited a significantly greater parasympathetic response—as indicated by increased high-frequency (HF) heart rate variability—when completing the task in the presence of the LW compared to the non-living wall (NLW) condition (i.e., the shelf filled with office objects). This suggests that biophilic exposure can enhance parasympathetic activity (relaxation response), even under cognitively demanding conditions.

In addition, during the LW session, the 5-min passive viewing of the LW elicited an increase in parasympathetic activity, indicative of a restorative physiological effect. In contrast, in the NLW session, passive viewing did not produce a comparable effect, and a significant reduction in %HF was observed during the final task phase relative to baseline. This suggests that participants concluded the session in a more physiologically aroused—or stressed—state.

Taken together, these results indicate that biophilic exposure can facilitate not only physiological recovery after cognitive effort but also autonomic regulation during cognitively demanding tasks. The ability of the LW to maintain a more balanced autonomic state, even in the face of high cognitive demands, highlights its potential to reduce task-related stress.

Results in the physiological response support the SRT<sup>18</sup>, which proposes that being exposed to non-threatening natural stimuli reduces stress and physiological arousal. This mechanism stems from our evolutionary heritage as a species and our inherent link to the natural world. For instance, physiological recovery—as measured by a decrease in skin conductance—was found to occur more effectively when participants viewed natural rather than urban environment scenes following a stressor<sup>18</sup>. Similarly, higher parasympathetic activity during recovery



**Fig. 6.** Environmental evaluation. Violin plots with embedded box plots showing scores for the environmental adjectives pleasant, unpleasant, cheerful, uncomfortable, fresh air, and stale air across living wall (LW) and non-living wall (NLW) conditions, independently from the environment (real vs. virtual). The width of each violin reflects the kernel density estimation of the data distribution. Box plots within violins represent the interquartile range, and white circles indicate medians. \*  $p < 0.05$ , \*\*  $p < 0.01$ , based on post hoc pairwise comparisons of estimated marginal means derived from cumulative link mixed models. Significance refers to differences in the ordinal response distribution after adjusting for covariates.

was observed when viewing natural scenes compared to built environments<sup>37</sup>. Participants exposed to virtual biophilic environments after stress-induction tasks also showed greater decreases in blood pressure compared to those in virtual non-biophilic environments<sup>36</sup>.

Our findings extend this framework by demonstrating that exposure to natural elements not only aids in recovery from stress but may also prevent or mitigate its onset during cognitive performance, effectively buffering its impact. Notably, this buffering effect was observed regardless of whether the environment was real or virtual, confirming our second prediction that a virtual simulation of the LW can reproduce similar beneficial effects on participants' physiological states. This result supports the potential of VR as a viable alternative in environments where real greenery is not feasible and extends previous research on stress recovery at rest in virtual biophilic environments<sup>36</sup>.

Cognitive performance data were analyzed to determine whether the positive physiological response during the task with the LW could be associated with improved task performance. According to ART<sup>19</sup>, exposure to nature can enhance cognitive functioning by replenishing cognitive resources. However, our analysis revealed that cognitive performance remained unaltered between the two LW/NLW conditions. This suggests that a brief exposure to real or virtual vegetation allowed participants to cope with a demanding task with lower stress while maintaining the same level of performance.

To gain a comprehensive understanding of the overall benefits of this biophilic design intervention, we also investigated whether these advantages extended to participants' emotional state and environmental perception. Our results show that the presence of a LW positively influenced both emotional responses and environmental evaluations. Specifically, participants reported higher positive emotions in the LW compared to the NLW condition, but only in the real environment. No difference was observed in the virtual condition.

This result is consistent with previous findings in the literature. For example, previous research<sup>14</sup> reported an increase in positive emotions in a biophilic condition only when the environment was real, with no significant difference between biophilic and non-biophilic conditions in VR. This discrepancy could be related to the quality of experience participants had in the virtual environment. Indeed, based on the IPQ results of our study, only spatial presence reached moderately high levels in both conditions, while the score to the general item, as well as the experienced realism and involvement subscales, ranged from low to moderately low (see Supplementary Material, Table S6). This suggests that, in the emotional domain, exposure to real nature may have a stronger impact than virtual simulations. This result could be explained by the fact that the low sense of realism and engagement in the VR environment reduces the emotional benefits typically associated with biophilic exposure<sup>38</sup>.

Ultimately, the participants rated the environment with the LW more favorably, both in the real and the virtual environment. To our knowledge, this is the first study that directly compares environmental evaluations across real and virtual biophilic settings, as previous research on the perception of these environments has been conducted exclusively in real-world settings<sup>9,10,39</sup>. This comparison provides new insights. Indeed, we found that

the presence of the LW not only enhanced aesthetic perceptions (e.g., pleasantness, comfort, and cheerfulness) but also influenced participants' evaluation of the physical characteristics of the indoor space, such as perceived ventilation. Although the experimental room was the same in biophilic and non-biophilic sessions, participants rated the same room as better ventilated and less stuffy in the presence of the LW. This effect occurred regardless of the type of environment (real or virtual), suggesting that the presence of natural elements can influence subjective perceptions of an indoor space's qualities beyond visual aesthetics.

Taken together, these findings demonstrate the potential of biophilic design interventions to promote well-being and enhance the experience of indoor spaces. Although the present study focused on short-term exposure, these findings have important implications for highly demanding real-world contexts where people spend long periods of time, such as workplaces, schools, and healthcare facilities. Future research should investigate whether the stress-buffering effects associated with biophilic elements persist or even accumulate over longer timeframes, such as a full workday. Addressing this question would strengthen the ecological validity of our results and help inform the design of indoor environments that could benefit most from biophilic interventions.

### Limitations

This study has some limitations that could be addressed in future investigations. First, technical issues with physiological registration reduced the sample size available for physiological analyses. Second, the study design did not adequately control for potential external environmental factors (e.g., outdoor noise and light) that could have influenced participants' responses. However, evenly distributing these factors across conditions would enhance the study's ecological validity by better reflecting real-world conditions. Third, the lack of a baseline emotional assessment at the beginning of each session did not allow us to determine the emotional changes linked to each environmental condition more reliably. In addition, the within-subject design may have introduced order or carry-over effects. Specifically, participants' responses during the task with the LW/NLW could have been influenced by the preceding passive exposure. Adopting a between-subjects design or a two-session protocol in which each session begins with a cognitively demanding task and is followed by either passive or task-based exposure would allow overcoming this issue. A further limitation is the absence of a control condition featuring an empty space. Including this condition, in addition to a non-biophilic one, would help to more reliably assess the specific effects of biophilic exposure.

Despite these limitations, significant psychophysiological effects were observed. Future investigations should consider the aforementioned issues and recommendations to validate and strengthen the findings of the present study.

### Conclusions

The results of the present study demonstrate the positive effects of a brief exposure to a living wall on physiological and psychological well-being and support classical theories that emphasize the beneficial effects of contact with nature (i.e., Biophilia Hypothesis and Stress Recovery Theory). A key implication of our findings is that biophilic design elements, including virtual reality reproductions, can effectively enhance physiological relaxation during cognitively demanding tasks. This is of practical relevance for workplace and educational settings, where integrating living walls or virtual nature elements could help mitigate stress without influencing cognitive performance. They are also relevant for the design of effective nature-based interventions—whether in real-world or virtual reality—targeted at individuals with attentional<sup>40–43</sup> or mood<sup>4</sup> disorders.

Finally, the ease of implementing this kind of biophilic intervention makes them particularly suitable for healthcare facilities, where their stress-reducing effects could benefit individuals experiencing temporary or permanent confinement due to illness or aging.

### Data availability

The data analyzed in this study are available from the corresponding authors upon reasonable request.

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### Author contributions

H. S. contributed to the study design, conducted the data collection and analyses, and wrote the manuscript. C. Z. contributed to the study design, developed the virtual environment, conducted the data collection, and assisted with data analysis and manuscript revision. M. E. and P. F. supported project coordination and reviewed the manuscript. D. A. contributed to data collection. E. C. and R. G. contributed to the methodological framework and manuscript revision. L. C. and V. S. contributed to supervision and funding acquisition. R. R. supervised the project and contributed to the study design, manuscript writing, and funding acquisition.

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### Declarations

#### Competing interests

M. E., L. C., V. S., and R. R. applied for a patent (Italian patent application 102022000023421) for the living wall. M. E. and P. F. are employees of Blue Engineering. The other authors declare no competing interests.

#### Additional information

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