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Effects of biophilic interventions in office on stress reaction and cognitive function: A randomized crossover study in virtual reality

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Abstract
Biophilia hypothesis suggests humans have an innate connection to nature which may affect our health and productivity. Yet we currently live in a world that is rapidly urbanizing with people spending most of their time indoors. We designed a randomized crossover study to let 30 participants experience three versions of biophilic design in simulated open and enclosed office spaces in virtual reality (VR). Throughout the VR session, we measured blood pressure, heart rate, heart rate variability, and skin conductance level and administered cognitive tests to measure their reaction time and creativity. Compared to the base case, participants in three spaces with biophilic elements had consistently lower level of physiological stress indicators and higher creativity scores. In addition, we captured the variation in the intensity of virtual exposure to biophilic elements by using eye-tracking technology. These results suggest that biophilic interventions could help reduce stress and improve creativity. Moreover, those effects are related to both the types of biophilic elements and may be different based on the workspace type (open vs enclosed). This research demonstrates that VR-simulated office spaces are useful in differentiating responses to two configurations and among biophilic elements.

KEYWORDS
biomonitoring sensors, biophilic design, eye-tracking, human responses, virtual reality, workspace

1 | INTRODUCTION

Indoor environmental quality (IEQ) plays an essential role in affecting productivity, health, and well-being.[1] Those effects may be particularly prominent in workplaces, where full-time workers spend approximately one-third of their day, 5 d/wk.[2] Evidence from public health and building sciences have demonstrated that environmental elements, including indoor air quality, ventilation, thermal health, water quality, moisture, safety and security, lighting and views, noise, dust and pests, are foundational to human health.[3] Beyond looking at indoor exposures which lead to adverse health effects, researchers have also discussed, although less frequently, how optimizing indoor environment and building design could promote cognitive function, productivity, health, and well-being.[4-7]

Bringing natural elements indoors (ie, biophilic design) has received increasing attention recently due to its potential health benefits.[8,9] It stems from the concept of *biophilia*, which literally means "love of life and living systems," which was popularized by Edward O. Wilson in 1984.[10] He and Stephen R. Kellert proposed the biophilic hypothesis in 1993, suggesting that human beings' innate connection with nature is essential for their well-being.[11] Nowadays, our accessibility to natural environments is decreasing since we live in a world that is rapidly urbanizing with people spending majority of their time indoors.[12] As a response, biophilic design works to enhance the individual connection with nature by incorporating natural features into built environments where we live and work.[13,14] Efforts to promote the biophilic design in practice include identifying design attributes and categorizing them into three domains (ie, nature in the spaces, natural analogues, and nature of the space) and 14 patterns, prioritizing the most prominent nature-health relationships in the built environment.[13,15]

A significant body of existing research has shown the health benefits derive from contact with or emersion in nature occurring outdoors.[16-20] Less is known about possible health and well-being benefits of encountering nature indoors.[21] What evidence exists is mainly focused on the benefits of "nature in the space," including natural views from window, indoor plants, and natural light. Specifically, viewing nature through a window had effects for patients on reducing recovery time and reliance on pain medication[22-24] and helped students recover from mental fatigue and stress.[25] Indoor plants could provide psychological benefits such as stress reduction, increased pain tolerance, and restoration of attention capacity.[26,27] Natural light has known benefits for circadian rhythm and sleep quality, and it could also increase feeling of vitality, activity patterns, and quality of life.[28,29] In addition to indoor plants and natural light, materials and patterns mimicking nature, which were termed as "natural analogues," are also at the core of biophilic design. However, there are few studies examining their health benefits, most of which focused on wooden materials. The use of interior wooden materials has been found to have effects on reducing autonomic stress responses, tension and fatigue, increasing positive emotions and comfortability.[30-32] In addition to virtual exposure, haptic exposure such as touching wood has been found to have the effect on inducing physiological relaxation.[33] Lastly, natural forms and organizations in architecture were thought valuable for human emotional and cognitive function, but little empirical evidence has been provided.[34]

These initial investigations have their limitations. First, the environmental exposure had often been based on a simplistic "nature/green" versus "built/lean" dichotomy.[35] Unresolved is how specific natural elements affect occupants' health and well-being. Second, little is known about whether natural elements would have similar effects in different workspaces. Studies have shown that open spaces are usually beneficial for collaborative works, while enclosed spaces are more conducive to activities that require focus with fewer distractions.[36] A recent review pointed out that research on nature and health conducted to date fails to capture variations in how people experience nature and does not quantify the level of immersion or exposure while in a space with biophilic elements.[37] Lastly, most of the studies used self-reported measures of health and well-being, which may introduce response bias.

Emerging technologies have the potential to address some limitations of previous studies. Virtual reality (VR) allows systematic manipulations of indoor environment that could not effectively be implemented in the real world.[38] It could provide more immersive experiences of different natural environments than video, photograph, and sketches under controlled laboratory circumstances. Several studies found that exposure to virtual environments in VR may have similar effects comparing to those in real environments.[38-41] Virtual display of natural environments in various settings (eg, forest, urban green space, streetscapes, biophilic indoor space) had been used to detect the effects on stress reduction, attention restoration, and cognitive function.[41-44] Eye-tracking, combined with VR, provides a unique opportunity to measure people's visual attention to specific elements in a simulated virtual environment by calculating the amount of time individual focuses on specific objects. Wearable biomonitoring sensors combined with a VR experience monitor a participant's physiological responses, such as heart rate variability and skin conductance level, over the course of the experiment.

Combining VR, eye-tracking, and wearable biomonitoring sensors, we designed a Biophilic Interventions in Office (BIO) study examining participants' responses to different biophilic designs (ie, *natural elements*, *natural analogues*, and combination of both, referred to as "*combination*") across two types of workspaces (ie, open space vs enclosed space). In addition to physiological measurements of stress reaction, we included cognitive assessments of creativity and attention.

Practical Implications

- VR simulated office spaces are useful in differentiating responses to two configurations and among biophilic elements.
- Combining virtual reality, eye-tracking and wearable bio-monitoring sensors is a new empirical research tool to quantify the human responses to virtual biophilic environments, which could be used for preoccupancy evaluation.
- Findings of this study benefit architects, designers and office managers to understand how biophilic office design affects occupants' health and performance.

2 | METHODS

2.1 | Study population

The BIO study enrolled 30 participants through email invitations and posted flyers, representing a convenience sample of students and staff from the Harvard TH Chan School of Public Health. Recruited between May and September in 2018, they were invited to visit the VR laboratory on two occasions (the same time of day and the same day of week). Exclusion criteria included taking medicine or stress treatment, use of tobacco or alcohol within 24 hours prior to the experiment, and participation in intensive exercise within 6 hours prior to the experiment. The study protocol was reviewed and approved by the Institutional Review Board of Harvard TH Chan School of

FIGURE 1 Simulated virtual environments in enclosed spaces (E1~E4) and open spaces (O1~O4). Note [a]Biophilic intervention that incorporates green plants and natural light into office. [b]Biophilic intervention that incorporates biomorphic patterns and natural materials into office. [c]Biophilic intervention that incorporates biophilic elements from both "natural elements" and "natural analogues" interventions

Public Health. All participants provided informed consent and were compensated with $40.

2.2 | Study design

We used randomized crossover design for this study, in which participants acted as their own control and their physiological and cognitive responses were measured repeatedly, with the purpose of controlling for potential time-invariant confounding factors and increasing statistical power (Figure 2). All participants visited the VR laboratory twice to experience both open and enclosed spaces in a randomize order, one space at a time. During each visit, they were exposed to four different virtual environments, with the order randomized.

2.3 | Environment simulation and eye-tracking

Choosing four patterns out of the 14 patterns of biophilic design,[15] we simulated four types of indoor environment, including three natural (biophilic) conditions and one non-biophilic environment as control, in two workspace types (open and enclosed) based on real spaces from an architectural design and consulting firm (Figure 1). We combined patterns of "visual connection with nature" and "dynamic & diffuse light" to represent *natural elements* since these two patterns always come together in design practice, which included green plants and access to natural light and view. Similarly, we combined patterns of "biomorphic forms & patterns" and "material connection with nature" to represent *natural analogues*, which included products that were made of or looked like natural materials and furniture with biomorphic shapes. The rationales for choosing these four biophilic patterns were as follows: (a) They were relevant to office design and indoor spaces; (b) they could be simulated in virtual reality; and (c) they were conducive to brief exposure time. Further, our experiment included two common configurations: open and enclosed office spaces. The indoor scenes were modeled by using Rhino5 software in advance and rendered in real time during experiment by Unity software (version 2017.1.0f3).

To better understand the intensity of virtual exposure to biophilic elements, we incorporated eye-tracking device, Tobii Pro VR Integration with HTC Vive (Tobii Technology Inc), to record participants' foveal attention during the exposure period. Biophilic elements in the virtual environment were pre-labeled, and gaze intersection point data were used to annotate object in view at each time. Two eye-tracking parameters, saccades and fixations, were separated through a velocity-based algorithm marking any movement slower than 100 degrees per second (deg/s) as fixation

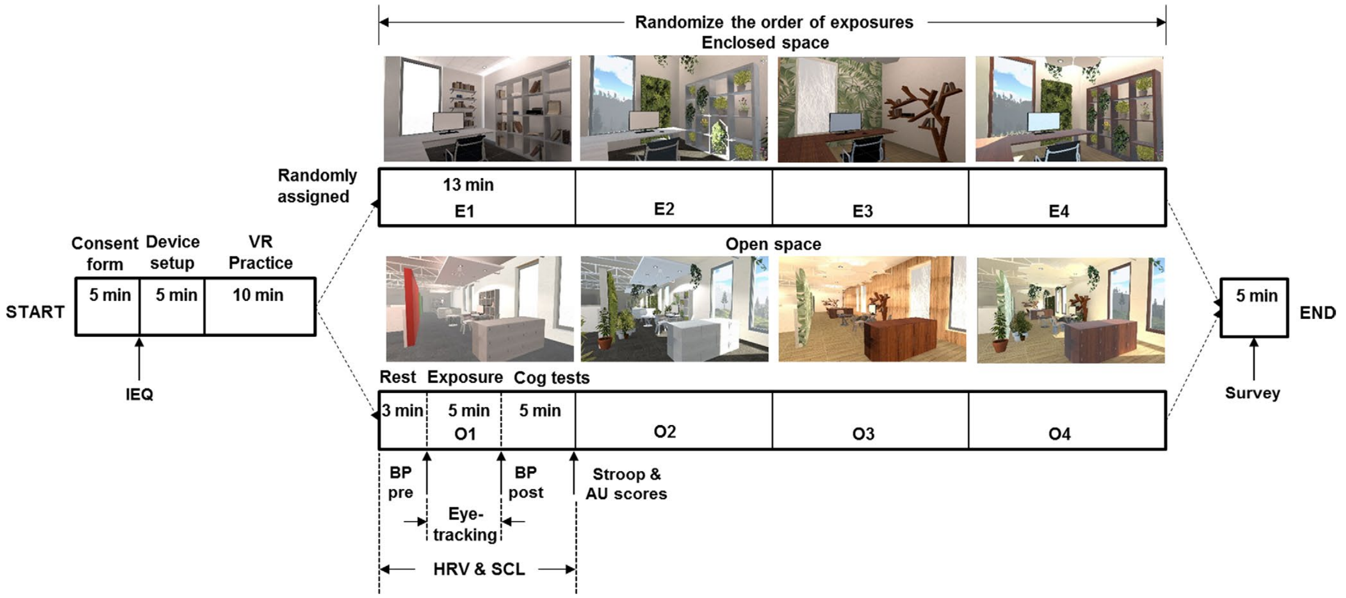

FIGURE 2 Timeline of experimental procedure and sampling (one visit)

and movements faster than 300 deg/s as saccades.[45] Velocity of eye movement was calculated using the two-dimensional position of pupil in the tracking coordinates, and then translated into angle change and divided by time from previous data point. This was calculated separately for each eye and then averaged.[46] Only fixations were used to calculate the intensity of exposure to each object in the virtual biophilic environments.

2.4 | Physiological indicators of stress reaction

Blood pressure (BP), heart rate (HR), heart rate variability (HRV), and skin conductance level (SCL) were measured by wearable biomonitoring sensors as physiological indicators to acute stress reaction. Specifically, the Omron EVOLV blood pressure monitor was attached to the left upper arm of each participant to measure systolic and diastolic blood pressure (Omron Healthcare Inc). We conducted momentary measures of blood pressure before and after exposing to each virtual environment. HR, HRV, and SCL were measured continuously during the experiment.

Heart rate variability describes a dynamic interplay between the parasympathetic and sympathetic branches of the autonomic nervous system (ANS), which is associated with physiological stress response.[47] We chose the root mean square of successive differences between normal heartbeats (RMSSD) as the indicator of the short-term HRV because it reflects parasympathetic activity which is related to the stress relief and it is reliable for short-term measure (ie, five minutes or less).[48] The Movisens EcgMove3 (Movisens GmbH) was worn on a chest belt underneath clothes to collect the electrocardiogram (ECG) data from each participant. The DataAnalyzer software (Movisens GmbH) was used to convert the ECG signals into time-series HR (1/min) and RMSSD (milliseconds [ms]). All HRV calculations were performed internally every 30 seconds, which is the minimal time interval to calculate HRV of this sensor.

Skin conductance level measures the electrodermal activity in the sweat glands under the sensor, which is controlled by the autonomic nervous system.[49] It is a widely used indicator for measuring physiological stress related to exposure to the natural environment.[25,41,43,50] The electrodermal activity sensor, Movisens EdaMove3 (Movisens GmbH), was attached on the left wrist to collect the skin conductance level (μS) of each participant. The continuous SCL measure was also averaged every 30 seconds.

2.5 | Cognitive function measures

Thinking is characterized by divergent and convergent cognitive processes. Convergent tasks are mostly related with intelligence and could be divided into subcategories of attentional and data processing tasks, while divergent tasks are related to creativity. Since attention restoration is one of the proposed mechanisms for explaining the psychological benefits of exposure to natural environments on humans,[51] our previous study has assessed the effect of indoor biophilic environment on attention, which is a key part of convergent thinking.[41] However, divergent tasks add more complexity to the cognitive assessment of the effects of biophilic environments on humans and perhaps associate different features as more of a facilitator in either of these two categories of cognitive tasks. It has been proposed that VR has the potential to facilitate the assessment of cognitive performance beyond what is currently possible by using traditional methods.[52]

In this study, participants' selective attention related cognitive function was measured by Stroop color-word test (Stroop test) and their creativity related cognitive function was measured by Guilford's Alternative Uses test (AU test). The Stroop test included 48 trials of congruent and incongruent word-color stimuli, with the order randomized. Participant was expected to identify the color of the displayed word and click 1 of 4 buttons (ie, R: red; B: blue; Y: yellow;

G: green) accordingly.[53] Reaction time for each individual trial was measured as the performance metric. AU test is a widely used and validated test for evaluation of creativity.[54] This test measures creativity by asking participants to list as many unconventional possible uses for a common everyday object. In this experiment, we included eight items, including newspaper, cup, umbrella, match, brick, plastic bottle, tire, and pen. Aggregated answers for those questions were evaluated independently by two judges based on fluency (ie, the number of interpretable, meaningful, and relevant responses), flexibility (ie, the number of different categories implied by responses), and originality (ie, measured by the statistical rarity of the responses in a given sample).[54,55]

2.6 | Experimental procedure

The indoor environmental conditions of the VR laboratory were kept consistent throughout all visits. The IEQ indicators, including temperature, relative humidity, and $PM_{2.5}$ concentrations, were measured by real-time sensor package. Noise disturbance was kept to a minimum by closing the door of the laboratory.

At the beginning of the experiment, we introduced the experimental procedure and let participants read and sign the consent form. After that, we set up the devices (ie, VR headset and biomonitoring sensors) and provided general instructions on safety and navigation in VR environment. During this period, participants were given 10 minutes to get familiar with the VR experience and the approach to perform cognitive tests in VR. They spent the recommended first seven minutes to get used to VR as a novel stimulus and the rest three minutes for eye tracker calibration. Afterward, participants were randomly assigned to view four virtual environments (E1, E2, E3, and E4 or O1, O2, O3, and O4) under one workspace type (enclosed or open) (Figure 1).

In each environment, they started with a 3-minute rest while seated with only the default gray background environment showing in VR. This period allowed their physiological conditions to stabilize, during which their baseline physiological status including BP, HR, HRV, and SCL was collected. Following the period of rest, participants were virtually exposed to the indoor office environment for five minutes, which has been shown in previous research to be a sufficient period of time for changing acute physiological stress level.[41,56,57] They could walk and observe the surrounding environment freely in this period, during which we collected their gaze data by using eye-tracking device. After that, they remained in this virtual environment and took a 5-minute cognitive test by using a virtual desktop in VR (Figure S1). After experiencing those four environments, they completed a 5-minute online survey about their background information, including demographics (only for the first visit), general health condition (excellent, very good, good, fair, or poor), and stress level (Likert scales from 1 to 5, with 1 being very little stress and 5 being extreme stress.), caffeinated beverage drinking (yes/no), and good sleep quality of the night before (yes/no). In addition, they also reported how much they feel the connection with nature in the four conditions they experienced with the Likert scales from 1 to 10 and ranked the four biophilic patterns ("visual connection with nature," "dynamic & diffuse light," "biomorphic forms & patterns," and "material connection with nature") in order of their preferences. The whole experiment took around 80 minutes per visit (Figure 2). In the second visit, participants repeated this procedure and experienced the remaining workspace.

2.7 | Statistical analyses

For physiological measures (BP, HR, HRV, and SCL), the pre-post-exposure changes were used as outcome variables after considering the different baseline measures among four virtual exposures in each visit. Since the HR, HRV, and SCL data were collected continuously and skewed, we used the median of HR, HRV, and SCL during exposure periods versus those during rest periods to calculate the pre-post changes. We conducted two-way ANOVA with repeated measures on physiological data during all rest periods to test whether there were order effects of four virtual exposures in two workspaces after randomization.

For cognitive outcomes (creativity and reaction time) which did not have baseline measures, we incorporated between-visit covariates, including caffeinated beverage drinking, sleep quality before the experiment day, and the self-reported stress level before experiment given their potential impacts on cognitive performance.[58] We found the IEQ indicators (ie, temperature, relative humidity, and $PM_{2.5}$) were stable by running paired t test. Therefore, we did not add those indicators into the regression model to avoid potential overfitting issue. Since the reaction time data were right-skewed, we log-transformed them. In addition, we normalized the scores from AU test by using Z-scores to adjust the different difficulties among eight questions in AU tests.

Generalized additive mixed-effect models (GAMM) (R package "gamm4," version 0.2-5) were used to analyze the associations between biophilic interventions and physiological and cognitive outcomes while controlling for the correlated nature of the repeated measures from the same participant (Models 1~3).[59] Participant was treated as a random intercept to control for variability across individuals. Four virtual environments in each workspace had been categorized with the non-biophilic environments used as the reference group. Each biophilic intervention was examined in model to obtain beta estimate and 95% confidence interval for each outcome measure, and a two-sided alpha level of .05 was used to determine statistical significance.

For physiological data (BP, HR, RMSSD, SCL),

$$\Delta Y_{ij} = \beta_0 + \beta_{1\sim3}\text{environment} + \beta_4\text{workspace} + e_{ij} + \mu_i \quad (1)$$

where ΔY_{ij} = the average pre-post changes of physiological measures for participant *i* at visit *j;* environment = 1 if participant was in non-biophilic environment, 2 in the *natural elements* condition, 3 in the *natural analogues* condition, and 4 in the *combination* condition; workspace = 1 if participant was in open spaces and 0 in enclosed spaces; $\beta_{1\sim3}$ = fixed effects of specific biophilic environment

TABLE 1 Characteristics of study population (n = 30) and indoor environmental quality, baseline physiological measures, and other characteristics of visits (n = 60)

Category	Mean ± SD or n (%)
Demographics of the 30 participants	—
Gender	—
Male	8 (26.7)
Female	22 (73.3)
Age	26.3 ± 5.1
18-20	5 (16.7)
21-30	20 (66.6)
31-40	5 (16.7)
Ethnicity	—
White/Caucasian	15 (50.0)
Asian	10 (33.3)
Latino	3 (10.0)
Multiracial	2 (6.7)
Occupation	—
Student	23 (76.7)
Staff	7 (23.3)
Area they were raised	—
Urban	15 (50)
Suburban	11 (26.7)
Rural	4 (13.3)
General self-reported health condition	—
Excellent	6 (20.0)
Very good	17 (56.7)
Good	7 (23.3)
Characteristics from the 60 visits	—
Indoor Environmental Quality	—
Temperature (F°)	74.7 ± 1.5
Relative humidity (%)	41.8 ± 10.0
$PM_{2.5}$ (μg/m^3)	5.8 ± 5.4
Caffeinated beverage drinking	—
Yes	17 (28.3)
No	43 (71.7)
Good sleep quality	—
Yes	50 (83.3)
No	10 (16.7)
Self-reported stress level	—
1 (Lowest)	16 (26.7)
2	20 (33.3)
3	19 (31.7)
4	5 (8.3)
5 (Highest)	0 (0)
Average baseline physiological measures	—
Systolic blood pressure (mm Hg)	107.8 ± 9.2
Diastolic blood pressure (mm Hg)	69.9 ± 8.5
Heart rate (1/min)	71.4 ± 11.2
RMSSD (ms)	47.9 ± 26.5
Skin conductance level (μS)	5.7 ± 3.8
Self-reported connection with nature in the environment (score: 0 ~ 10)	
Natural elements	8.3 ± 1.2
Natural analogues	4.7 ± 1.7
Combination	8.4 ± 1.4

(Continues)

TABLE 1 (Continued)

Abbreviations: —, no data; RMSSD, root mean square of successive differences of beat intervals; SD, standard deviation.

compared to the non-biophilic environment; β_4 = fixed effect of open spaces compared to the enclosed spaces; μ_i = random effect of intercept for participant *i*.

For reaction time (Stroop test),

$$\log Y_{ij} = \beta_0 + \beta_{1\sim3}\text{environment} + \beta_4\text{workspace} + \beta_5\text{incongruence} + \beta_6\text{testnumber} + \beta_7\text{coffee} + \beta_8\text{sleep} + \beta_9\text{genstress} + e_{ij} + \mu_i \quad (2)$$

$\log Y_{ij}$ = reaction time for participant *i* at trial *j* in *log* scale; incongruence = 1 if words presented in different color and 0 if congruently colored words; testnumber = the number of times participant was tested (1~8); coffee = 1 if had caffeinated beverages before experiment, and 0 otherwise; sleep = 1 if had a nice sleep, and 0 otherwise; genstress = self-reported stress level, which has a range from 1 (very little stress) to 5 (extreme stressful); β_5 = mean difference of reaction time between congruent test and incongruent test (ie, Stroop effect) in *log* scale; β_6 = learning effect; $\beta_{7\sim9}$ = fixed effect of caffeinated beverages drinking, sleep quality, and general stress level; environment, workspace, $\beta_{1\sim4}$, and μ_i have the same meanings as those in Model (1).

For standardized creativity score (AU test),

$$Y_{ij} = \beta_0 + \beta_{1\sim3}\text{environment} + \beta_4\text{workspace} + \beta_5\text{testnumber} + \beta_6\text{coffee} + \beta_7\text{sleep} + \beta_8\text{genstress} + e_{ij} + \mu_i \quad (3)$$

Y_{ij} = standardized Z-score of AU test for participant *i* at test *j*; environment, workspace, $\beta_{1\sim4}$, and μ_i have the same meanings as those in Model (2), and $\beta_{5\sim8}$ have the same meanings as $\beta_{6\sim9}$ in Model (2), respectively.

The gaze data collected from eye-tracking device during the exposure period were used to calculate the percentage of time participants spent on looking at biophilic elements (ie, intensity of virtual biophilic exposure). We calculated the mean intensity of virtual biophilic exposure with standard deviation in three biophilic conditions to capture the variation of how participants experience their surrounding biophilic elements. Additionally, we combined summarized gaze data with demographic data for each participant to explore the differences of perception in gender (female vs male) and where participants were raised (urban vs rural area). Analyses were performed by using the open-source statistical package R (v.3.5.1).[60]

3 | RESULTS

3.1 | Demographics and baseline measures

Demographics of the 30 study participants and characteristics of the 60 visits are presented in Table 1. The participants had an average age of 26.3 ± 5.1 years, most of whom were graduate students with good health condition. Over two-thirds of participants were female, and half of the participants were Caucasian. The VR laboratory is in a mechanical ventilated office building, and overall IEQ was consistent during the experimental period. In approximately one-fourth of the visits, participants reported that they had caffeinated beverage before the experiment. 83.3% of participants reported they had good sleep quality before the experiment.

There were no statistically significant differences among the four pre-exposure (baseline) conditions for BP, HR, RMSSD, and SCL in both enclosed space and open space (all $P > .05$) (Table S1). This suggests that there were no order effects of these four types of exposure in the protocol on physiological responses. The subsequent changes of physiological measures are likely attributed to the different virtual exposures.

3.2 | Stress reactions

The overall effects of biophilic interventions (after adjusting for types of workspace) and their separated effects in enclosed and open workspaces on physiological indicators of stress compared to those in the non-biophilic environments are shown in Table 2. The biophilic interventions had significant overall effects on reducing both systolic and diastolic blood pressure (SBP and DBP). Specifically, the *natural elements*, *natural analogues*, and *combination* conditions were associated with 1.8 (95% CI: 0.0, 3.5), 2.2 (95% CI: 0.5, 4.0), and 2.0 (95% CI: 0.3, 3.8) mm Hg more SBP decreases and 2.8 (95% CI: 1.2, 4.4), 2.3 (95% CI: 0.75, 3.92), and 2.7 (95% CI: 1.1, 4.3) mm Hg more DBP decreases, compared to those changes in non-biophilic environments. Patterns of associations between different biophilic interventions and pre-post changes of SBP and DBP were consistent in both workspace types. Particularly, those associations were stronger in open spaces and all statistically significant, with effect estimates of 3.2 (95% CI: 0.9, 5.6), 2.7 (95% CI: 0.3, 5.0), and 2.4 (95% CI: 0.0, 4.8) mm Hg more SBP decreases and 4.1 (95% CI: 0.4, 5.1), 3.3 (95% CI: 1.3, 5.2), and 2.6 (95% CI: 0.7, 4.6) mm Hg more DBP decreases in the *natural elements*, *natural analogues*, and *comboination* conditions, respectively.

Biophilic interventions were consistently associated with more decreasing heart rate. This association was significant in the *natural elements* condition, with 1.63 (95% CI: 0.07, 3.18) beats per minute more decrease of HR. Similar to the effect differences of SBP and DBP, biophilic environments had larger effect in open spaces versus enclosed space on reducing HR, with significant decreases of HR in the *nature elements* (1.6 (95% CI: 0.1, 3.2)) and *natural analogues* conditions (1.5 (95% CI: 0.0, 3.1)).

We observed a discrepancy in the effects of biophilic interventions on pre-post changes in heart rate variability. Participants had more increases of RMSSD, which means increased parasympathetic activities related to stress relief, in the *natural elements* and *combination* conditions but less in the *natural analogues* condition. However,

TABLE 2 Estimated difference (β and 95% confidence intervals) on pre-post physiological changes of stress reaction in biophilic environments compared to those in the non-biophilic environment among different workspaces

	Δ Systolic blood pressure (mm Hg)	Δ Diastolic blood pressure (mm Hg)	Δ Heart rate (1/min)	Δ RMSSD (ms)	Δ Skin conductance level (µS)
Overall					
Natural elements	**−1.8 (−3.5, 0.0)**	**−2.8 (−4.4, −1.2)**	**−1.3 (−2.7, 0.0)**	1.5 (−1.6, 4.7)	−0.1 (−0.5, 0.3)
Natural analogues	**−2.2 (−4.0, −0.5)**	**−2.3 (−3.9, −0.8)**	−0.8 (−2.1, 0.6)	−1.5 (−4.7, 1.7)	−0.1 (−0.5, 0.3)
Combination	**−2.0 (−3.8, −0.3)**	**−2.7 (−4.3, −1.1)**	−0.8 (−2.2, 0.5)	1.4 (−1.8, 4.6)	−0.2 (−0.6, 0.2)
Enclosed space					
Natural elements	−0.3 (−3.0, 2.3)	−1.4 (−3.8, 1.0)	−1.1 (−2.6, 0.5)	1.0 (−2.6, 4.6)	0.0 (−0.4, 0.4)
Natural analogues	−1.8 (−4.4, 0.8)	−1.4 (−3.8, 1.0)	0.0 (−1.6, 1.6)	−0.5 (−4.1, 3.0)	−0.1 (−0.5, 0.3)
Combination	−1.6 (−4.3, 1.0)	**−2.8 (−5.1, −0.4)**	−0.7 (−2.2, 0.9)	0.7 (−2.9, 4.2)	−0.2 (−0.6, 0.2)
Open space					
Natural elements	**−3.2 (−5.6, −0.9)**	**−4.1 (−6.1, −2.2)**	**−1.6 (−3.2, −0.1)**	2.1 (−2.0, 6.2)	−0.3 (−0.8, 0.3)
Natural analogues	**−2.7 (−5.0, −0.3)**	**−3.3 (−5.2, −1.3)**	**−1.5 (−3.1, 0.0)**	−2.1 (−6.6, 1.6)	−0.1 (−0.6, 0.5)
Combination	**−2.4 (−4.8, 0.0)**	**−2.6 (−4.6, −0.7)**	−1.0 (−2.6, 0.5)	1.6 (−2.0, 6.2)	−0.2 (−0.7, 0.4)

Note: Δ (delta) indicates the changes of physiological measures from baseline. Each exposure is in a separate generalized additive mixed-effect model with a random effect for participant. Significant results are in bold.

Abbreviation: RMSSD, root mean square of successive differences of beat intervals.

TABLE 3 Estimated differences on mean Z-score of creativity and percentage changes on geometric mean of reaction time (β and 95% confidence intervals) in biophilic environments compared to those in the non-biophilic environment among different workspaces

	Differences on mean Z-score of creativity	Percentage changes on geometric mean of reaction time
Overall		
Natural elements	**0.3 (0.1, 0.5)**	**5.0% (3.5%, 6.5%)**
Natural analogues	0.2 (−0.1, 0.4)	0.5% (−0.9%, 1.9%)
Combination	**0.2 (0.0, 0.4)**	**2.9% (1.5%, 4.4%)**
Enclosed space		
Natural elements	**0.4 (0.1, 0.7)**	**5.0% (2.9%, 7.1%)**
Natural analogues	**0.3 (0.0, 0.6)**	−0.1% (−2.1%, 1.9%)
Combination	**0.4 (0.1, 0.7)**	**3.6% (1.6%, 5.7%)**
Open space		
Natural elements	0.1 (−0.2, 0.4)	**5.1% (2.9%, 7.3%)**
Natural analogues	0.0 (−0.2, 0.3)	1.4% (−0.6%, 3.5%)
Combination	0.0 (−0.2, 0.3)	**2.3% (0.2%, 0.04)**

Note: Significant results are in bold.

all those effect estimates on RMSSD changes were not statistically significant. Biophilic interventions were associated with slightly decreasing skin conductance level (SCL) in both enclosed and open spaces, though effect estimates were generally close to the null with wide confidence intervals.

3.3 | Cognitive function

The effects of biophilic interventions on cognitive function are depicted in Table 3. Biophilic interventions had positive effects on improving creativity scores. Compared to the performance in the non-biophilic environment, participants' scores of creativity test (ie, AU test) were 0.3 (95% CI: 0.1, 0.5) and 0.2 (95% CI: 0.0, 0.4) standard deviation higher in the *natural elements* and *combination* conditions, respectively, after adjusting for types of workspaces and between-visit variables. Those effects were significant and more prominent in enclosed spaces than those in open spaces, with the estimate effects of 0.4 (95% CI: 0.1, 0.7), 0.3 (95% CI: 0.0, 0.6), and 0.4 (95% CI: 0.1, 0.7) standard deviation higher in the *natural elements*, *natural analogues*, and *combination* conditions, respectively.

Meanwhile, participants in biophilic environments had longer reaction times in the Stroop test compared to the non-biophilic environment. Specifically, the *natural elements* and *combination* conditions were associated with 5.0% (95% CI: 3.5%, 6.5%) and 2.9% (95% CI: 1.5%, 4.4%) increases in the geometric mean of reaction time, after adjusting for types of workspaces and between-visit variables. The relative effects of natural analogues condition were not statistically significant. Patterns of those associations were similar in enclosed and open spaces. We detected the learning effect in eight Stroop tests each participant took. In general, one more test was associated with a 2.5% (95% CI: 2.3%, 2.8%) decrease in the geometric mean of reaction time, after adjusting for other variables. Those effects in enclosed and open spaces were almost the same as those in general. We did not find significant learning effect in the AU test.

3.4 | Eye-tracking

The percentage of time participants spent on specific biophilic patterns in three biophilic environments is presented in Table 4. We first observed that people spent over two-thirds of their time looking at biophilic elements across three biophilic environments. Specifically, they spent more time on green plants and biomorphic shapes patterns, 51.0 ± 9.7% in the *nature elements* condition and 55.1 ± 11.9% in the *natural analogues* condition, respectively.

The overall differences in percentage of time participants spent on biophilic elements in three biophilic environments are presented in Table 5. We found female participants generally spent 2.2% (95% CI: −0.3%, 4.8%) more time looking at biophilic elements, after adjusting for biophilic conditions, where they were raised, and type of space. The difference was significant in the *combination* condition with the estimate of 3.3% (95% CI: 0.0%, 6.8%). We also found that participants who were raised in rural area and suburban area spent 3.9% (95% CI: 0.4%, 7.3%) and 2.8% (95% CI: 0.3%, 5.2%) more time looking at biophilic elements, respectively.

3.5 | Self-reported connection with nature and preference to biophilic patterns

Using self-reported scores (1 ~ 10), participants reported higher level of connection with nature in the *natural elements* condition (8.3 ± 1.2) than in the *natural analogues* condition (4.7 ± 1.7). In addition, 84% of participants ranked "visual connection with nature" and "dynamic & diffuse light" as their top two choices of preferred biophilic patterns.

4 | DISCUSSION

All 30 participants completed two visits for overall contrasting reactions across 240 scenarios. Biophilic office environments were associated with the reductions in physiological stress and improvements

TABLE 4 Percentage (%) of time participants spent on specific biophilic patterns measured by eye-tracking in three biophilic environments (mean ± SD (%))

Environment	Biophilic patterns				
	Green plant	Natural daylight and view	Biomorphic shape	Wooden material	Overall
Natural elements	51.0 ± 9.7	14.9 ± 11.7	—	—	65.8 ± 10.8
Natural analogues	—	—	55.1 ± 11.9	29.8 ± 9.3	86.3 ± 5.8
Combination	27.2 ± 12.9	14.5 ± 9.6	24.0 ± 12.1	19.9 ± 7.3	85.8 ± 7.8

TABLE 5 Estimated differences in percentage (%) of time participants spent on biophilic elements measured by eye-tracking in three biophilic environments (β (%) and 95% confidence intervals)

Environment	Differences		
	Female vs Male	Rural vs Urban	Suburban vs Urban
Natural elements	2.5 (−2.8, 7.8)	5.5 (−1.5, 12.5)	**5.1 (0.0, 10.1)**
Natural analogues	0.9 (−1.3, 3.2)	**3.7 (0.5, 6.9)**	1.2 (−0.9, 3.4)
Combination	**3.3 (0.0, 6.6)**	2.4 (−2.2, 7.0)	2.0 (−1.2, 5.1)
Overall	2.2 (−0.3, 4.8)	**3.9 (0.4, 7.3)**	**2.8 (0.3, 5.2)**

Note: Significant results are in bold.

in creative test scores for both enclosed and open spaces, with the largest effects seen with *natural elements* conditoin. Reaction times on focused tasks, however, were slower in the biophilic environments. By using similar biophilic interventions, participants in the open biophilic spaces had more physiological stress reduction than those in the enclosed biophilic spaces. Additionally, participants in the enclosed biophilic spaces had higher creativity score increase than those in the open biophilic spaces.

4.1 | Physiological stress level

Our physiological results indicated consistently that biophilic interventions had positive effects on reducing stress level (Table 2). The positive effects of biophilic interventions on blood pressure and heart rate are consistent with previous studies on the health benefits of windows and daylight, indoor green plants, and wooden environments.[32,61,62] Interestingly, those results were also consistent with a recent meta-analysis summarizing the health benefits of outdoor nature, which showed increased green space exposure was associated with significant decreases in diastolic blood pressure and heart rate.[16] We found increased RMSSD, although not statistically significant, in both the *natural elements* and *combination* conditions. These suggested increased parasympathetic activities, which are related to stress relief, in these two environments. Short-term HRV was rarely reported in experiments on indoor nature. Two experimental studies were conducted to examine the effect of viewing outdoor nature scenes on autonomic function, specifically parasympathetic activity. One showed that participants increased their RMSSD while viewing nature as compared to viewing buildings,[63] and the other reported that RMSSD was higher in recovery process after viewing scenes of nature compared to viewing scenes of buildings following a mental stressor.[64]

4.2 | Creativity and reaction time

Biophilic interventions generally had positive effects on improving participants' creativity yet increasing their reaction time in attention task. Office spaces with natural elements that simulate creative thinking but adversely affect attention intensive reaction times is an apparent contradiction. Together with the physiological findings discussed above, it appears that biophilic elements have a calming influence allowing access to more creative thinking (ie, higher score from AU test) but distract from attention task which needs participants to be more focused (ie, longer reaction time from Stroop test). Shibata and Suzuki investigated the effects of indoor plants on subjects' task performance and reported that plants facilitated performance on association task (a creative task) but distracted participants from working on sorting task (a attention task).[65] Larsen et al found that participants' performance on a letter identification task, which is repetitious and needs concentration, decreased with the increase of indoor plants in the office.[66] Earlier, Stone and Irvine examined the effects of window access on task performance and found that participants in a room with windows had better perceptions in creative task and a windowless room was beneficial for tasks requiring concentration effort. They suggested that views from windows provided more stimulation but less attention to the task.[67] A recent study testing the effects on indoor plants and artificial window in an underground environment reported that participants' reaction time in a response-time task was reduced in an environment with indoor plants but increased in an environment with artificial window with a pleasing outdoor view.[50] These findings being similar to our results from VR-simulated office environments is encouraging because of the obvious advantages of VR-enabled research presented earlier.

4.3 | Different effects among biophilic designs and workspaces

Simulating three types of biophilic design interventions (ie, *natural elements*, *natural analogue s*, and *combination*) allowed further differentiation in the effects of biophilic exposure types. Offices with natural elements outperformed designs with natural analogues on creativity measures but underperformed for the attention task. Concurrently, participants had lower stress levels in office settings with *natural elements*. This trend was consistent with our discussion above that calming effect may facilitate creative thinking but distract attention task. Those differences may due to the degree of how participants feel their connection with nature in those environments, since they reported they felt more connected with nature in the *natural elements* condition than in the *natural analogues* condition. Participants' preference of biophilic patterns may also contribute to those differences. Generally, participants preferred natural light, having a view and indoor plants over natural materials (wood) and biomorphic forms. Having some of these preferred biophilic elements available to indoor environments may increase participants' positive affect, which could reduce their stress level and promote creativity in problem solving.[68]

Although we did not find a statistically significant interaction term between biophilic interventions and workspace types (enclosed vs open), we observed from stratified analysis that similar biophilic interventions had different effects on physiological and cognitive outcomes in open vs enclosed workspaces (Tables 2 and 3) . In general, effects of biophilic interventions on physiological stress reduction were consistently better in open spaces while the effect on creativity was better in enclosed space. On the one hand, those effect differences may be due to the characteristics of workspace (eg, size, layout, function). On the other hand, participants were generally more physiologically stressed in the non-biophilic open space while they performed worse in the non-biophilic enclosed space. Since we used the non-biophilic environment as the reference group in analyses, these difference responses in non-biophilic environments (ie, reference group) provided potential for the biophilic interventions in open and enclosed spaces to have relatively larger impacts on physiological responses and cognitive improvement, respectively (Tables S2 and S3).

4.4 | Intensity of virtual exposure to biophilic environments

Eye-tracking data allow us to capture for the first time peoples' individualized exposure to biophilic design rather than simply the level of biophilia in their surrounding environment. The results indicated that participants spent most of their time looking at biophilic elements, rather than staring at non-biophilic elements or even closing their eyes for a long time in three biophilic environments. A rational next step is to design virtual environments with better control of the amount of biophilic elements to investigate how the variations of virtual biophilic exposures could relate to participants' physiological and cognitive responses, if any. It would provide a complementary approach to analysis of the exposure-response relationship between biophilic patterns and health outcomes, which is different from previous studies that set up different levels of natural exposures in advance but does not consider how people experience those natural environments.[43,69] It would be also interesting to observe whether those exposure-response relationships are different by gender and early childhood experience since we found that female participants and participants who were raised in rural or suburban area spent more time on biophilic elements during experiment.

4.5 | Strengths and limitations

The study design has several strengths. First, the repeated measures of physiological and cognitive outcomes on the same individual could help to control for potential time-invariant factors (eg, gender, socioeconomic factors). Second, randomizing the order of visits and sequence of the exposure within each visit could help reduce any order effects, reducing potential bias in comparisons among different scenarios. Third, all the experiments were conducted in a stable environment with real-time IEQ measures, which would help control confounding factors from the physical environment (eg, $PM_{2.5}$, temperature, relative humidity). Fourth, combining VR, eye-tracking, and wearable biomonitoring sensors provides objective measures to quantify the acute effects of virtual biophilic exposure on stress and cognitive function.

Our study has a few limitations. First, we simulated exposures to biophilic design using VR, which may have a differential effect on physiology and cognitive function than the same interventions in a real environment. Previous research by our team showed consistent physiological and cognitive responses to biophilic interventions when participants experience them in the real world as well as 360° video in VR.[41] More evidence on comparing virtual environment from VR modeling with real environment is stilled needed. Second, we do not have the eye-tracking data when participants were doing cognitive tests in VR, which could be used to measure whether they got distracted by the surrounding biophilic elements or not during the actual test taking process. Third, we did not have baseline cognitive measures in order to reduce potential learning effects. We still saw evidence of a learning effect in the Stroop test but not in the AU test. Therefore, we incorporated both between-visit variables and numbers of test as covariates into the final regression model for cognitive measures. Lastly, our results have limited generalizability for two reasons. One is that most our participants were young healthy knowledgeable adults, which limits the generalizability to the general population, but could be used for knowledge workers who spend a lot of their time in office spaces. Another limitation is that our simulated biophilic interventions were modeled after office environments and may not be applicable to other building types such as homes, hospitals, or retail settings.

5 | CONCLUSION

Biophilic design, as a health promotion approach, could help reduce stress and improve creativity in office settings. Those effects differed in different types of biophilic interventions and in different workspace (open vs enclosed). This study introduces a new empirical research tool to quantify the human responses to virtual biophilic environments by combining virtual reality, eye-tracking, and wearable biomonitoring sensors. Our findings should benefit architects, designers, and office managers to understand how biophilic office design affects occupants' health and performance.

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CONFLICT OF INTEREST

The authors declare they have no actual or potential competing financial interests.

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REFERENCES

1. Samet J, Spengler J. Indoor environments and health: moving into the 21st century. *Am J Public Health*. 2003;93(9):1489-1493.
2. Centers for Disease Control and Prevention. Workplace Health Model. 2016; https://www.cdc.gov/workplacehealthpromotion/model/index.html. Accessed April 13, 2019.
3. Cedeño-Laurent JG, Williams A, MacNaughton P, et al. Building evidence for health: green buildings, current science, and future challenges. *Annu Rev Public Health*. 2018;39(1):291-308.
4. Allen JG, MacNaughton P, Satish U, Santanam S, Vallarino J, Spengler JD. Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: a controlled exposure study of green and conventional office environments. *Environ Health Perspect*. 2016;124(6):805-812.
5. MacNaughton P, Satish U, Laurent JGC, et al. The impact of working in a green certified building on cognitive function and health. *Build Environ*. 2017;114:178-186.
6. Allen J, MacNaughton P, Laurent J, Flanigan S, Eitland E, Spengler J. Green buildings and health. *Curr Environ Health Rep*. 2015;2(3):250-258.
7. Loftness V, Hakkinen B, Adan O, Nevalainen A. Elements that contribute to healthy building design. *Environ Health Perspect*. 2007;115(6):965-970.
8. Kaitlyn G, Birgitta G. A review of psychological literature on the health and wellbeing benefits of biophilic design. *Buildings*. 2015;5(3):948-963.
9. Newman P, Soderlund J. Biophilic architecture: a review of the rationale and outcomes. *AIMS Environ Sci*. 2015;2(4):950-969.
10. Wilson EO. *Biophilia*. Cambridge, MA: Harvard University Press; 1984.
11. Kellert SR, Wilson EO. *The Biophilia Hypothesis*. Washington, DC: Island Press; 1993.
12. Klepeis NE, Nelson WC, Ott WR, et al. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J Expo Anal Environ Epidemiol*. 2001;11(3):231-252.
13. Kellert SR, Heerwagen J, Mador M. *Biophilic Design: The Theory, Science, and Practice of Bringing Buildings to Life*. Hoboken, NJ: John Wiley; 2008.
14. Yin J, Spengler JD. Going biophilic: Living and working in biophilic buildings. In: Galea S, Ettman CK, Vlahov D, eds. *Urban Health*. New York, NY: Oxford University Press; 2019:369-374.
15. Ryan C, Browning W, Clancy J, Andrews S, Kallianpurkar N. Biophilic design patterns: emerging nature-based parameters for health and well-being in the built environment. *ArchNet-IJAR*. 2014;8(2):62-76.
16. Twohig-Bennett C, Jones A. The health benefits of the great outdoors: a systematic review and meta-analysis of greenspace exposure and health outcomes. *Environ Res*. 2018;166:628-637.
17. Fong K, Hart J, James P. A review of epidemiologic studies on greenness and health: updated literature through 2017. *Curr Envir Health Rpt*. 2018;5(1):77-87.
18. van Den Bosch M, Ode SÅ. Urban natural environments as nature-based solutions for improved public health – a systematic review of reviews. *Environ Res*. 2017;158:373-384.
19. James P, Banay RF, Hart JE, Laden F. A review of the health benefits of greenness. *Curr Epidemiol Rep*. 2015;2(2):131-142.
20. Kuo M. How might contact with nature promote human health? Exploring promising mechanisms and a possible central pathway. *Front Psychol*. 2015;6:1093.
21. McSweeney J, Rainham D, Johnson SA, Sherry SB, Singleton J. Indoor nature exposure (INE): a health-promotion framework. *Health Promot Int*. 2015;30(1):126-139.
22. Ulrich RS. View through a window may influence recovery from surgery. *Science*. 1984;224(4647):420-421.
23. Dijkstra K, Pieterse ME, Pruyn A. Stress-reducing effects of indoor plants in the built healthcare environment: The mediating role of perceived attractiveness. *Prevent Med*. 2008;47(3):279-283.
24. Choi J-H, Beltran LO, Kim H-S. Impacts of indoor daylight environments on patient average length of stay (ALOS) in a healthcare facility. *Build Environ*. 2012;50(Supplement C): 65-75.
25. Li D, Sullivan CW. Impact of views to school landscapes on recovery from stress and mental fatigue. *Landsc Urban Plan*. 2016;148:149-158.
26. Bringslimark T, Hartig T, Patil GG. The psychological benefits of indoor plants: a critical review of the experimental literature. *J Environ Psychol*. 2009;29(4):422-433.
27. Raanaas RK, Evensen KH, Rich D, Sjøstrøm G, Patil G. Benefits of indoor plants on attention capacity in an office setting. *J Environ Psychol*. 2011;31(1):99-105.
28. Smolders K, de Kort Y, van den Berg SM. Daytime light exposure and feelings of vitality: results of a field study during regular weekdays. *J Environ Psychol*. 2013;36(Supplement C):270-279.
29. Boubekri M, Cheung IN, Reid KJ, Wang C-H, Zee PC. Impact of windows and daylight exposure on overall health and sleep quality of office workers: a case-control pilot study. *J Clin Sleep Med*. 2014;10(6):603.
30. Burnard M, Kutnar A. Wood and human stress in the built indoor environment: a review. *Wood Sci Technol*. 2015;49(5):969-986.
31. Zhang X, Lian Z, Ding Q. Investigation variance in human psychological responses to wooden indoor environments. *Build Environ*. 2016;109:58-67.

32. Zhang X, Lian Z, Wu Y. Human physiological responses to wooden indoor environment. *Physiol Behav*. 2017;174:27-34.
33. Ikei H, Song C, Miyazaki Y. Physiological effects of touching wood. *Int J Environ Res Public Health*. 2017;14(7):801.
34. Joye Y. Architectural lessons from environmental psychology: the case of biophilic architecture. *Rev Gen Psychol*. 2007;11(4):305-328.
35. Dreyer BC, Coulombe S, Whitney S, Riemer M, LabbA D. Beyond exposure to outdoor nature: exploration of the benefits of a green building's indoor environment on Wellbeing. *Front Psychol*. 2018;9:1583.
36. Vischer JC. Towards an environmental psychology of workspace: how people are affected by environments for work. *Architect Sci Rev*. 2008;51(2):97-108.
37. Frumkin H, Bratman GN, Breslow SJ, et al. Nature contact and human health: a research agenda. *Environm Health Perspect*. 2017;125(7):75001.
38. Kuliga SF, Thrash T, Dalton RC, Hölscher C. Virtual reality as an empirical research tool — exploring user experience in a real building and a corresponding virtual model. *Comput Environ Urban*. 2015;54:363-375.
39. Kjellgren A, Buhrkall H. A comparison of the restorative effect of a natural environment with that of a simulated natural environment. *J Environ Psychol*. 2010;30(4):464-472.
40. Higuera-Trujillo JL, López-Tarruella Maldonado J, Llinares MC. Psychological and physiological human responses to simulated and real environments: a comparison between Photographs, 360° Panoramas, and Virtual Reality. *Appl Ergon*. 2017;65:398-409.
41. Yin J, Zhu S, Macnaughton P, Allen JG, Spengler JD. Physiological and cognitive performance of exposure to biophilic indoor environment. *Build Environ*. 2018;132:255-262.
42. Valtchanov D, Barton KR, Ellard C. Restorative effects of virtual nature settings. *Cyberpsychol Behav Soc Netw*. 2010;13(5):503-512.
43. Jiang B, Chang C-Y, Sullivan WC. A dose of nature: tree cover, stress reduction, and gender differences. *Landsc Urban Plan*. 2014;132:26-36.
44. Tabrizian P, Baran PK, Smith WR, Meentemeyer RK. Exploring perceived restoration potential of urban green enclosure through immersive virtual environments. *J Environ Psychol*. 2018;55:99-109.
45. Salvucci D, Goldberg J. Identifying fixations and saccades in eye-tracking protocols. ACM Press. 2000;71-78.
46. Diaz G, Cooper J, Kit D, Hayhoe M. Real-time recording and classification of eye movements in an immersive virtual environment. *J Vision*. 2013;13(12):5.
47. McCraty R, Shaffer F. Heart rate variability: new perspectives on physiological mechanisms, assessment of self-regulatory capacity, and health risk. *Global Adv Health Med*. 2015;4(1):46-61.
48. Shaffer F, McCraty R, Zerr C. A healthy heart is not a metronome: an integrative review of the heart's anatomy and heart rate variability. *Front Psychol*. 2014;5:1040.
49. Ulrich RS, Simons RF, Losito BD, Fiorito E, Miles MA, Zelson M. Stress recovery during exposure to natural and urban environments. *J Environ Psychol*. 1991;11(3):201-230.
50. Kim J, Cha S, Koo C, Tang S-K. The effects of indoor plants and artificial windows in an underground environment. *Build Environ*. 2018;138:53-62.
51. Kaplan S. The restorative benefits of nature: toward an integrative framework. *J Environ Psychol*. 1995;15(3):169-182.
52. Parsons TD, Rizzo AA. Initial Validation of a virtual environment for assessment of memory functioning: virtual reality cognitive performance assessment test. *CyberPsychol Behav*. 2008;11(1):17-25.
53. Cedeno Laurent JG, Williams A, Oulhote Y, Zanobetti A, Allen JG, Spengler JD. Reduced cognitive function during a heat wave among residents of non-air-conditioned buildings: An observational study of young adults in the summer of 2016. *PLoS Medicine*. 2018;15(7):e1002605.
54. Guilford JP. *The nature of human intelligence*. New York, NY: McGraw-Hill; 1967.
55. Pásztor A, Molnár G, Csapó B. Technology-based assessment of creativity in educational context: the case of divergent thinking and its relation to mathematical achievement. *Think Skills Creat*. 2015;18:32-42.
56. van den Berg M, Maas J, Muller R, et al. Autonomic nervous system responses to viewing green and built settings: differentiating between sympathetic and parasympathetic activity. *Int J Environ Res Public Health*. 2015;12(12):15860-15874.
57. Barton J, Pretty J. What is the best dose of nature and green exercise for improving mental health? A multi-study analysis. *Environ Sci Technol*. 2010;44(10):3947.
58. Lieberman H, Tharion W, Shukitt-Hale B, Speckman K, Tulley R. Effects of caffeine, sleep loss, and stress on cognitive performance and mood during U.S. Navy SEAL training. *Psychopharmacology*. 2002;164(3):250-261.
59. *gamm4*. Generalized Additive Mixed Models using 'mgcv' and 'lme4' [computer program]. 2017.
60. R Core Team. *R: A Language and Environment for Statistical Computing* [computer program]. Vienna, Austria: R Foundation for Statistical Computing; 2018.
61. Zadeh RS, Shepley MM, Williams G, Chung S. The impact of windows and daylight on acute-care nurses' physiological, psychological, and behavioral health. *HERD*. 2014;7(4):35-61.
62. Park S-H, Mattson RH. Ornamental indoor plants in hospital rooms enhanced health outcomes of patients recovering from surgery. *J Altern Complement Med*. 2009;15(9):975-980.
63. Gladwell VF, Brown DK, Barton JL, et al. The effects of views of nature on autonomic control. *Eur J Appl Physiol*. 2012;112(9):3379-3386.
64. Brown DK, Barton JL, Gladwell VF. Viewing nature scenes positively affects recovery of autonomic function following acute-mental stress. *Environ Sci Technol*. 2013;47(11):5562-5569.
65. Shibata S, Suzuki N. Effects of the foliage plant on task performance and mood. *J Environ Psychol*. 2002;22(3):265-272.
66. Larsen L, Adams J, Deal B, Kweon B-S, Tyler E. Plants in the workplace: the effects of plant density on productivity, attitudes, and perceptions. *Environ Behav*. 1998;30(3):261-281.
67. Stone NJ, Irvine JM. Direct or indirect window access, task type, and performance. *J Environ Psychol*. 1994;14(1):57-63.
68. Isen AM. Positive affect and decision making. In: Lewis M, Haviland-Jones JM, eds. *Handbook of Emotions*. New York, NY: Guilford Press; 1993:261-277.
69. Tsunetsugu Y, Miyazaki Y, Sato H. Physiological effects in humans induced by the visual stimulation of room interiors with different wood quantities. *J Wood Sci*. 2007;53(1):11-16.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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