Bringing Nature Indoors With Virtual Reality: Human Reponses to Biophilic Design in Buildings

Bringing Nature Indoors with Virtual Reality:

Human Reponses to Biophilic Design in Buildings

A dissertation presented

by

Jie Yin

to

The Department of Population Health Sciences

In the Environmental Health Area of Study

in partial fulfillment of the requirements

for the degree of

Doctor of Philosophy

in the subject of

Population Health Sciences

Harvard University

Cambridge, Massachusetts

August 2019

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ABSTRACT

Biophilia hypothesis suggests humans have innate connections to nature which may affect their health and productivity. Yet we currently live in a world that is rapidly urbanizing with people spending most of their time indoors. Therefore, biophilic design, which incorporates natural elements into the indoor environment, has received increasing attention in both design and health fields. Previous research has demonstrated the associations between outdoor nature contact and health and well-beings. But study quantifying health impacts of indoor biophilic features is limited. The objective of this dissertation is to investigate the short-term health impacts of biophilic design in buildings. To achieve that, we developed a tool by combining virtual reality (VR), eye-tracking and wearable biomonitoring sensors. With that tool, we conducted multiple experiments with different study design to measure physiological and cognitive responses to different biophilic indoor environments.

First, 28 participants spent time in an indoor environment featuring biophilic design elements and one without. In each visit, they experienced the environment for 5 minutes in reality and virtually by using VR. We found that participants experiencing biophilic environment virtually had similar physiological and cognitive responses, including reduced blood pressure and skin conductance and improved short-term memory, as when experiencing the actual environment. Second, we designed a randomized crossover study to let 30 participants experience three versions of biophilic design in simulated open and enclosed office spaces in VR. 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. Lastly, we conducted a between-subjects experiment with 100 participants using VR. Participants were randomly assigned to experience one of four virtual offices (i.e. one non-biophilic base office and three similar offices enhanced with different biophilic design features) for six minutes after stressor tasks. We found that participants in biophilic indoor environments had consistently better recovery responses after a mental stressor compare to those in the non-biophilic environment. Those restorative effects differed among three different types of indoor biophilic environments.

We show significant physiological and cognitive benefits in indoor environments with diverse biophilic design features, which could help in understanding, applying and promoting biophilic design in buildings.

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ACKNOWLEDGMENTS

This dissertation would not have been possible without the support of my mentors, colleagues, friends and family. First and foremost, I'd like to express my sincere gratitude to my advisor, Dr. Jack Spengler. He transformed me from a practicing urban planner to a public health researcher and guided me through the past four years at Harvard, intellectually, socially and personally. His insights and vision inspired my work at every stage of this dissertation. I'd also like to thank my co-advisor, Dr. Joe Allen. Bi-weekly discussion with Joe defined the path and framework of this dissertation. His unique perspective through the lens of practical need made sure this work was always well grounded, aiming to benefit both designers and public health practitioners. Importantly, I am very fortunate to have Dr. Paul Catalano in my dissertation committee. Paul introduced biostatistics to me; his passion impressed and encouraged me to put biostatistics as one of my minors. I'm very grateful to his invaluable guidance on statistical methods and interpretation of results.

I'd like to thank Dr. Gary Adamkiewicz, who was my master's academic advisor and my oral exam committee member, Dr. Francine Laden and Dr. Jaime Hart for their inspiring suggestions that have strengthened my dissertation. I'd also like to acknowledge my co-authors, Dr. Piers MacNaughton, Nastaran Arfaei, Jing Yuan and Shihao Zhu, who provided advice and assistance for conducting experiment and analysis. Special thanks to Joan Arnold for all her administrative support. I would like to thank the Spengler group and the Healthy Building Team led by Joe, especially those people I worked with since day one: Linda Tomasso, Dr. Memo Cedeño Laurent, Augusta Williams, and Erika Eitland.

The Chapters 2 and 4 were supported by the Campus Sustainability Innovation Fund, administered by the Harvard University Office for Sustainability. The Chapter 3 was funded by

Grant No. T42 OH008416 from National Institute for Occupational Safety and Health (NIOSH) and Greenlight Fund from Stantec Architecture Inc. I thank Harvard Decision Sciences Laboratory for providing space and recruiting system for the experiment in Chapter 4.

Lastly, I especially thank my parents Xianran Yin and Ling Hu, my in-laws Xiaoan Tan and Feifei Sheng, my wife Dr. Jiaying Tan and my daughter Alicia Yin for their continuous support and unconditional love.

ABBREVIATIONS

VR: virtual reality

BIDI: biophilic interior design index

HVAC: heating, ventilation, and air conditioning

BP: blood pressure

SBP: systolic blood pressure

DBP: diastolic blood pressure

SCL: skin conductance level

HR: heart rate

SRT: stress recovery theory

ART: attention restoration theory

IEQ: indoor environmental quality

$PM_{2.5}$: particulate matter that have a diameter of less than 2.5 micrometers

HRV: heart rate variability

RMSSD: root mean square of successive differences of beat intervals

LF/HF ratio: Ratio of low frequency to high frequency

STAI: State-Trait Anxiety Inventory score

Chapter 1 - Introduction: Going Biophilic, Living and Working in Biophilic Buildings

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Publication

Yin J, Spengler JD. Going Biophilic: Living and Working in Biophilic Buildings. In: Galea S, Ettman CK, Vlahov D, eds. *Urban Health.* New York: Oxford University Press; 2019:369-374.

1.1 Biophilia, Biophilic Design and Health: Why it Matters

1.1.1 Nature Contact and Human Health

The rapid trend toward global urbanization, resulting in more than half of the world's population living in cities, is associated with decreased access to natural environments. Additionally, the industrialized world spends up to 90% of its time inside buildings, further distancing people from nature. This urban living is associated with increased stress-related diseases.[1] One factor contributing to this increase may be the routine separation of humans from contact with nature when indoors. Research in recent decades has yielded substantial evidence that exposure to nature is associated with positive impacts on human health and well-being.[2] Specifically, epidemiological studies provided population-level evidence that greater exposure to greenness is associated with reduced absenteeism in schools; improved student academic performance; increased physical activity; improved mental health, brain development, and cognitive function; higher birth weights; and lower mortality rates.[3-7] In addition, experimental studies showed positive effects of contact with nature on stress reduction, improvement of cognition and affect, enhanced immune function, and increased parasympathetic and lower sympathetic nerve activity.[8-11] However, because most of the previous studies were conducted in outdoor spaces, the potential for similar health benefits of incorporating natural elements indoors remains unclear. To address this gap, we review current theories, tools, and research opportunities in this chapter.

1.1.2 Biophilia: Hypothesis and Theories

Biophilia, defined as "love of life or living system," was introduced within the context of preserving life and fighting against death by psychoanalyst and social philosopher Erich Fromme in 1964.[12] The concept was later popularized by Harvard biologist E.O. Wilson in 1984, who suggested that human beings, from an evolutionary biology perspective, have an inherent affinity for the natural world.[13] This biophilia hypothesis has since been supported by two complementary theories: *Stress Recovery Theory* (SRT) and *Attention Restoration Theory* (ART). SRT explored the physiological impacts of contact with nature on stress reduction, indicating that natural elements could activate our parasympathetic nervous system, leading to decreased heart rate, blood pressure, skin conductance, and salivary cortisol level.[14] These responses could induce relaxation and help to reduce stress and autonomic arousal. ART explained how the experience of nature influences cognition, suggesting that natural environments could invoke involuntary attention in people.[15] This attentional recovery could in turn have restorative effects for mental fatigue caused by overstimulation from the urban environment and thus improve people's cognitive performance that requires direct attention.

1.2 Biophilic Buildings and Well-being: Evidence and Practice

1.2.1 Design Attributes and Health Benefits

Stephen Kellert initiated biophilic design to incorporate natural features and systems into indoor environments.[16] To operationalize and promote the adoption of biophilic design, he developed six elements (environmental features, natural shapes and forms, natural patterns and processes, light and space, place-based relationships, evolved human-nature relationships) and 72 attributes of biophilic design.[16] Ryan et al. summarized these attributes into three categories (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 and providing a framework to study the health impacts more directly.[17]

Specific aspects of the physiological and psychological benefits of biophilic design elements in buildings have been studied.[18] For example, indoor plants have demonstrated benefits for stress reduction and pain tolerance, as well as producing increased emotional satisfaction and productivity.[19] Viewing nature through a window has also been shown to have beneficial effects in the hospital setting, including reducing recovery times and reliance on pain medication.[20] In addition, having natural views through windows could also increase productivity, decrease sick days, and decrease absenteeism in office settings.[18] Natural light has known benefits for circadian rhythm and sleep quality, and it can boost cognitive attention and memory, which could increase worker productivity.[18] The use of interior wooden materials has been found to have similar biorestorative effects on the autonomic, respiratory, and visual systems and contributes to a decrease in tension and fatigue and an increase of positive emotions and comfort.[21] Last, natural analogues (e.g., a mural of a natural scene) in a patient's room or other healthcare space can help to reduce stress levels and relieve pain.[16] Interestingly, while the health benefits of individual design attributes have been studied, there is limited research examining the impact on health and well-being when multiple design attributes are combined.

1.2.2 From Green Building to Healthy Building: Role of Biophilia

Green building design has been broadly accepted as an approach to minimize detrimental impacts to the environment through reductions in both energy and water usage. However, the impact of improved indoor environmental quality on population health in green buildings has only recently been investigated.[22] Evidence from nine foundational environmental elements has demonstrated how buildings affect human health.[23] Previously, most research on the health impact of building focused on negative factors, including poor indoor air quality, inadequate ventilation, unconformable thermal conditions, extensive artificial lighting, mold, dust and pests, and materials with toxic chemical substances. These factors are commonly associated with various symptoms identified as “sick building syndrome”. Biophilic design dovetails with the green building movement to provide specific building design strategies. Inclusion of natural elements indoors are considered positive attributes encompassing views to nature, natural ventilation and daylight, access to green plants and water features, and the use of natural materials and biomorphic forms for indoor elements.

The increasing evidence for health benefits from nature-inspired spaces has given rise to building rating systems like the *WELL* building standard and *Living Building Challenge* (LBC), both of which highlight biophilia as an important component of their standards.[24,25] Specifically, the *WELL* standard examines biophilia qualitatively in terms of nature and pattern incorporation, and natural interaction. Moreover, it sets up some quantitative indicators of coverage and accessibility to outdoor greenery, percentage of wall and potted plants in indoor spaces, and water features.[24] LBC requires the design team to have a one-day exploration of potential biophilic features, as proposed by Kellert, to provide a biophilic framework and plan early in the design process. It also requires that goals be tracked during and after construction to ensure they are met.[16,25]

1.3 New Approaches to Quantify the Health Impact of Biophilic Indoor Environments

Although the health benefits of biophilic design have been part of the green building conversation, they are not easily quantified in comparison to energy and water consumption. Here, we propose several research approaches to generate more evidence about how biophilic design could affect population health.

1.3.1 Biophilic Exposure Simulation and Assessment

Modern advancements in virtual reality (VR) technology provide an opportunity to replicate and customize visual environmental exposures through an immersive experience that is more effective than photographs or panoramas.[26] *Eye tracking*, a sensor technology that measures eye positions and movement, has been integrated into VR headset to measure attention to specific elements in simulated environments. Specific elements within the visual field that hold attention can be identified and, with other sensors of physiologic responses (e.g. electroencephalography, heart rate variability, skin conductance, blood pressure), help to identify positive or negative responses. Doing these experiments with VR offers the advantage of testing many more participants across many standardized visual fields. However, evidence is needed to detect differences between virtual exposures versus the real environment since the experience of nature is multisensory.[27] Another challenge to coherent findings is the specification of the biophilic exposure in different indoor settings. We need a tool that allows observers to objectively rate indoor environments based on their biophilic qualities.[28]

1.3.2 Objective Outcome Measures

With increasingly affordable, comfortable, and accurate wearable biomonitoring sensors, researchers can collect objective physiological measurements. Many studies have used noninvasive biomonitoring sensors to measure acute physiological markers, including heart rate, heart rate variability, skin conductance level and blood pressure, to estimate nervous system arousal and assess autonomic function and short-term stress responses to stimuli. Electroencephalography (EEG) could objectively measure the potential connection between the biophilic environmental exposure and changes in brain activity in real time. Combining VR and wearable biomonitoring sensors makes it possible to quantify subjects' acute physiological responses to many simulated biophilic-enhanced indoor spaces.[28]

1.4 Research Framework

In this chapter, we have briefly presented the historical development of biophilic design and its application in buildings, but more evidence regarding the health benefits of natural elements indoors is needed. Emerging technologies like VR, eye tracking, and wearable biomonitoring sensors could provide a powerful way for designers and public health professionals to quantify human responses, both physiological and cognitive, short-term and long-term, in biophilic buildings.

Therefore, this dissertation intended to quantify the short-term health impacts of biophilic design by using those emerging technologies through three experimental approaches, which have the following aims and research questions (**Table 1.1**).

Table 1.1 Research framework of dissertation

Papers	Aims	Research Questions
Physiological and Cognitive Performance of Exposure to Biophilic Indoor Environment (Chapter 2)	Demonstrate that new tool can test effects of biophilic environment and is valid	Would exposure to simulated environments produce effects similar to those in real environments?
Effects of Biophilic Interventions in Office on Stress Reaction and Cognitive Function: A Randomized Crossover Study in Virtual Reality (Chapter 3)	Use this tool to test independent effects of biophilic patterns on objective outcomes in office setting	How would different biophilic design patterns impact occupants in different workspaces (enclose vs. open)?
Restorative Effects of Biophilic Indoor Environment: A Between-subjects Experiment in Virtual Reality (Chapter 4)	Test these effects in recovery process after mental stressor (restorative effects)	How do different biophilic design strategies impact the stress recovery process of stress and anxiety?

Chapter 2 - Physiological and Cognitive Performance of Exposure to Biophilic Indoor Environment

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J.Y. designed the experiments, analyzed and interpreted the data and took the lead in writing the manuscript. J.Y. and S.Z. performed the experiments and processed the data. P.M., J.G.A. and J.D.S provided critical revision of the manuscript for important intellectual content. J.D.S supervised the project.

Publication

Yin J, Zhu S, MacNaughton P, Allen JG, Spengler JD. Physiological and cognitive performance of exposure to biophilic indoor environment. *Building and Environment.* 2018.

Abstract

Biophilic design, which incorporates natural elements into the built environment, has received increasing attention in both the design and health fields. But research quantifying physiological and cognitive benefits of indoor biophilic features is sparse. This randomized crossover study examines the physiological and cognitive responses to natural elements in an office building. Twenty-eight participants spent time in an indoor environment featuring biophilic design elements and one without, with the order of the visit randomized. In each visit, they experienced the environment for 5-minutes in reality and virtually by using virtual reality (VR). Wearable sensors were used to measure blood pressure, galvanic skin response and heart rate. Cognitive tests were administrated after each exposure. The indoor biophilic environment was associated with a decrease in participants' blood pressure. The overall differential effects for participants experiencing an indoor environment with biophilic elements versus none was 8.6 mmHg lower systolic and 3.6 mmHg lower diastolic blood pressure. In addition, their skin conductance decreased 0.18µS greater than when they experienced the non-biophilic setting. Short-term memory improved by 14%. Participants reported a decrease in negative emotions and an increase in positive emotions after experiencing the biophilic setting. Moreover, our findings indicate that participants experiencing biophilic environment virtually had similar physiological and cognitive responses as when experiencing the actual environment. This gives rise to the possibility of reducing stress and improving cognition by using virtual reality to provide exposures to natural elements in a variety of indoor settings where access to nature may not be possible.

Keywords: Biophilic indoor environment, Blood pressure, Skin conductance, Heart rate, Cognitive function, Virtual reality

2.1 Introduction

The unprecedented rate of urbanization globally is associated with a decrease of access to natural environments.[29] Distancing us further from nature is the amount of time spent inside buildings which by some reports is up to 90% of our time.[30] Urban living is also associated with increased stress related diseases.[1,31,32] One contributing factor to this increase may be the lack of access to nature in the built environment. Research has shown that exposure to nature is associated with positive impacts on human health and wellbeing.[14,33,34] Epidemiological studies provided evidence at regional level that exposure to green space ('greenness') is positively associated with physical activity.[35] and reduced absenteeism in schools,[3] and negatively associated with mental distress,[36,37] cardiovascular disease,[38] and mortality.[39,40] Experimental studies conducted at local level observed positive effect of nature on recovery from surgery,[20] stress reduction,[8] improvement of cognition and affect,[41] and productivity.[42] The potential for similar benefits in indoor environments that incorporate natural elements are plausible. The biophilia hypothesis, proposed by Harvard biologist E.O. Wilson in 1984, suggests that human beings have an innate biological connection with nature.[13] Based on this hypothesis, biophilic design has been promoted to incorporate natural features and systems into indoor environment.[16] Architects and interior designers cite psychological and health benefits of biophilic architecture.[18,43,44] However, research quantifying physiological and cognitive benefits of indoor biophilic features is limited.

Different experimental designs have been used to examine the impacts of biophilic design. Virtual stimuli were widely used to represent the environmental exposures. Berto used the photographs as stimuli and found exposure to restorative environments improved participants' performance on attention test.[45] Similarly, Brown et al. used images in the slideshows to depict scenes of natural and built environments. They introduced both physiological indicators, including blood pressure, respiration and heart rate variability, and psychological questionnaires as measures of stress level. Their finding suggested that viewing nature scenes could improve the recovery of autonomic function following a stressor.[46] Kahn et al. investigated physiological responses of incorporating real-time natural view through a plasma display “window” and found that working in the office with a glass window on natural scene had better restorative effect compare to that with blank wall. But the “plasma window” could not induce the similar effect.[47] Jiang et al. conducted an experiment by using 3-D visual media of streetscapes to represent different tree cover density and measuring participants’ stress level through salivary cortisol and skin conductance level. They observed an inverted U-shape dose-response curve for the impact of tree cover density on stress reduction among men.[48] Their another experiment with the same stimuli but subjective measure of stress level found the linear dose-response curve for the effect of tree density on self-reported stress reduction.[49] As an emerging technology, virtual reality (VR) was used to provide more immersive experience of exposing to natural environment. Valtchanov et al. designed a study in VR and found that participants exposed to virtual computer-generated forest exhibited increased positive effect and decreased stress compare to those experienced a slideshow.[50] In addition to virtual stimuli, experiments conducted in the real environment also found the benefits of exposing to natural elements. Zhang et al. measured the differences of physiological and psychological responses of exposing to wooden versus non-wooden indoor environment and concluded that the wooden indoor environment could benefit autonomic nervous system, respiratory system, visual system, increase positive affect and reduce tension and fatigue.[21,51]

Limitations of these initial investigations include using virtual stimuli with limited visual angle and/or resolution, which could affect participant's experience compare to those in the real environment. In addition, the potential differences of participants' responses in real environment and those in the virtual representation of the same place have not been examined. Also, stress indicators were usually measured by stationary devices in the lab or subjective surveys, which lead to the difficulty of collecting real time data in field or less accuracy, respectively. Moreover, several studies used between subject design though they did not have large sample size, which resulted in the lack of statistical power to detect the effect of short-time exposure.

To further explore the relationship between biophilic design and human response, we designed a research study that leveraged and advanced upon these prior research studies to test two main hypotheses: First, would exposure to natural elements into indoor environment ("biophilic design") improve our physiological and cognitive performance? Second, would virtual representation of the same test settings evoke similar effects? To address these questions, we tested participants' responses as they experienced the actual physical environment and the virtual representation of that environment using VR technology. Wearable biomonitoring sensors and validated cognitive tests were used to measure physiological responses and cognitive function, respectively.

2.2 Methods

2.2.1 Study Design

A randomized crossover study design was used in this study; each participant acted as their own control, with the purpose of attaining the same level of statistical power as parallel design with fewer participants. Each participant visited two different environments, biophilic and non-biophilic, on different days. For each visit, they experienced each environment with both a 'physical' and 'virtual' exposure. The order of presentation of the two different test environments and the physical and virtual exposures were randomized, and each visit occurred on the same day of week and time of day to reduce the potential effect of circadian rhythm on the physiological and cognitive performance.

2.2.2 Participants

Based on the similar environmental psychology studies with crossover study design that had sufficient statistical power.[20,45,46,50-53] and limiting of the environmental time window (February to April) to minimize the seasonal differences of natural light and view in the experiment, we designed our study with a goal of 30 participants. Participants from around the Harvard T.H. Chan School of Public Health campus were recruited via posted flyer and email invitation. 31 adults between the ages of 23 and 42 agreed to participate in our study. They were asked to visit our office space twice for a one-hour long experiment between February and April in 2017. 28 participants completed both sets of tests. 55.6% of them were female and 44.4% were male. The average age of participants was 26, and 96.4% of them self-reported good general health condition.

For each participant, we gathered demographic data, general health condition, information about taking stress related medicine or treatment, caffeinated beverage drinking, and sleep quality last night, and current stress level in the baseline survey. Individual were excluded who were taking medicine or stress treatment, who had used tobacco or alcohol within 24 hours prior to the experiment, and who had participated in intensive exercise within 6 hours prior to the experiment. The study protocol was reviewed and approved by the Harvard T.H. Chan School of Public Health's Institutional Review Board. All participants signed informed consent.

2.2.3 Environmental Exposures

We tested participants in two different environments in the same floor served by the same HVAC unit: 1) non-biophilic environment: a classroom that does not have windows or indoor plants, 2) biophilic environment: an office common area with plants, bamboo floor and external views of green space and a river (**Figure 2.1**).

Figure 2.1 Test environments and physical vs. virtual exposure. A: biophilic environment with physical exposure; B: biophilic environment with virtual exposure; C: non-biophilic environment with physical exposure; D: non-biophilic environment with virtual exposure.

Physical vs. Virtual exposure

In each test space, participants were exposed to environment in both physical and virtual scenarios (**Figure 2.1**). "Physical exposure" is when participants were in the test environment and observed their surroundings. In contrast, in "virtual exposure", participants were in those places but they observed the exact same environment by watching immersive 360-degree field-of-view videos through VR. Two 5-minutes videos were taken by Kodak PIXPRO SP360 4K

Action Cams (JK Imaging Ltd.) at the office common area and classroom on February as the sources of "virtual exposure". These videos were taken at noon in a clear day and all the experiments in the office common area were conducted between 10am to 2pm in clear days to ensure similar biophilic exposure such as natural light and clear long-distance view comparable to the video recordings. The length of VR task was set to be 5 minutes since research suggests that this would be an adequate minimum length for inducing a stress or restorative effect.[54,55]

Biophilic Interior Design Index

We created a tool for participants to objectively rate each indoor environment based on the biophilic quality of the environment. The tool, Biophilic Interior Design Index (BIDI), was developed based on the 14 patterns of biophilic design proposed by Terrapin Bright Green LLC.[17] We designed a questionnaire asking participants' perception of the biophilic features in the study environment such as plants, water, airflow, light, materials, biomorphic patterns, long-distance view (**Survey A1.2**). Their responses of these questions were used to calculate the score of the BIDI (**Table A1.1**).

2.2.4 Outcome Measures

In order to assess the short-term stress responses between two experimental environments, both physically and virtually, we used validated immediate stress indicators, including heart rate (HR), skin conductance level (SCL) and blood pressure (BP) in the experiment.[8,21,46,48] They were objectively measured by three wearable biomonitoring sensors: Movisens EcgMove3 (Movisens GmbH), Empatica E4 wristband (Empatica Inc) and Omron EVOLV blood pressure monitor (Omron Healthcare Inc.), respectively. The first two sensors collected data in real-time, measuring the HR (in unit of 1/min) and SCL (in unit of micro-

Siemens (μS)) every second throughout the experiment. BP (in unit of mmHg) was measured after each 5-minutes exposure and rest period (**Figure 2.2**).

Participants' cognitive function were measured by a cognitive test battery after each exposure, including: 1) visual reaction time task: this simple reaction time task recorded participant's average reaction time (mS) of a graphic change on the screen of laptop, which is an important indicator of attention.[56] The response speed would be influenced by age, intelligence and conditions of performing the task;[57,58] 2) Stroop task: time of semantic interference, which is the time difference between responding to incongruently-colored words and words presented in the same color, were collected to measure selective attention and cognitive flexibility;[59,60] and 3) visual backward digit span task: a string of numbers (start with three numbers) was sequentially displayed on the screen, with each number displayed for approximately one second. Participants were asked to remember those numbers and type them in the reverse order. Average span was calculated to measure the direct-attention performance, which is an essential part of short-term working memory.[61] This task was previously used to measure the cognitive benefits of interacting with nature.[41,53]

To augment physiological and cognitive measures, self-reported emotion changes were also collected. Participants were requested to rate their emotion, including stress, frustration, engagement and excitement before (i.e. baseline) and after the experiment in test spaces. Scores of each emotion indicator were designed with a ranged from -2 to +2.

2.2.5 Procedure

Participants were randomly assigned into one of the following four exposure orders: 1) classroom with the virtual exposure first, 2) classroom with the physical exposure first, 3) office common area with the virtual exposure first and 4) office common area with the physical exposure first. All participants started each visit in a reception room with no windows and no plants (BIDI score = 0) where they completed the 5-minutes online baseline survey on a laptop (**Survey A1.1**). Following this, they took a 5-minutes rest at the reception room. During this period, their baseline physiological status including HR, SCL and BP were collected. After that, they moved to the test space. During the "physical exposure" part, they were required to spend 5-minutes sitting in the place without using any electronic devices (e.g. computer, phone or tablet device). During the "virtual exposure" part, the 360-degree video of the same environment (office common area/classroom) was projected on the VR device for participants to watch freely in 5 minutes. After each 5-minutes exposure, they were administered the cognitive test battery. After completing the test, there was a 5-minutes "washing out" period for them to have a rest in the reception room between cognitive test and the next exposure period. After finishing both the "physical" and "virtual" exposure, they last completed a space survey about their emotion and perception of the surrounding environment in the test space (**Survey A1.2**). Taken together, the experiment lasted approximately 1 hour, and a timeline summary of the procedure is shown in **Figure 2.2**. A week later, participants returned to the same building and repeated the procedure in the complementary environment with order randomly assigned.

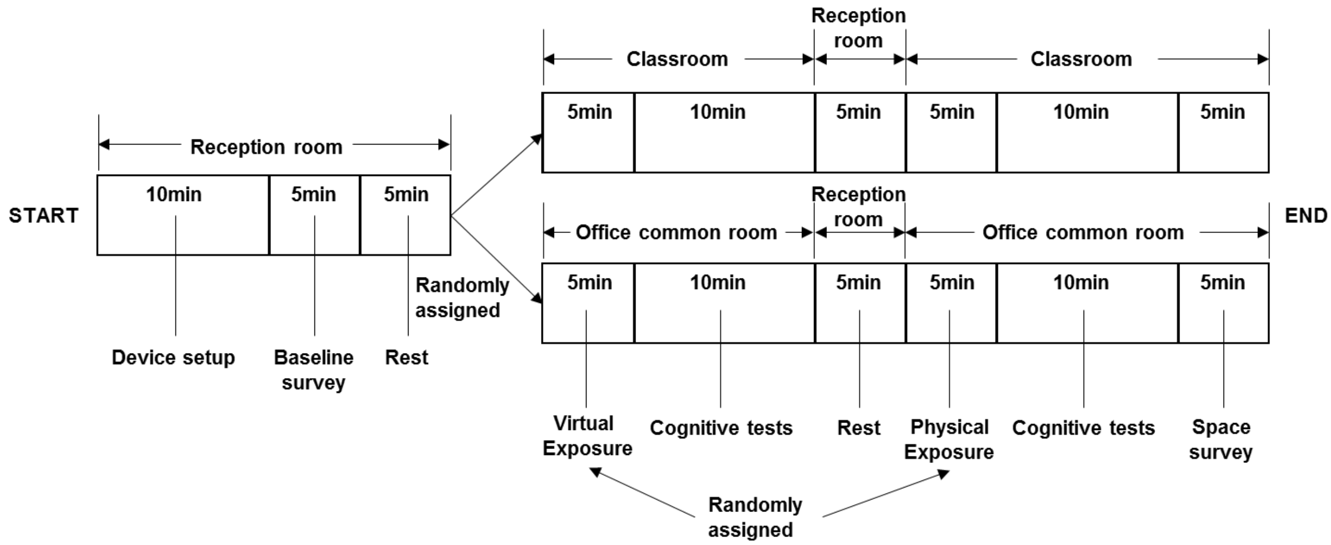

Figure 2.2 Timeline of experimental procedure (one visit)

2.2.6 Quality Assurance / Quality Control

Several empirical checks were implemented to ensure the validity of the experiment. First, we checked the balance among the sequences in the experiment after the randomization. There were four groups of the experiment for participants and the randomization of 56 visits yielded a ratio of 14:14:16:12, suggesting the different sequences are almost balanced. Second, we compared the physiological measures between the two rest periods by using paired t-test and found that the difference of their physiological measures were not statistically significant, indicating that the 5-minutes rest period had a successful washing out effect, which makes the measures between the physical and virtual exposure periods comparable.

2.2.7 Statistical Analyses

Paired t-tests (for data that is normally distributed) and Wilcoxon signed-rank tests (for data that is not normally distributed) were used to test the significance of the differences of physiological and cognitive responses between biophilic and non-biophilic environment, physical and virtual exposure, before adjusting for other variables. Since the data of outcome measures was clustered by the repeated measurements on each participant, marginal generalized linear models with generalized estimating equations (GEEs) were used to model the association between biophilic versus non-biophilic environmental exposure, physical versus virtual exposure and their physiological and cognitive outcomes, using participant's ID to identify the repeated observations of the same person. The statistical package SAS (version 9.4) was used for all statistical analysis.

For analyses of physiological data, we considered two main binary variables of interest: *environment* (biophilic vs. non-biophilic environment) and *approach* (physical vs. virtual exposure) in the marginal model. In order to assess whether the biophilic environment had the similar effect on physiological responses between physical and virtual exposures, we also added an interaction term between *environment* and *approach* in the model. We used the change of physiological measures from baseline as the outcome variables (e.g. ΔSBP) to adjust the potential differences of baseline measures for the same participant in two visits. We also assumed that the possible factors that may affect the baseline measure, including caffeinated beverage drinking, sleep quality before the experiment day and the stress level before experiment would have the same effect on the repeated measures during the same visit. Therefore, the regression model could be written as

$$E(Y) = \beta_0 + \beta_1 environment + \beta_2 approach + \beta_3 environment * approach \tag{2.1}$$

Where:

- Y = the changes of physiological measures (e.g. ΔSBP) from baseline

- *environment* =1 if participant was in biophilic environment, 0 in non-biophilic environment
- *approach* =1 if participant was virtually exposed, 0 if physically exposed
- β_1 = the main effect of biophilic environment compared to the non-biophilic environment
- β_2 = the main effect of virtual exposure compared to physical exposure
- β_3 = the difference of the effect of biophilic environment on responses in virtual vs. physical exposure

For analyses of cognitive data, we incorporated between-visit factors, including caffeinated beverage drinking, sleep quality before the experiment day and the stress level before experiment, which could affect the cognitive performance. In addition, we added the measure of time of visit to adjust for potential learning effect for cognitive performance. Therefore, the regression model could be written as

$$log(E(Y)) = \beta_0 + \beta_1 envrionment + \beta_2 approach + \beta_3 envrionment * approach$$

$$+\beta_4 coffee + \beta_5 sleep + \beta_6 genstress + \beta_7 visit \quad (2.2)$$

where:

- Y = the different cognitive measures. Since they were skewed, we used log link function in the model to log transfer the Y
- *coffee* =1 if had caffeinated beverages before experiment, 0 otherwise
- *sleep* =2 if had a nice sleep for sure, sleep=1 if maybe had a good sleep, 0 otherwise
- *genstress* = general stress level, which has a range from 1 (very little stress) to 5 (extreme stressful) to measure general stress level
- *visit*=1 if the first visit, visit=2 if the second visit

- β_{4-7} are the effect of caffeinated beverages drinking, sleep quality, general stress level and the time of visit
- *environment*, *approach*, and β_{0-3} have the same meanings as those in Model (2.1)

2.3 Results

2.3.1 Environmental Perception

According to participants' responses for the BIDI questionnaire in the space survey, the office common area was generally rated as "biophilic environment" (mean BIDI score=27 (out of 54)), while the classroom was generally rated as "non-biophilic environment" (mean BIDI score=3). The reception room is also a non-biophilic place (mean BIDI score =0).

2.3.2 Physiological Response

Participants showed more reductions in BP and SCL from baseline when in biophilic environment compare to that in the non-biophilic environment (**Figure 2.3**). The overall differential effects for participants experiencing an indoor environment with biophilic elements versus none was 8.56 (95%CI: 5.60-11.52) mmHg lower systolic and 3.57 (95%CI: 0.36-6.78) mmHg lower diastolic blood pressure. In addition, their skin conductance decreased 0.18μS (95%CI: -0.004-0.36) greater in biophilic environment than when they experienced the non-biophilic environment (**Table 2.1**). Significant changes in HR were not observed between the two environments.

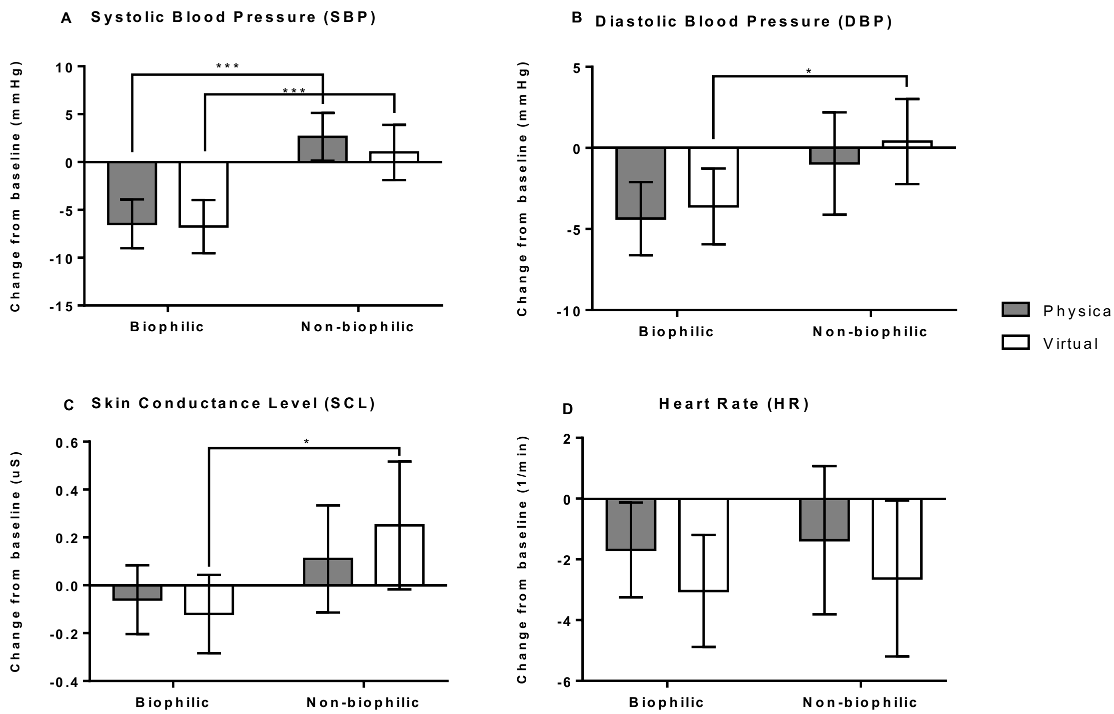

Figure 2.3 Physiological changes (SBP, DBP, SCL and HR) from baseline to physical and virtual exposure to biophilic and non-biophilic environments.
Note: * = p<.05, *** = p<0.001, generated by paired t-test. Error bars depict 95% confidence interval.

Table 2.1 Associations between physical and virtual exposure to biophilic and non-biophilic environments on the changes in SBP, DBP, SCL and HR compared to baseline.

	Environment (Biophilic vs. Non-biophilic)		*Approach* (Virtual vs. Physical)		*Environment* Approach*	
	Estimate	*p*	Estimate	*p*	Estimate	*p*
Incorporating interaction term						
ΔSBP (mmHg)	-9.11	<0.001	-1.64	0.17	1.36	0.44
ΔDBP (mmHg)	-3.39	0.055	1.36	0.24	-0.61	0.68
ΔSCL (μS)	-0.17	0.055	0.14	0.19	-0.20	0.17
ΔHR (1/min)	-0.33	0.80	-1.27	0.18	-0.08	0.94
After removing interaction term						
ΔSBP (mmHg)	-8.56	<0.001	-1.03	0.22		
ΔDBP (mmHg)	-3.57	0.03	1.20	0.17		
ΔSCL (μS)	-0.18	0.04	1.00	0.24		
ΔHR (1/min)	-0.37	0.76	-1.27	0.18		

Participants' responses to the environment were similar when they experienced it physically and virtually. The model results showed that there was no significant interaction between *environment* and *approach*, indicating that the physical and virtual exposure in biophilic environment had the similar effect on physiological responses. After removing the interaction term from the model, we found that the changes of physiological measures are not significantly different in physical exposure versus virtual exposure to the same environment.

2.3.3 Cognitive Function

Overall, participants performed better on the cognitive tests when they were in the biophilic environment. In the visual backward digital span task (**Figure 2.4 C**) where more digital memorized means better performance, participants scored 14% (95%CI: 5.3%-23.2%) higher in the biophilic environment compared to non-biophilic environment, after adjusting for caffeine intake, sleep quality, self-reported stress level and time of visit (Table 2). In the visual reaction time task and Stroop task, although participants scored higher when in the biophilic environment (2% and 6%, respectively), those improvements were not statistically significant at the 95% confidence level (**Figure 2.4 A&B**). In addition, we did not find an association between the time of visit and cognitive performance, indicating that there is no significant learning effect in the second visit.

Physical and virtual biophilic exposure had the similar impact on participants' cognitive performance. Since the estimate of interaction between environment and approach was not significant from the model result, it was removed from the model (**Table 2.2**). The results indicated that the improvements of cognitive performance were not dependent upon how the indoor environment was experienced (physical vs. virtual).

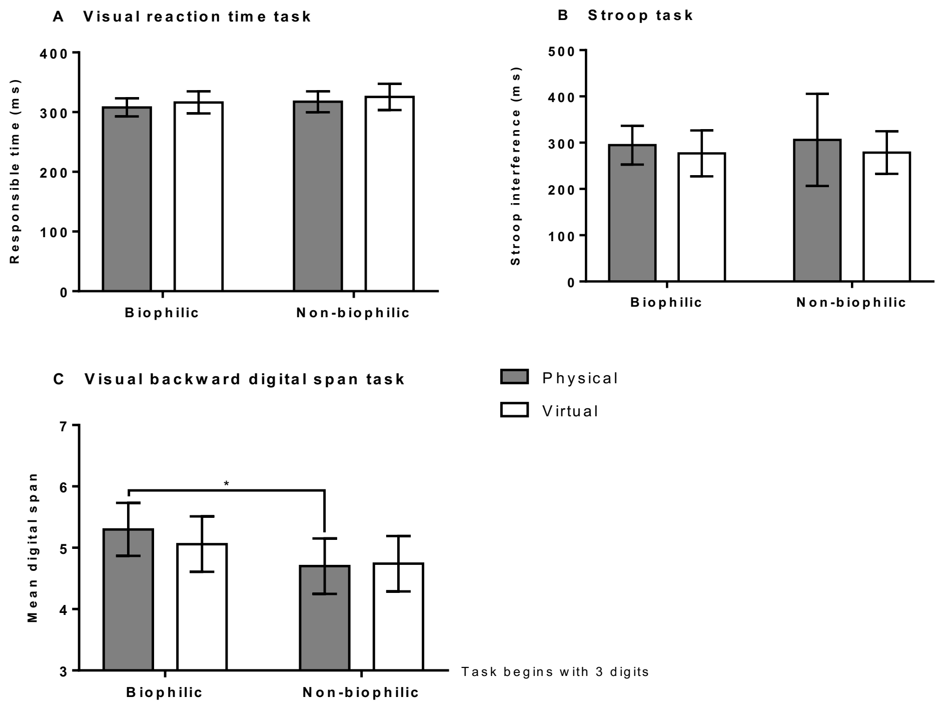

Figure 2.4 Cognitive performance (reaction time, Stroop inference and mean digital span) of physical and virtual exposure to biophilic and non-biophilic environments.
Note: *=*p*<.05, generated by Wilcoxon signed-rank test. Error bars depict 95% confidence interval.

Table 2.2 Associations between physical and virtual exposure to biophilic and non-biophilic environments on cognitive outcomes.

	Environment (Biophilic vs. Non-biophilic)		*Approach* (Virtual vs. Physical)		*Environment* Approach*	
	Estimate*	*p*	Estimate*	*p*	Estimate*	*p*
Incorporating interaction term						
Reaction time (mS)	-0.02	0.34	0.03	0.39	0.002	0.96
Stroop inference (mS)	-0.07	0.60	-0.09	0.61	0.03	0.88
Mean digit span	0.16	<0.001	0.01	0.77	-0.06	0.24
After removing interaction term						
Reaction time (mS)	-0.02	0.20	0.03	0.16		
Stroop inference (mS)	-0.06	0.44	-0.07	0.45		
Mean digit span	0.13	<0.001	-0.02	0.28		

*All the estimates were adjusted for caffeinated beverage drinking, sleep quality, general stress level and time of visit.

2.3.4 Self-reported Emotion Change

Participants reported reduced negative emotion and increased positive emotion. As shown in **Figure 2.5**, participants in the biophilic environment reported lower stress and frustration levels, higher engagement and excitement level compare to their responses in the non-biophilic environment. These findings are in line with our physiological and cognitive results, suggesting the improved emotion in experiencing the biophilic environment.

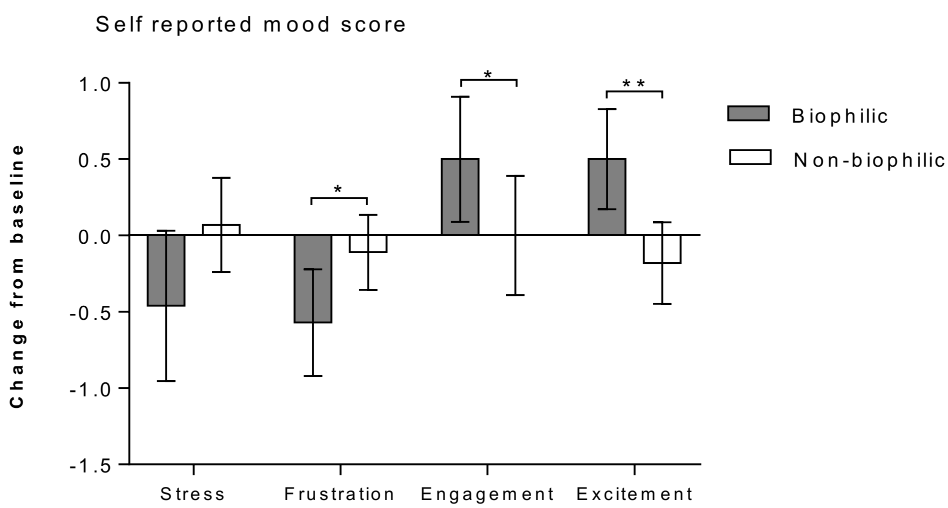

Figure 2.5 Self-reported emotion changes (stress, frustration, engagement, excitement) from baseline to biophilic and non-biophilic environments.

Note: Scores of each emotion indicator were designed with a ranged from -2 to +2. *=p<.05, generated by Wilcoxon signed-rank test. Error bars depict 95% confidence interval.

2.4 Discussion

This study investigated the physiological and cognitive responses to natural elements in indoor environment. Our findings indicate that including natural elements in the design of indoor spaces has “calming” effects as seen in the changes to blood pressure and skin conductance, as well as positive impacts on short-term memory. Importantly, the presentation of each environment in a virtual reality environment versus actual environment did not lead to significant differences in physiological or cognitive results, suggesting that virtual reality may elicit a similar biological response. This finding has two important implications: 1) it demonstrates that using VR to simulate visual exposures in research studies may be an appropriate alternative to experiencing the environment in person, which enables many research applications that may not be feasible without using VR, and 2) it suggests that experiencing nature in VR may be used to reduce stress.[2]

Our physiological results are consistent with the results from previous studies that were motivated by the *Stress Recovery Theory* (SRT).[14,62] which demonstrated the physiological impacts of nature elements on stress reduction.[11,14,41,63,64] According to the SRT, natural elements (e.g. scenes and sounds) activate our parasympathetic system that causes decreased heart rate, blood pressure, skin conductance, and salivary cortisol level. These responses could induce relaxation and help to reduce stress and autonomic arousal. This mechanism comes from our evolution as a species and our innate connection to natural world.[14] Although heart rate changes were not statistically significantly different, it was directionally consistent. In future studies of short-term effects, we will include measures of heart rate variability (HRV).[46,65]

Our cognitive results suggest that participants in the biophilic indoor environment performed better, especially for the short-term memory, after controlling for caffeine intake, sleep quality, general stress level and time of visit. These findings along with improved emotional affect are consistent with the *Attention Restoration Theory* (ART).[15,41,53] In urban environments, we can often be over-stimulated effecting our ability to concentrate and contributing to mentally and physical fatigue. Natural environments, on the contrary, contain elements which promote renewed attention by providing a sense of “fascination”, “being away”, "extent" and "compatibility".[15] Those could in turn have restorative effect and improve people's cognitive performance that requires direct attention.[53]

Despite observing differences by biophilic versus non-biophilic environments, we did not observe any differences based on how the participant experienced those environments; there were no statistically significant differences between the actual physical environment versus the presentation of the environment in a virtual setting. This finding related to the virtual reality environment aligns with Kjellgren et al. who found restorative effect were demonstrated when having a physical presence in a simulated natural environment.[52] These findings suggest that virtual reality may be a useful surrogate for actual exposure, in particular for populations who may be immobile (e.g., hospital patients) or office workers looking for a short-term respite from their typical office environment.

Our study has some important limitations. First, participants were young healthy adults. In that case, the generalizability of our results is limited. In addition, since this was the first study testing the physiological and cognitive response of biophilic indoor environment in both real environment and VR, we had no prior information on the variability of physiological and cognitive responses to do more formal power-sample size calculations. However, with data from this study, it's possible to estimate the sample size of similarly designed experiment going forward. Second, our study included only two conditions, one of which had a low biophilic design score (BIDI=3) and one with a moderate score (BIDI=27); it is possible that comparing a room with additional biophilic design components would lead to greater impacts. Third, our study was conducted in a building with good air quality and thermal comfort, as determined by previous indoor air quality investigations. Therefore, our study design does not allow parsing of effects to any single natural element or determining if there are interactions with biophilic design elements, air quality and/or noise. Different results might be expected if the settings had distracting noise, odors, lighting for example. Fourth, our design attempted to minimize differences in the physical and virtual settings by matching the temperature and weather, and time of the days between visits. We did observe that participants differed in some physiological measures at the baseline assessments between visits. Randomizing assignment to one of the four test settings was an attempt to minimize differences in participants at baseline. Although we tested for baseline differences and controlled for the between-visit variables in the analysis of the cognitive data, it's still possible that the differences in their baseline between visits may affect the physiological and cognitive changes during the experiment. Lastly, we were not blinding participants the test environments and they may realize that they were in biophilic or non-biophilic environment, which could affect their performance and therefore result in biased estimates of the effect of environment on their physiological and cognitive performance, although impacts on physiological performance would be less prone to bias.

2.5 Conclusion

We found that even short exposure to a biophilic indoor environment was associated with lower systolic and diastolic blood pressure and skin conductance level in comparison to their baseline measures. In addition, participants in biophilic environment had 14% better performance in short-term memory and improved emotions compare to their performance in the non-biophilic environment. These results may be partially explained by both the *Stress Recovery Theory* and the Attention Restoration Theory. Biophilic indoor environment may play an important role in improving population health and cognitive function yet have been overlooked. Moreover, our findings indicate that participants could gain the similar acute physiological and cognitive benefits of exposing to virtual biophilic indoor environment, which suggests that virtual reality might have the potential for reducing stress and improving cognitive function by providing exposures to natural elements in a variety of indoor settings where access to nature may not be possible, such as waiting rooms in clinics, dental offices, etc., where occupants often experience discomfort and anxiety. In addition, combining VR and wearable biomonitoring sensors makes it possible to test subjects' physiological responses to many simulated environments in a short period. Finally, the novel components of this study provide a methodology to further research on quantifying the health and cognitive impact applicable to many fields of endeavor, not just interior design of biophilic enhanced indoor spaces.

Chapter 3 - Effects of Biophilic Interventions in Office on Stress Reaction and Cognitive Function: A Randomized Crossover Study in Virtual Reality

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Authors contributions:

J.Y., N.A., and P.M. designed the study. J.Y. and N.A. performed the experiments and processed the data. J.Y. analyzed and interpreted the data with support from P.M. and P.J.C. J.Y. took the lead in writing the manuscript and N.A., P.M., P.J.C., J.G.A. and J.D.S provided critical revision of the manuscript for important intellectual content. P.M. coordinated this project. J.D.S and J.G.A supervised the project.

Publication

Yin J, Arfaei N, MacNaughton P, Catalano PJ, Allen JG, Spengler JD. Effects of Biophilic Interventions in Office on Stress Reaction and Cognitive Function: A Randomized Crossover Study in Virtual Reality. *Indoor Air.* 2019.

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 type 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 differentiate responses to two configurations and among biophilic elements.

Keywords: Biophilic design, Workspace, Human responses, Virtual reality, Eye-tracking, Biomonitoring sensors

3.1 Introduction

Indoor environmental quality (IEQ) plays an essential role in affecting productivity, health and well-being.[66] Those effects may be particularly prominent in workplaces, where full-time workers spend approximately one-third of their day, five days per week.[67] 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.[23] 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.[22,68-70]

Bringing natural elements indoors (i.e. biophilic design), has received increasing attention recently due to its potential health benefits.[18,44] It stems from the concept of *biophilia*, which literally means "love of life and living systems", which was popularized by Edward O. Wilson at 1984.[13] He and Stephen R. Kellert proposed the biophilic hypothesis in 1993, suggesting that human beings' innate connection with nature is essential for their wellbeing.[71] 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.[30] 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.[16,72] Efforts to promote the biophilic design in practice include identifying design attributes and categorizing them into three domains (i.e. 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.[16,17]

A significant body of existing research has shown the health benefits derive from contact with or emersion in nature occurring outdoors.[6,7,10,73,74] Less is known about possible health and well-being benefits of encountering nature indoors.[75] 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,[20,76,77] and helped students recover from mental fatigue and stress.[78] Indoor plants could provide psychological benefits such as stress-reduction, increased pain tolerance and restoration of attention capacity.[19,79] 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.[80,81] 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.[21,51,82] In addition to virtual exposure, haptic exposure such as touching wood has been found to have the effect on inducing physiological relaxation.[83] Lastly, natural forms and organizations in architecture were thought valuable for human emotional and cognitive function but little empirical evidence has been provided.[43]

These initial investigations have their limitations. First, the environmental exposure had often been based on a simplistic “nature/green” versus “built/lean” dichotomy.[84] 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.[85] 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.[2] Lastly, most of studies used self-reported measures of health and wellbeing, 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.[86] 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.[26,28,52,86] Virtual display of natural environments in various settings (e.g. forest, urban green space, streetscapes, biophilic indoor space) had been used to detect the effects on stress reduction, attention restoration, and cognitive function.[28,48,50,87] Eye-tracking, combining 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 (i.e. *natural elements*, *natural analogues*, and combination of both, referred to as '*combination*') across two types of workspaces (i.e. open space vs. enclosed space). In addition to physiologic measurements of stress reaction, we included cognitive assessments of creativity and attention.

3.2 Methods

3.2.1 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 T.H. Chan School of Public Health. Recruited between May and September in 2018, they were invited to visit the VR lab on two occasions (same time of day and 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 T.H. Chan School of Public Health. All participants provided informed consent and were compensated with $40.

3.2.2 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 increase statistical power (**Figure 3.2**). All participants visited the VR lab 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.

3.2.3 Environment Simulation and Eye-tracking

Choosing four patterns out of the 14 patterns of biophilic design,[17] 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 3.1**).

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: (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-labelled, and gaze intersection point data was 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 degree per second (deg/sec) as fixation and movements faster

Figure 3.1 Simulated virtual environments in enclosed space (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

than 300 deg/sec as saccades.[88] 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.[89] Only fixations were used to calculate the intensity of exposure to each object in the virtual biophilic environments.

3.2.4 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.[90] 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 (i.e. five minutes or less).[91] 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.[14] It's a widely used indicator for measuring physiological stress related to exposure to the natural environment.[28,48,78,92] 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.

3.2.5 Cognitive Function Measures

Thinking is characterized by divergent and convergent cognitive processes. Convergent tasks are mostly related with intelligence and could be divided into sub-categories 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 human,[15] our previous study has assessed the effect of indoor biophilic environment on attention, which is a key part of convergent thinking.[28] 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.[93]

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 (i.e. R: red, B: blue, Y: yellow, G:

green) accordingly.[94] Reaction time for each individual trial was measured as the performance metrics. AU test is a widely used and validated test for evaluation of creativity.[95] 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 (i.e. the number of interpretable, meaningful and relevant responses), flexibility (i.e. the number of different categories implied by responses) and originality (i.e. measured by the statistical rarity of the responses in a given sample).[95,96]

3.2.6 Experimental Procedure

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

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 (i.e. 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. Afterwards, 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 3.1**).

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, SCL were 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 an sufficient period of time for changing acute physiological stress level.[28,55,97] 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 A2.1**). After experiencing those four environments, they completed a 5-minute online survey (**Survey A2.1/A2.2**) 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 3.2**). In the second visit, participants repeated this procedure and experienced the remaining workspace.

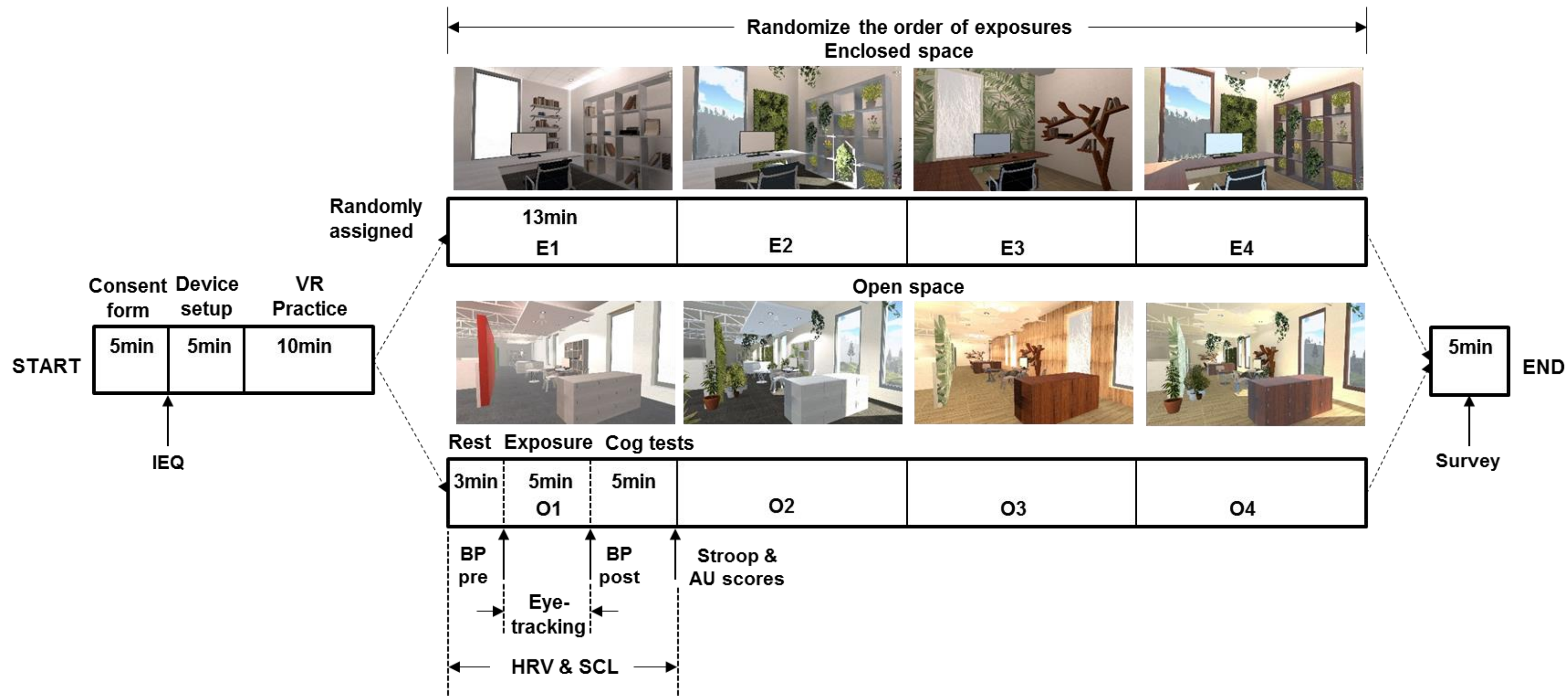

Figure 3.2 Timeline of experimental procedure and sampling (one visit)

3.2.7 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.[98] We found the IEQ indicators (i.e. 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 was right skewed, we log-transformed it. 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 (Model 3.1~3.3).[99] 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 0.05 was used to determine statistical significance.

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

$$\Delta Y_{ij} = \beta_0 + \beta_{1\sim3} environment + \beta_4 workspace + e_{ij} + \mu_i \quad (3.1)$$

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, 4 in the *combination* condition
- $workspace$ = 1 if participant was in open spaces, 0 in enclosed spaces
- $\beta_{1\sim3}$ = fixed effects of specific biophilic environment 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)

$$logY_{ij} = \beta_0 + \beta_{1\sim3} environment + \beta_4 workspace + \beta_5 incongruence + \beta_6 testnumber + \beta_7 coffee + \beta_8 sleep + \beta_9 genstress + e_{ij} + \mu_i \quad (3.2)$$

- $logY_{ij}$ = reaction time for participant *i* at trial *j* in *log* scale
- $incongruence$ = 1 if words presented in different color, 0 if congruently colored words
- $testnumber$ = the number of times participant was tested (1~8)
- *coffee* = 1 if had caffeinated beverages before experiment, 0 otherwise
- *sleep* = 1 if had a nice sleep, 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 and incongruent test (i.e. Stroop effect) in *log* scale
- β_6 = learning effect
- $\beta_{7\sim9}$ = fixed effect of caffeinated beverages drinking, sleep quality, general stress level
- *environment*, *workspace*, $\beta_{1\sim4}$ and μ_i have the same meanings as those in Model (3.1)

For standardized creativity score (AU test)

$$Y_{ij} = \beta_0 + \beta_{1\sim3} environment + \beta_4 workspace + \beta_5 testnumber + \beta_6 coffee + \beta_7 sleep + \beta_8 genstress + e_{ij} + \mu_i \tag{3.3}$$

- 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 (3.2), $\beta_{5\sim8}$ have the same meanings as $\beta_{6\sim9}$ in Model (3.2), 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 (i.e. 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 surroundings 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).[100]

3.3 Results

3.3.1 Demographics and Baseline Measures

Demographics of the 30 study participants and characteristics of the 60 visits are presented in **Table 3.1**. The participants had an average age of 26.3 ± 5.1 years, most of whom were graduate student 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 $p > 0.05$) (**Table A2.1**). 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.

Table 3.1 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
$PM_{2.5}$ ($\mu g/m^3$)	5.8 ± 5.4
Caffeinated beverage drinking	—
Yes	17 (28.3)
No	43 (71.7)

Table 3.1 (Continued)

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 (mmHg)	107.8 ± 9.2
Diastolic blood pressure (mmHg)	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

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

3.3.2 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 compare to those in the non-biophilic environments are shown in **Table 3.2**. The biophilic interventions had significant overall effects on reducing both systolic and diastolic blood pressure (SBP and DBP). Specifically, *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), 2.0 (95% CI: 0.3, 3.8) mmHg more SBP decreases and 2.8 (95% CI: 1.2, 4.4), 2.3 (95% CI: 0.75, 3.92), 2.7 (95% CI: 1.1, 4.3) mmHg more DBP decreases, comparing 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), 2.4 (95% CI: 0.0, 4.8) mmHg more SBP decreases and 4.1 (95% CI: 0.4, 5.1), 3.3 (95% CI: 1.3, 5.2), 2.6 (95% CI: 0.7, 4.6) mmHg more DBP decreases in *natural elements*, *natural analogues* and *combination* 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) beat 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 *nature elements* condition (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 meaning increased parasympathetic activities that related to stress relief, in *natural elements* and *combination* conditions but less in *natural analogues* condition. However, 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.

Table 3.2 Estimated difference (β and 95% confidence intervals) on pre-post physiological changes of stress reaction in biophilic environments compare to those in the non-biophilic environment among different workspaces.

	ΔSystolic Blood Pressure (mmHg)	ΔDiastolic Blood Pressure (mmHg)	ΔHeart Rate (1/min)	ΔRMSSD (ms)	ΔSkin Conductance Level (μS)
Overall					
Natural elements	-1.78 (-3.54, -0.02)	-2.77 (-4.35, -1.18)	-1.34 (-2.72, 0.04)	1.53 (-1.63, 4.70)	-0.13 (-0.51, 0.25)
Natural analogues	-2.23 (-3.99, -0.47)	-2.33 (-3.92, -0.75)	-0.75 (-2.13, 0.63)	-1.51 (-4.68, 1.65)	-0.08 (-0.46, 0.30)
Combination	-2.02 (-3.78, -0.26)	-2.70 (-4.29, -1.11)	-0.84 (-2.22, 0.54)	1.41 (-1.75, 4.58)	-0.18 (-0.55, 0.20)
Enclosed Space					
Natural elements	-0.33 (-2.96, 2.29)	-1.40 (-3.77, 0.97)	-1.05 (-2.63, 0.52)	0.99 (-2.57, 4.55)	0.01 (-0.40, 0.41)
Natural analogues	-1.80 (-4.42, 0.82)	-1.40 (-3.77, 0.97)	0.01 (-1.57, 1.58)	-0.53 (-4.09, 3.03)	-0.10 (-0.50, 0.31)
Combination	-1.63 (-4.26, 0.99)	-2.77 (-5.14, -0.40)	-0.66 (-2.23, 0.92)	0.68 (-2.88, 4.24)	-0.21 (-0.61, 0.20)
Open Space					
Natural elements	-3.23 (-5.59, -0.88)	-4.13 (-6.11, -2.16)	-1.63 (-3.18, -0.07)	2.08 (-2.02, 6.17)	-0.27 (-0.84, 0.31)
Natural analogues	-2.67 (-5.02, -0.31)	-3.27 (-5.24, -1.29)	-1.51 (-3.06, 0.04)	-2.06 (-6.59, 1.60)	-0.06 (-0.64, 0.51)
Combination	-2.40 (-4.76, -0.04)	-2.63 (-4.61, -0.66)	-1.03 (-2.58, 0.52)	1.56 (-1.95, 6.24)	-0.15 (-0.72, 0.43)

Note: Δ (delta) indicates the changes of physiological measures from baseline. RMSSD, root mean square of successive differences of beat intervals. Each exposure is in a separate generalized additive mixed effect model with a random effect for participant.

3.3.3 Cognitive Function

Effects of biophilic interventions on cognitive function are depicted in **Table 3.3**. Biophilic interventions had positive effects on improving creativity scores. Comparing to the performance in the non-biophilic environment, participants' scores of creativity test (i.e. AU test) were 0.3 (95% CI: 0.1, 0.5) and 0.2 (95% CI: 0.0, 0.4) standard deviation higher in *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), 0.4 (95% CI: 0.1, 0.7) standard deviation higher in *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, *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 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 that in general. We did not find significant learning effect in the AU test.

Table 3.3 Estimated differences on mean Z score of creativity and percentage changes in the geometric mean of reaction time (β and 95% confidence intervals) in biophilic environments compare to those in the non-biophilic environment among different workspaces.

	Differences on mean Z score of creativity	Percentage changes in the 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 were bolded.

3.3.4 Eye-tracking

Percentage of time participants spent on specific biophilic patterns in three biophilic environments are presented in **Table 3.4**. 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 *nature elements* and 55.1 ± 11.9% in *natural analogues* conditions, respectively.

Table 3.4 Percentage (%) of time participants spent on specific biophilic patterns measured by eye-tracking in three biophilic environment (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

The overall differences in percentage of time participants spent on biophilic elements in three biophilic environment are presented in **Table 3.5**. 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.

Table 3.5 Estimated differences in percentage (%) of time participants spent on biophilic elements measured by eye-tracking in three biophilic environment (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 were bolded.

3.3.5 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 *natural elements* condition (8.3 ± 1.2) than those 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.

3.4 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 in creative test scores for both enclosed and open spaces, with the largest effects seen with *natural elements* condition. 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.

3.4.1 Physiological Stress Level

Our physiological results indicated consistently that biophilic interventions had positive effects on reducing stress level (**Table 3.2**). 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.[21,101,102] 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 of diastolic blood pressure and heart rate.[73] We found increased RMSSD, although not statistically significant, in both *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 whilst viewing nature as compared to viewing buildings,[103] 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.[46]

3.4.2 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 (i.e. higher score from AU test) but distract from attention task which need participants to be more focused (i.e. 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).[104] 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.[105] 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.[106] 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 were reduced in an environment with indoor plants but increased in an environment with artificial window with a pleasing outdoor view.[92] 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.

3.4.3 Different Effects among Biophilic Designs and Workspaces

Simulating three types of biophilic design interventions (i.e. *natural elements*, *natural analogues*, 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 *natural analogues* condition. Participants' preference of biophilic patterns may also contribute to those difference. 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.[107]

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 (**Table 3.2** and **Table 3.3**). 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 one hand, those effect differences may be due to the characteristics of workspace (e.g. size, layout, function). On the other hand, participants were generally more physiologically stressed in the non-biophilic open space while 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 (i.e. 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 (**Table A2.2** and **Table A2.3**). Since we used the non-biophilic environment as the reference group in analyses, this would contribute to the different effects of biophilic interventions in enclosed vs. open workspace.

3.4.4 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 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 doesn't consider how people experience those natural environments.[48,108] 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.

3.4.5 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 (e.g. 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 (e.g. $PM_{2.5}$, temperature, relative humidity). Fourth, combining VR, eye-tracking and wearable biomonitoring sensors provide 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 degree video in VR.[28] More evidence on comparing virtual environment from VR modeling with real environment are 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 Stroop test but not in 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 adults 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.

3.5 Conclusion

Biophilic design, as a health promotion approach, could help reduce stress and improve creativity in office settings. Those effects differed in different type 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.

Chapter 4 - Restorative Effects of Biophilic Indoor Environment: A Between-subjects Experiment in Virtual Reality

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J. Yin, J. Yuan and N.A. designed the study. J. Yin and J. Yuan performed the experiments. J. Yin, J. Yuan and N.A. processed the data. J. Yin and J. Yuan analyzed and interpreted the data with support from P.J.C. J.Y. took the lead in writing the manuscript with support from J. Yuan. N.A., P.J.C., J.G.A., and J.D.S provided critical revision of the manuscript for important intellectual content. J.D.S and J.G.A. supervised the project.

Abstract

Previous research has demonstrated the positive associations between outdoor nature contact and stress reduction. However, similar effects of incorporating natural elements into indoor environment (i.e. biophilic design) have been less well studied. We hypothesize that exposure to biophilic indoor environments help people recover from stress and anxiety and those effects differ among different types of biophilic elements. To test these hypotheses, we conducted a between-subjects experiment with 100 participants using virtual reality (VR). Participants were randomly assigned to experience one of four virtual offices (i.e. one non-biophilic base office and three similar offices enhanced with different biophilic design elements) after stressor tasks. Their physiological indicators of stress reaction, including heart rate variability, heart rate, skin conductance level and blood pressure, were measured by biomonitoring sensors. Their anxiety level was measured using State-Trait Anxiety Inventory test (short version). We found that participants in biophilic indoor environments had consistently better recovery responses after stressor compare to those in the non-biophilic environment, in terms of reduction on stress and anxiety. Effects on physiological responses are immediate after exposure to biophilic environments with the larger impacts in the first four minutes of the 6-minute recovery process. Additionally, these restorative effects differ among three different types of indoor biophilic environments. This research provides evidence that biophilic design elements that impact stress recovery and anxiety. It also demonstrated the potential that virtual reality may be a way to bring nature and its therapeutic benefits to patients in hospitals.

Keywords: Biophilic design, Indoor environment, Environmental simulation, Stress recovery, Virtual reality, Biomonitoring sensors

4.1 Introduction

Human health and well-being have been affected by the quality of environments that people live in.[109] Urban living is usually related to long working hours, heavy workload, tight deadline and unsatisfied working environments.[110] Concurrently, the risk of mental disorders has been increased in the population bearing psychosocial work stressors in their working environments.[111,112] Previous studies have shown that city living and urban upbringing could affect people's neural social stress processing,[1,113] and are associated with higher rates of psychosis,[114] anxiety disorders and depression[31] than those growing up in rural areas. Moreover, mental disorders have already become one of largest factors in global disease burden.[115] Approximately one in five adults in the U.S. (i.e. 46.6 million) experienced mental illness, including anxiety and depression, which are often associated with, or triggered by, high level of stress.[116] Better understanding of interventions that ameliorate stress and anxiety are needed given their negative consequences on human health.[117]

Contacting with outdoor natural elements, settings and process has become a frequently used approach to seek relief from stressful urban lives,[118] which could be explained by people's innate affinity with nature since we were primarily exposed to nature during our evolutionary process.[13,14] Consensus has been reached that experience of natural environments are associated with increased psychological well-being and reduced risk factors of some types of mental illness.[119] Two theories have been proposed to explain the effect of exposure to natural environments on restorative benefits: attention restoration theory (ART)[15,120] and stress reduction theory (SRT).[14] ART proposed that natural environments abound with "soft fascinations" could replenish people's cognitive capacity and thus reduce their mental fatigue and increase their focus and attention.[15] SRT suggested that exposure to nature activate our parasympathetic nervous system and facilitate the psychophysiological stress recovery because of our innate preference for natural environment developed through evolution.[14] Although these two theories are debating the mechanisms of how nature affect human health, they both emphasized that exposure to natural environments could contribute to recovering from stress. Nowadays, we are living in a rapidly urbanizing world where accessibility to nature is typically limited.[29,121] Moreover, based on the statistic from the National Human Activity Pattern Survey (NHAPS), people spend almost 90% of their time indoors,[30] which indicates the further disconnected from nature.

In recent decades, biophilic design, stemming from the concept of *biophilia* which hypothesizes human have innate connection with nature, has become a new approach to incorporate the positive experiences of nature into the design of the built environment.[13,16,27,71] By bringing nature into living and working building spaces, people could increase their time and frequency of connecting with natural elements while being indoors.[72] Recently, building evaluating system, such as the *WELL*,[24] *Living Building Challenge*,[25] and *The 9 Foundations of a Healthy Building*[122] have listed biophilia into their design categories as a key element that can be implemented into the indoor environment to positively impact mood, sleep, stress levels and psychosocial status. In clinic settings, studies found that the inclusion of natural sounds, aromatherapy, green plants and views of nature into hospital interior spaces reduced mental stress, increased pain tolerance and shortened hospital stays.[17,19,20] Generally, although the effect of biophilic design on psychological responses has been previously summarized,[18] study investigating how it affects the physiological response in stress recovery process is limited,[78] and less is known about how different elements of biophilic design (e.g. green plants, long-distance natural view, biomorphic shape, natural materials) contribute to these health and well-being outcomes. Research on exploring independent effect of these biophilic elements is important for both research purposes and future design practices.

Previously, most of studies on assessing impacts of biophilic design elements were based on post-occupancy evaluation, one of the commonly used design evaluation methods. It is conducted by users after the completion of construction which prone to bias subjective. A pre-occupancy evaluation, on the other hand, could intentionally evaluate people's psychological and physiological responses to biophilic design and improve design strategies based on those responses prior to the construction. Virtual Reality (VR) provides us an innovative approach to achieve this goal.[86] By using simulated indoor environments in a laboratory setting, we could control variables, such as size and layout of the spaces and indoor environment quality, whilst enabling tailor different types of biophilic elements in a convenient way, to estimate the impact of a particular design strategy.

To contribute to the literature on restorative impact of biophilic indoor environment, this experimental study investigated effects of simulated biophilic indoor environments in VR on stress reaction and anxiety level in the recovery process following acute-mental stress. Our research hypotheses were: (1) recovery from stress and anxiety would be greater after exposure to biophilic environments compared to that in non-biophilic environment; (2) different biophilic environments have different impacts on physiological and psychological responses.

4.2 Method

4.2.1 Study Population

We recruited 100 healthy adults to participate in this study via the Harvard Decision Science Lab (HDSL, a university-wide research facility for behavior research) recruitment system (n=3619) from October to December in 2018. All qualified participants were Harvard affiliated faculty, staff and students. We posted the brief information of this study without disclosing the study objectives in HDSL's recruitment system to reduce the potential bias from self-selection. Participants voluntarily signed up for experiment with $15 compensation. Through the prescreening process, we excluded participants who self-reported that they took stress recovery medicine or therapy. The study was approved by the Institutional Review Board of Harvard T.H. Chan School of Public Health and all participants signed the consent form before the experiment.

4.2.2 Study Design

We used between-subjects design for this study based on two main reasons. First, to test the restorative effects of biophilic environments, we need to first increase participants' mental stress level. Using stressor only once for each participant would get the optimal effect on stress increase and avoid potential carry-over effect in experiment with within-subject design. Second, we intended to minimize the time of wearing VR headset to avoid potential negative feelings like nausea and headache from participants. Therefore, all participants engaged in a pre-designed stressor in VR to induce their mental stress level and were then randomly assigned to explore one of four virtual indoor office settings: one non-biophilic base office and three similar offices enhanced with different biophilic design elements (**Figure 4.1**).

4.2.3 Environmental Simulation

To test participants' responses in office with different biophilic design elements, we stimulated four three-dimensional virtual offices in VR by using Rhino5 software in advance and rendered in real time during experiment by using Unity software (version 2017.1.0f3) (**Figure 4.1**). We categorized different biophilic design elements into two conditions, "*indoor green*" and "*outdoor view*", for two reasons. First, we considered two major types of office spaces: with and without windows. Second, we re-organized biophilic elements based on their tangibility. Specifically, *indoor green* condition indicated that we incorporated green plants, water (fish tank), natural materials and biomorphic shapes into indoor space; *outdoor view* condition represented long-distance natural view and daylight through windows. In addition, we designed an office with the combination of both conditions, referred to as "*combination*", and used a non-biophilic office as the control setting. All four offices were identical in terms of all other elements.

A: *Non-biophilic* B: *Indoor green*

C: *Outdoor view* D: *Combination*

Figure 4.1 Four virtual reality office layouts

Note: *indoor green* incorporates green plants, water, natural materials and biomorphic shapes into indoor space; *outdoor view* incorporates long-distance natural view and daylight into indoor space through windows; *combination* incorporates biophilic elements from *indoor green* and *outdoor view.*

4.2.4 Outcome Measures

We measured participants' acute stress reaction through physiological indicators, including heart rate variability (HRV), heart rate (HR), skin conductance level (SCL) and blood pressure (BP). Specifically, the Movisens EcgMove3 (Movisens GmbH) was worn by participants with a chest belt and it acquired raw data of a single channel electrocardiography (ECG), from which secondary parameters like HRV and HR (1/min) were calculated. For HRV, we calculated time-domain HRV indicator: the root mean square of successive differences between normal heartbeats (RMSSD (milliseconds [ms]), and frequency-domain HRV indicator: low to high frequency ratio (LF/HF ratio). Higher value of RMSSD indicates increased parasympathetic activities, which results in stress relief.[123] LF/HF ratio is the ratio between the low frequency band power (0.04-0.15Hz) and high frequency band power (0.15-0.4 Hz), which estimates the balance between parasympathetic and sympathetic nervous activities, with low value indicating parasympathetic dominance.[123] The Movisens EdaMove3 (Movisens GmbH) collected SCL data (µS) to reflect the electro-dermal activity (EDA), and was worn on the left wrist of participants. SCL changes are caused by sweat gland secretions, which is controlled by the sympathetic nervous system activity.[14] The Omron EVOLV wireless upper arm blood pressure monitor (Omron Healthcare Inc.) was used to measure systolic and diastolic blood pressures (SBP and DBP (mmHg)). The ECG and EDA sensors collected data in real-time, measuring and calculating the HRV, HR and SCL every 30 seconds throughout the experiment. BP was measured at three timepoints: baseline, after stressor induction tasks (i.e. pre-recovery) and after 6-minutes recovery period (i.e. post-recovery) (**Figure 4.2**).

Additionally, we measured psychological indicator of anxiety level by using the six-item short-form of State-Trait Anxiety Inventory (STAI).[124,125] This short version consists of six questions and has been tested to have similar mean score from the full form of STAI, which includes 20 questions for anxiety state.[126] Test-retest reliability was maximized by preparing two versions test with different questions selected from the full STAI and randomly implementing for the pre-post recovery measures. Each short version STAI included three anxiety-positive questions (e.g. “I am nervous”; “I am sad”, etc.) and three anxiety-negative questions (e.g. “I am content”; “I am happy”). Items questioned participants on how they felt at the test moment which were rated on a four level scale (e.g., “Not at all”, “Moderately”, “Somewhat” and “Very Much”), and anxiety-positive questions were rated from one to four with higher scores indicating greater anxiety, vice versa for anxiety-negative questions. Mean scores of six questions indicated degrees of anxiety.

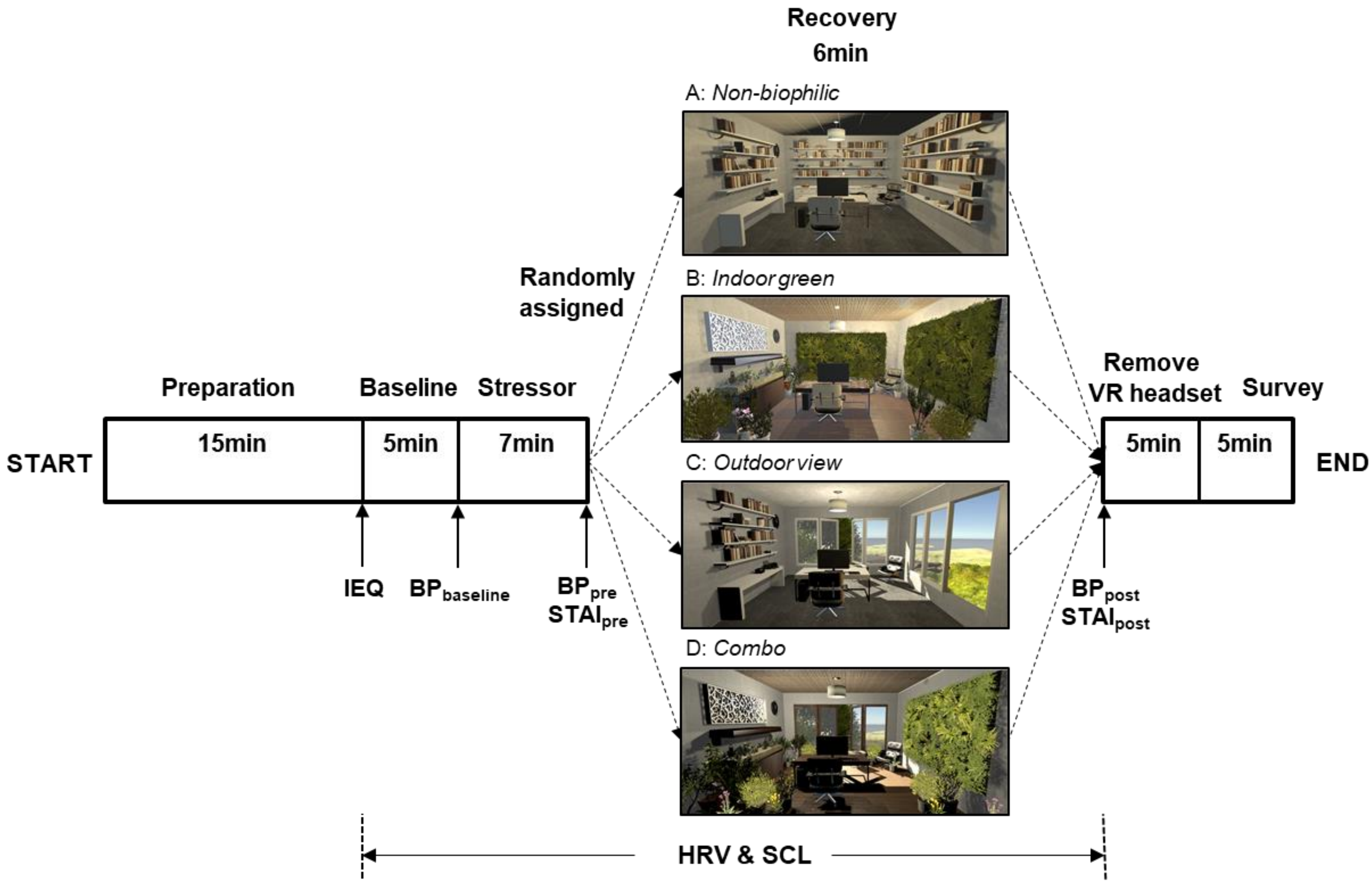


Figure 4.2 Experimental procedure

Note: IEQ: indoor environmental quality; BP: blood pressure; STAI: State-Trait Anxiety Inventory; HRV: heart rate variability; SCL: skin conductance level

4.2.5 Experimental Procedure

All experiments were conducted in the Harvard Decision Science Lab. The indoor environmental quality (IEQ) of the experimental settings, including temperature, relative humidity, CO_2 and $PM_{2.5}$ concentrations, were monitored by using a real-time sensor package.

The experiment includes three parts: preparation and baseline, stressor, and recovery (**Figure 4.2**). In the preparation and baseline period, participants signed the informed written consent. Then, they wore HTC Vive VR headset and biomonitoring sensor with the assistant of research staff. After that, participants were given a five-minute break and their baseline physiological measurements were recorded at the end of the rest.

In the stressor period, participants were exposed to a virtual office with untidy conditions and background noises from traffic, machinery and household appliances. They were instructed to finish two stress induction tasks (i.e. memory task and arithmetic task).[127,128] In the two-minute memory task, a series of three-digits numbers were displayed one after another on the screen of a virtual computer in VR. Each number was shown for only one second. After each series of numbers, participants had 20 seconds to put those numbers in the correct order. Each participant performed this task four rounds, with amount of those numbers increased from four to ten with increments of two. In the five-minute arithmetic task, participants were asked to keep counting backward from a random four-digit number in steps of a random two-digit number.[129] During these two tasks, to keep participants under alertness, they were informed that they would be carefully monitored during the tasks by the research staff and a buzzer would sound when incorrect answers were given.

After completion of these stress-induction tasks, participants were given the pre-recovery blood pressure measure and short version of STAI. Then, they were randomly assigned to experience a virtual office for six minutes recovery, slightly longer than 5-minute which has been shown in previous studies to be a sufficient time for inducing restorative effect.[28,46,55,97] They could walk and observe the indoor space freely for the first four minutes and then seat on a revolving chair and keep looking around for the rest two minutes. After that, post-recovery blood pressure was measured and a STAI was administrated again. Finally, all devices were removed from participants and they completed an online survey about their demographic information (age, gender and ethnicity), general health condition (excellent, very good, good, fair or poor), caffeinated beverage drinking (yes/no) and good sleep quality of the night before (yes/no), and stress level (Likert scales from 1 to 5: with 1 being very little stress, and 5 being extreme stress) (**Survey A3.1**). The whole experiment lasted around 45 minutes.

4.2.6 Statistical Analyses

To test the effectiveness of randomization, we conducted ANOVA to test whether IEQ, baseline physiological measures, stress and anxiety levels after stressor among four conditions were similar or not. To test the effectiveness of stressor, we conducted paired t-test, or Wilcoxon signed-rank test if the distribution of observed variable is not normally distributed, to determine if participants' physiological stress levels after the stress-induction tasks were significantly higher than their baseline measures.

We used the pre-post recovery differences among BP and STAI scores as the dependent variables in a linear model to analyze the differences of pre-post changes of BP and STAI scores in biophilic environments versus those in non-biophilic environment. The four virtual reality office layouts had been categorized as an independent variable with the non-biophilic environment as the reference (**Model 4.1**).

$$\Delta Y_i = \beta_0 + \beta_{1\sim3} environment + e_i \qquad (4.1)$$

Where:

- ΔY_i = the average pre-post changes of BP or STAI scores for participant *i*
- *environment* = 1 if participant was in non-biophilic environment, 2 in the *indoor green* condition, 3 in the *outdoor view* condition, 4 in the *combination* condition
- $\beta_{1\sim3}$ = effect of specific biophilic environment compared to the non-biophilic environment

For continuous measures like HRV, HR and SCL, we used a mixed effect model to analyze the effect of biophilic environments on recovery rate of those physiological indicators **(Model 4.2)** (R package 'gamm4', version 0.2-5). We treated participant as a random intercept in this model to control for the variability across individuals. In addition, we log transformed HRV and SCL data since they were right skewed.

$$(log)Y_{ij} = \beta_0 + \beta_{1\sim3} environment + \beta_4 time + \beta_{5\sim7} environment * time + e_{ij} + \mu_i \qquad (4.2)$$

Where:

- $(log)Y_{ij}$ = HR, *log* scale of HRV or SCL for participant *i* at time *j*
- $time$ = 1 if words presented in different color, 0 if congruently colored words
- $(exp)\beta_{5\sim7}$ = difference of mean recovery rates of HR or ratio of geometric mean recovery rate of HRV/SCL in biophilic environments versus those in non-biophilic environment

- μ_i = random effect of intercept for participant *i*
- *Environment* and $\beta_{1\sim3}$ have the same meanings as those in Model (4.1)

To better understand participants physiological responses within the six-minute recovery process, we extend the mixed effect model to compare the effect of biophilic environments on recovery rate of continuous outcome variables (i.e. HRV, HR and SCL) in every two minutes, representing the start, middle and end stages.

To test factors relating to participants' continuous physiological measures (e.g. HRV) recovery to their baseline (i.e. pre-stressor condition), we applied the Cox proportional hazards model for a time-to-event analysis (**Model 4.3**) (R package 'survival', version 2.44-1.1). In this model, we used the time it took each participant to recover physiological measures to pre-stressor conditions. We defined "complete recovery" as an event when participants' physiological measures recovery back to baseline measure. Individuals were censored if they did not achieve complete recovery during the 6-minute recovery period. We excluded participants whose physiological stress level did not increase after stressor in this model. The Cox model provided an estimate of the hazard ratio and its confidence interval, indicating the relative likelihood of complete recovery (i.e. recovery back to baseline measures) in participants in biophilic versus non-biophilic environment at any given point during recovery period. Since the hazard ratio (hr) also represents the odds that participants in biophilic environment will have complete recovery before participants in non-biophilic environment, we also calculated the probability of recovering first (P) = hr / (1 + hr).[130] All analyses were conducted in the open-source statistical package R (v.3.5.1)

$$\lambda(t; environment) = \lambda_0(t) exp(\beta_{1\sim3} environment) \tag{4.3}$$

Where

- t = time when participant had complete recovery
- $\lambda(t; environment)$ = hazard function determined by *environment*
- $\lambda_0(t)$ = baseline hazard. It corresponds to the value of the hazard in the non-biophilic environment
- $exp\ (\beta_{1\sim3})$ = hazard ratios. A hazard ratio greater than one in this case indicates that biophilic environment is positively associated with the probability for complete recovery, and thus indicates quicker recovery

4.3 Results

Results are presented in four sections. First, we report the demographic information and test the baseline (pre-stressor) differences of demographics, IEQ and physiological measures to confirm the effectiveness of randomization. We also test the post-stressor differences of physiological measure to ensure there are no pre-recovery group differences. Second, we examine effects of biophilic environments on pre-post changes for momentary measures (i.e. BP, STAI). Third, we explore the same effects on recovery rate for continuous measures (i.e. HRV, HR and SCL). Finally, we investigate those effects on time to complete recovery for those continuous measures.

4.3.1 Demographics, Baseline Measures and Stressor

The overall characteristic of the 100 participants and characteristic of four conditions after randomization on demographics and the indoor environmental quality of their visits are presented in **Table 4.1**. Participants had an average age of 29.2 ± 11.8 y, with 63% of whom were female and 41% of whom were white. 81% of participants self-reported very good or excellent health conditions. 75% of participants reported a good sleep and 44% of participants had caffeine beverage before they came to the experiment. The indoor environmental quality was consistent during the experimental periods. For example, the average $PM_{2.5}$, CO_2, temperature and relative humidity were 0.3 ± 0.6 μg/m^3, 716 ± 121 ppm, 21.3 ± 1.2 °C, and 36.7 ± 10.0 %, respectively. There were no statistically significant differences of demographics and IEQ among four conditions after randomization. In addition, the baseline physiological measures were similar among four conditions with no significant differences. The absence of differences across baseline measures among four groups indicated the success of the randomization (**Table 4.1**).

Participants' mean and median physiological and psychological measures among four groups at baseline, pre-recovery (i.e. post-stressor) and post-recovery are shown in **Figure 4.3** and **Table A3.1**. Our results from paired t-tests and Wilcoxon signed-rank tests suggest that participants' physiological stress level increased significantly after experiencing stressor. In addition, our ANOVA results suggest that effect sizes for between group differences in BP, STAI, SCL HR, and HRV are not significant with all p-values > 0.05. Therefore, there were no significant differences in stress and anxiety level after stressor among four groups.

Table 4.1 Characteristics of study participants (n=100) and indoor environmental quality at baseline of the experiment

Baseline characteristics	Mean ± SD or n (%)				
Environment	**Overall**	**Non-biophilic**	**Indoor Green**	**Outdoor View**	**Combination**
Number of Participant	100	25	25	25	25
Age	29.2±11.8	28.2±11.0	27.3±8.0	31.4±12.4	29.8±15.2
Gender	-	-	-	-	-
Female	63(63)	16(64)	15(60)	16(64)	16(64)
Male	37(37)	9(36)	10(40)	9(36)	9(36)
Ethnic	-	-	-	-	-
White	41(41)	9(36)	11(44)	7(28)	14(56)
Asian	24(24)	9(36)	5(20)	4(16)	6(24)
Black	17(17)	3(12)	6(24)	5(20)	3(12)
Multiracial	11(11)	3(12)	3(12)	5(20)	0(0)
Latino	6(6)	1(4)	0(0)	3(12)	2(8)
No response	1(1)	0(0)	0(0)	1(4)	0(0)
Self-reported health condition	-	-	-	-	-
Excellent	38(38)	13(52)	10(40)	6(24)	9(36)
Very good	43(43)	5(20)	10(40)	14(56)	14(56)
Good	17(17)	6(24)	5(20)	4(16)	2(8)
Fair	2(2)	1(4)	0(0)	1(4)	0(0)
Good sleep quality	-	-	-	-	-
Yes	75(75)	17(68)	18(72)	21(84)	19(76)
No	25(25)	8(32)	7(28)	4(16)	6(24)
Take coffee before experiment	-	-	-	-	-
Yes	44(44)	13(52)	12(48)	11(44)	8(32)
No	56(56)	12(48)	13(52)	14(56)	17(68)
Indoor environmental quality	-	-	-	-	-
$PM_{2.5}$ (μg/m^3)	0.3±0.6	0.4±0.4	0.4±0.7	0.3±0.7	0.3±0.5
Temperature (℃)	21.3±1.2	21.4±1.3	21.3±1.1	21.4±1.1	21.3±1.2
Relative Humidity (%)	36.7±10.0	32.3±10.0	38.6±8.9	39.6±8.9	36.4±9.8
CO_2 (ppm)	716±121	716±115	689±143	740±143	719±117

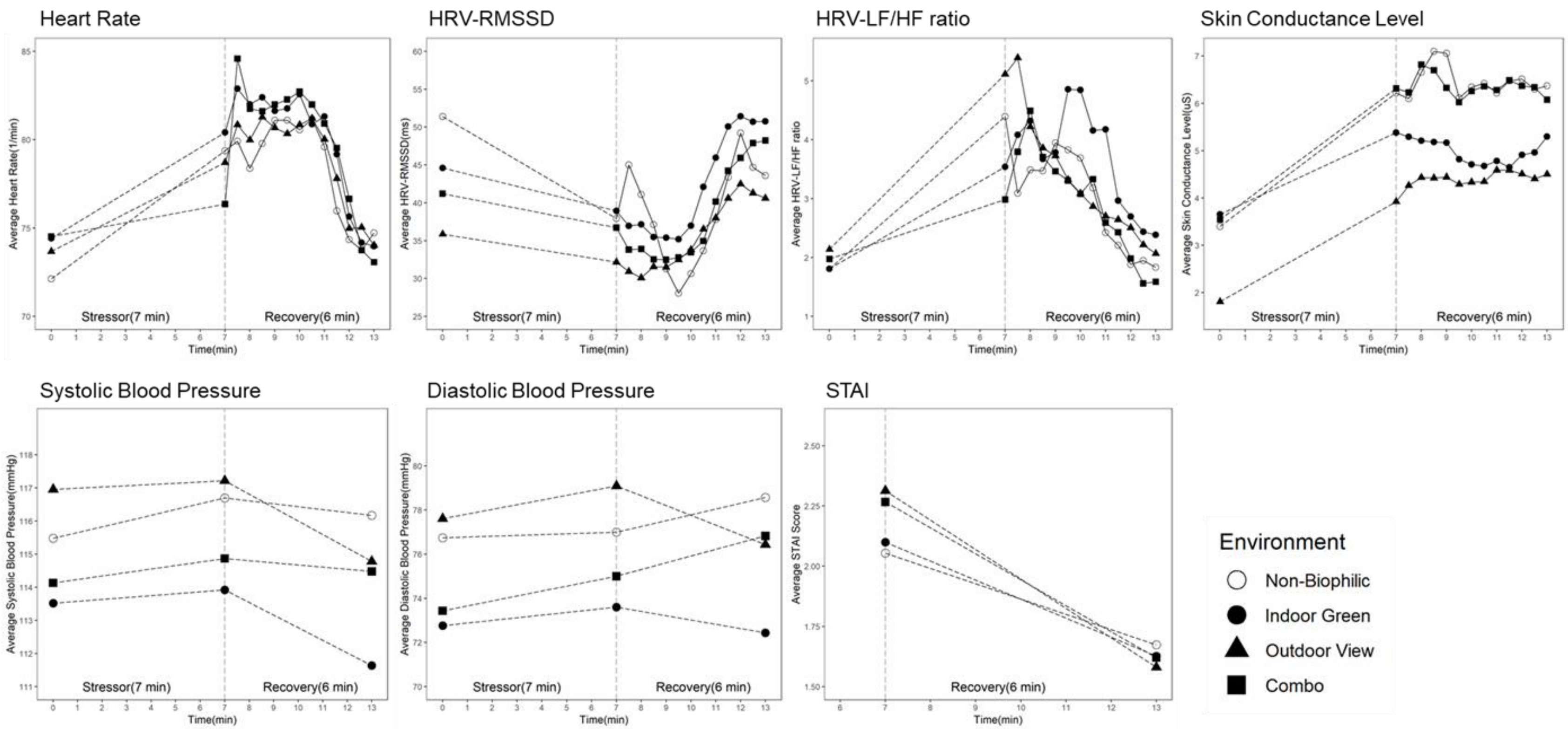


Figure 4.3 Mean physiological and psychological outcomes in baseline, after stressor and during the recovery period among four environments

Note: HRV: Heart Rate Variability; RMSSD: Root mean square of the successive differences; LF/HF Ratio: Low to high frequency ratio. STAI: State-Trait Anxiety Inventory. High RMSSD and low LF/HF indicate low stress level.

4.3.2 Effect of Biophilic Environments on Pre-post Changes of BP and STAI

Comparing to the non-biophilic environment, participants in biophilic environments during recovery process had consistently greater decreases of both systolic blood pressure (SBP) and diastolic blood pressure (DBP) (**Figure 4.4** and **Table A3.2**). Specifically, *indoor green, outdoor view* and *combination* conditions were associated with 3.1 (95% CI: -0.3, 6.5), 1.0 (95% CI: -2.5, 4.5), 1.3 (95% CI: -2.1, 4.7) mmHg greater decreases in SBP as well as 4.5 (95% CI: 0.7, 8.2), 3.9 (95% CI: 0.1, 7.7), 1.2 (95% CI: -2.5, 5.0) mmHg greater decreases in DBP, respectively.

In general, participants reported lower STAI scores after recovery compare to their scores before recovery (i.e. post-stressor) in all four conditions, indicating they were recovered from anxiety (**Figure 4.3** and **Table A3.2**). Comparing the decrease of STAI scores in non-biophilic environment, participants in the *outdoor view* and *combination* conditions had 0.4 (95% CI: 0.0, 0.7) and 0.3 (-0.1 0.6) greater decrease in STAI score reaching borderline significance, respectively (**Figure 4.4** and **Table A3.2**). However, the difference of STAI decreases between *indoor green* condition and non-biophilic environment was close to the null and not statistically significant.

4.3.3 Effect of Biophilic Environments on Recovery Rates of HRV, HR and SCL

Estimated differences of mean recovery rates of HR and percentage changes in the geometric mean recovery rate of HRV/SCL in biophilic environments (*indoor green*, *outdoor view* and *combination*) versus those in non-biophilic during the 6-minute recovery period are shown in **Figure 4.4** and **Table A3.2**. We assumed linear recovery rate during recovery process to compare the overall restorative effect between biophilic and non-biophilic environments. We found that participants in biophilic environments had faster RMSSD increase rates in the recovery process, comparing to the change rate in the non-biophilic environment. Especially, the geometric mean increase rate of RMSSD (ms/min) were 2.1% (95% CI: 0.0%, 4.3%) faster in *indoor green* conditions, suggest significantly better stress recovery in this environment.

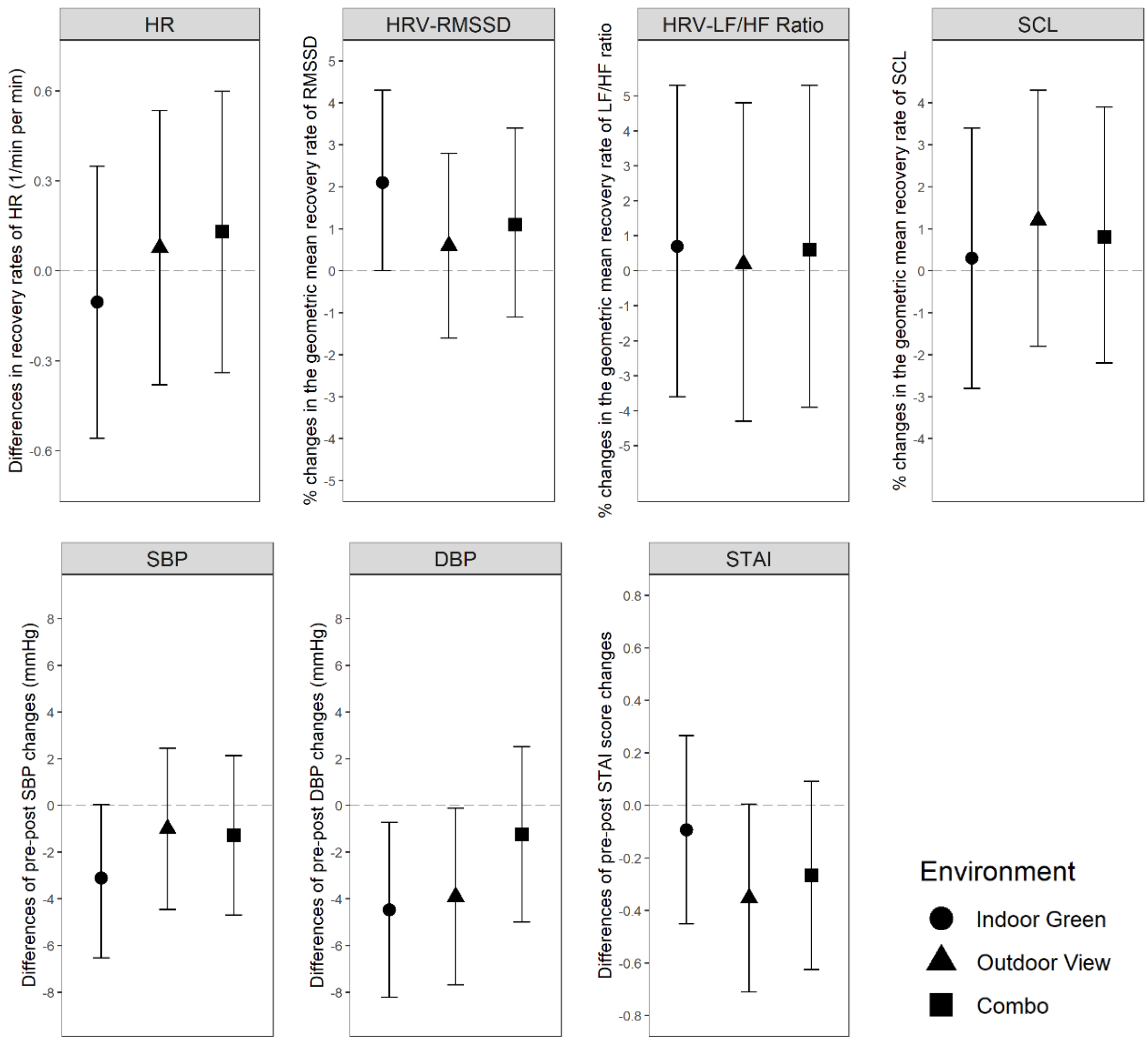


Figure 4.4 Estimated differences in recovery rates of heart rate (HR), percentage changes in the geometric mean recovery rate of heart rate variability (HRV) and skin conductance level (SCL), and differences in pre-post changes in blood pressure (SBP & DBP) and state-trait anxiety inventory (STAI) score in biophilic environments versus those in non-biophilic during the 6-minute recovery period.

Note: RMSSD: Root mean square of the successive differences; LF/HF: Ratio of low frequency to high frequency; We log transformed HRV, SCL data in the regression model. Error bars depict 95% confidence interval.

In addition, we also find the relative effect on RMSSD were different within three stages of recovery process. Specifically, in the middle stage, the geometric mean increase rate of RMSSD were 4.7% (95% CI: 0.6%, 8.9%) faster in *indoor green* condition and 4.3% (95% CI: 0.2%, 8.6%) faster in *outdoor view* condition, respectively (**Figure A3.1** and **Table A3.3**). However, we did not find significant difference of recovery rates of LF/HF ratio, HR and SCL between biophilic and non-biophilic environments.

4.3.4 Effect of Biophilic Environments on Time to Complete Recovery

Estimated hazard ratio of complete recovery for physiological measures in biophilic environments compare to non-biophilic environment in 6-minute recovery period are shown in **Figure 4.5**. Since SCL measure in four groups kept stable during recovery period rather than reduced back to baseline, we exclude it in the time-to-event analysis. After excluding participants whose stress level did not increase after stressor, we had n=70, n=45, n=63 in Cox model for HR, RMSSD and LF/HF ratio, respectively. The hazard ratios of complete recovery for HR in biophilic environments were all larger than 1, and significant in *indoor green* condition (hr=2.3, 95% CI: 1.0, 5.5) and *combination* condition (hr=2.5, 95% CI: 1.0, 6.2). These corresponds to a 70% and 72% chance of the participants' getting complete recovery of HR first in *indoor green* and *combination* condition, respectively. We also observed the similar trend for RMSSD measure in *indoor green* (hr=2.6, 95% CI: 0.9, 7.5), and *combination* (hr=2.8, 95% CI: 1.0, 8.1) conditions. However, we did not find significant hazard ratios for LF/HF ratio in biophilic environments. These results suggesting that throughout the recovery period, the participants in biophilic environments recovered faster.

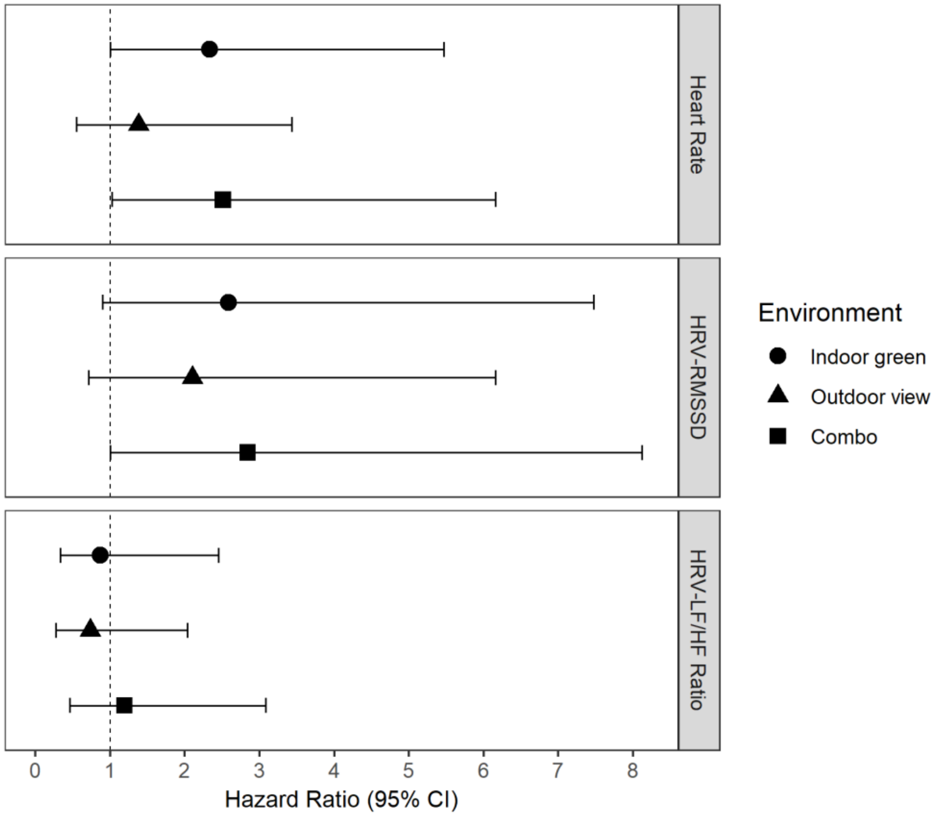


Figure 4.5 Estimated hazard ratio of complete recovery for physiological measures in biophilic environments compare to non-biophilic environment in 6-minute recovery period.

Note: HRV: Heart Rate Variability; RMSSD: Root mean square of the successive differences; LF/HF: Ratio of low frequency to high frequency. Error bars depict 95% confidence interval. Hazard ratio indicates the relative likelihood of complete recovery in participants in biophilic versus non-biophilic environment at any given point during recovery period.

4.4 Discussion

In this study, 100 participants were randomly assigned to explore one of four virtual indoor environments: one non-biophilic base office and three similar offices enhanced with different biophilic design elements termed as *indoor green*, *outdoor view* and *combination*, respectively. Overall, our results strongly support our first hypothesis that participants in biophilic environments had consistently better post-stress restorative responses on physiological stress level and psychological anxiety level compare to those in the non-biophilic environment. Although not statistically significant, those restorative effects differed among the three different types of indoor biophilic environments, with *indoor green* condition facilitated more on physiological stress recovery and *outdoor view* condition affected more on anxiety reduction. Within the recovery period, we also found the biophilic environments had the largest effect on reducing physiological stress in the first four minutes of the six-minute recovery process.

4.4.1 Benefits of Biophilic Environments on Restoration

Our physiological results from mixed effect model and Cox model indicated that participants in biophilic environments had consistently better recovery from stress. An study from Ulrich found that patients in a room with a window view of natural setting had shorter hospital stays and fewer analgesic than those in similar rooms with a view of brick building wall.[20] He and his colleagues also found physiological recovery (e.g. SCL, pulse transit time (correlated with SBP)) was faster and more complete when people were viewing natural rather than urban environments through videotapes.[14] Recently, a randomized controlled experiment testing restorative impact of views to school landscape suggested that window view to green landscapes significantly increased student's recovery from stressful experience by measuring their short-term HRV (LF/HF) and SCL.[78] Our findings on the physiological responses during the restoration process are in accordance with the stress recovery theory (SRT) which suggested viewing natural environments can reduce physiological stress and aversive emotion since we evolved to have an innate preference for those environments.[14] Moreover, the four physiological measures (i.e. heart rate variability, hear rate, skin conductance level and blood pressure) reflect activity in different bodily systems all relate to autonomic nervous system. The consistent trends across these physiological responses strengthened the SRT that biophilic environments could help reduce physiological stress level.

In addition, we could observe from **Figure 4.3** that mean value of most physiological indicators of post-recovery stress level went back to, or even lower than, their baseline measures for those participants in biophilic environments, indicating complete recovery. One exception is SCL, which kept stable and did not recover back to baseline in all these four environments, indicating sympathetic nervous system activity during 6-minute recovery period were still active and more time may be needed for its recovery. Further, the hazard ratio, which was derived from the Cox model, suggested participants' HR and RMSSD were recovering faster in the biophilic environment, which provides evidence that biophilic environments could promote restoration from another perspective.

4.4.2 Different Effects among Three Biophilic Environments

In this study, we found different restorative effects on physiological stress indicators among three different indoor biophilic environments. The *indoor green* condition had greater effects on reducing physiological stress than other conditions. Previous study found that indoor green plants in working environments reduced stress and increased the overall well-being. Indoor spaces with plants can improve human attitudes, behaviors and physiological responses.[42,131,132] The *outdoor view* condition had better effect on reducing anxiety (measured by STAI score) followed by *combination* condition. View of landscapes had more complexity compared to indoor environments and a glimpse of the world offered by the window view can quickly transport one's attention. This result was widely agreed by many studies that views to green spaces improved work performance, increased student's recovery from stressful experience and correlated with employees' satisfaction and stress reduction.[78,133]

The major difference between *indoor green* and *outdoor view* conditions is the type of the biophilic elements inside each environment. Specifically*, indoor green* condition had uniquely tangible items, such as green plants, wooden material and fish tank, while *outdoor view* condition incorporated intangible items, such as large windows with natural light and views of trees and water. Our results indicate that indoor biophilic elements facilitate the recovery of physiological stress and window with outdoor view and light facilitates the recovery of anxiety. The results from *combination* condition strengthen this argument since it had the moderate effect on improving both physiological stress level and psychological anxiety level.

4.4.3 Strengths & Limitations

Physiological monitoring of participants to assess stress and anxiety while experiencing three-dimensional simulated virtual environments in VR is an innovative approach. Compared to traditional 2-D video and picture, 3-D simulated virtual environment provides more immersive experience. Using VR simulations, we could control the design elements of indoor environment. Secondly, randomized between-subject design reduces confounding factors. Thirdly, the large sample size and balanced design led to distinguishing effects among the different biophilic designs. Forth, consistent results were obtained among multiple statistical approaches applied.

Our study has a few limitations. There is always the criticism that VR simulations are not "real world" conditions where other sensory stimulations are experienced. Studies found that stress recovery process also related to auditory,[134] olfactory,[135] thermal comfort,[136] or people's interaction with the surroundings.[137] VR simulations in this study did not include these factors which would be present in reality. As a counterpoint, however, using VR allows us to isolate and study specific pathways for study (e.g., visual impacts) that studies in the real-world may not be able to isolate due to the complex mix and pattern of other sensory factors (e.g., noise, light, temperature). In addition, our previous research showed consistent physiological and cognitive responses to biophilic interventions when participants experience them in the real-world as well as in VR.[28] Second, we did not measure changes affective state of mood, which may be an important mediator in the pathway of exposure to biophilic environments and reduced stress and anxiety.[134,138] Third, our studies should to be extended to indoor environments other than offices. It is our intention to apply VR simulations to other indoor settings including, assisted living, health care, hospitals, classroom, hospitality, and retail.

4.5 Conclusion

In this between-subject experiment with 100 participants, we combined virtual reality and wearable biomonitoring sensors to test the restorative effect of biophilic elements on stress and anxiety. Generally, biophilic environments had larger restorative impacts than non-biophilic environment in terms of reducing physiological stress and psychological anxiety level. Additionally, restorative effects differ among three different types of indoor biophilic environments with indoor biophilic elements (i.e. green plants, wooden material) facilitate the recovery of physiological stress, and having a window with daylight and an outdoor view to natural environments facilitated the recovery of anxiety. This research demonstrates a tool for architects, interior designers and developers to better understand human-environment interaction in the pre-occupancy building evaluation and aid in selecting biophilic design features to reduce stress and anxiety. Additionally, it provides evidences on the restorative effects of biophilic design in indoor environments and demonstrates the potential that virtual reality may be a way to bring nature and its therapeutic benefits to people who cannot get out to experience it firsthand, like patients in hospitals.

Chapter 5 - Conclusions

This dissertation set out to explore and quantify the short-term health impacts of brining nature indoors (i.e. biophilic design). Although benefits of contacting outdoor nature has been well documented, the literature on investigating physiological and cognitive responses to natural elements in indoor spaces is limited. The dissertation sought to provide evidences to answer three main questions:

1. Would virtual exposure to simulated indoor biophilic environments produce effects similar to those in real environments?
2. How would different biophilic design patterns impact occupants in different workspaces (enclose vs. open)?
3. How do different biophilic design strategies impact the recovery process of stress and anxiety after a mental stressor?

In this dissertation, we conducted three experiments through virtual reality (VR) to address those questions. The results from both within-subject (Chapter 2 and Chapter 3) and between-subject (Chapter 4) experiments clearly indicated that biophilic environments outperform non-biophilic environment in buildings in terms of reducing physiological stress and improving cognitive function.

5.1 Summary of Empirical Findings

In Chapter 2, we developed the Biophilic Interior Design Index (BIDI), which was based on the 14 patterns of biophilic design and centers around a questionnaire asking participants to rate their perceptions of biophilic features, such as plants, water, airflow, light, materials, biomorphic patterns, and long-distance view; response to these questions were used to calculate a space's score. We found that 5-minute exposure to biophilic indoor environment was associated with greater decrease in systolic blood pressure, diastolic blood pressure, skin conductance level, and improved short-term memory, comparing to those in the non-biophilic environment. More importantly, the presentation (i.e. 360-degree video) of each environment in a VR versus actual environment did not lead to significant differences in physiological or cognitive results, suggesting that experiencing in VR may elicit a similar acute biological response.

Following the findings from Chapter 2, we moved a step further in Chapter 3 and investigated the independent effects of specific biophilic design patterns in different workspaces. Instead of 360-degree video, we used VR modeling to tailor different biophilic features in office settings while keep all other features identical. We also added eye-tracking technology into VR headset to capture peoples' individualized exposure to biophilic design rather than simply the level of biophilia in their surrounding environment. Generally, biophilic office environments were associated with the reductions in physiological stress and improvements in creative test scores for both enclosed and open spaces, with the largest effects seen with *natural elements* condition, which included green plants and access to natural light and view. Reaction times on focused tasks, however, were slower in the biophilic environments. We also found that those effects of similar biophilic interventions were different in open vs. enclosed workspaces.

In Chapter 4, we sought to investigate the restorative effects of biophilic design by testing the effect of different indoor biophilic features on stress and anxiety during a 6-minute recovery process after a mental stressor. We found that biophilic environments have greater restorative impacts than non-biophilic environment, including greater decrease of blood pressure and anxiety, faster recovery rate of heart rate and indicators of heart rate variability (e.g. RMSSD). Additionally, restorative effects differ among three different types of indoor biophilic environments, with green plants facilitate the recovery of physiological stress and window with outdoor natural view facilitates the recovery of psychological anxiety.

5.2 Theoretical and Practical Implications

Empirical results of Chapter 2, 3 and 4 demonstrated the clear health benefits of bringing nature indoors. Our findings from VR studies are consistent with the previous evidence from other research on natural contact and benefits to several health outcomes. Our work supports the role of visual capture effect, which considers vision as the dominant sense over other sense modalities in creating a perception.[139] During the perceiving process, visual senses are influencing the other parts of the somatosensory system and guiding the rest of the somatosensory cues to be perceived as if they are associated with visual experience. More importantly, our findings support both *Stress Recovery Theory* (SRT) and *Attention Restoration Theory* (ART). Our physiological data indicated the consistent trends across different indicators on stress reduction. Specifically, participants in different biophilic environments had higher value of RMSSD, which is a time-domain HRV indicator, suggesting the increased parasympathetic activities, which were related to stress relief. Also, our cognitive data also demonstrated that biophilic features promote short-term memory and creativity, which could be triggered by attention restoration. However, the interrelationship between physiological and cognitive responses are still inconclusive.

The findings of this dissertation have several practical implications. First, this dissertation developed a new empirical research tool by combining virtual reality, eye-tracking and wearable biomonitoring sensors to quantify the human responses to virtual biophilic environments. This tool provides a potential for objective virtual exposure assessment, which could be useful for pre-occupancy building evaluation to better understand the human-environment interaction during the design process. Second, our findings give rise to the possibility of reducing stress and improving cognition by using virtual reality to provide immersive virtual experience of natural elements in a variety of indoor settings where access to nature may not be possible, for example, PTSD, pain and palliative care. Third, our findings suggest that people's physiological and cognitive responses to biophilic indoor environment related to both features of biophilic design and types of space. It encourages more research across different design patterns and indoor settings to explore what are the appropriate biophilic design features to use for reducing stress level and improving cognitive function. Collected scientific evidence could contribute to initiating design guidelines to promote tailored biophilic design for diverse indoor spaces.

5.3 Recommendations for Future Research

While this dissertation represents a significant step towards quantifying the health impact of biophilic design in buildings, there is still more to be done. To begin with, we could connect real-time eye-tracking data with biomonitoring sensors' data detect how different biophilic features affect physiological response specifically. Moreover, future works need to address the limitations mentioned in chapters like limited sensory approach and limited generalizability. Multi-sensory experiments could be conducted to investigate the effect of other sensory approaches like auditory and olfactory, as well as their interactions with virtual perception. Meanwhile, research on assessing health impact of biophilic design needs to extend to diverse population and places, such as patient in clinical setting, children in school, and seniors in assistant living. Finally, beyond short-term experimental studies, longitudinal cohort studies at the building level, such as the Harvard Global Buildings COGfx study[140], the Biophilic Site Offices study in Australia[132], and the BRE Biophilic Office project in the United Kingdom[141], are needed to test the chronic health impacts of long-term indoor biophilic exposures. We need to address how to change the collective consciousness to truly value nature. Testing for the short-term benefits of being surrounded by plants or having a park view from our office window is a beginning for urban dwellers; now we need to extend our quest to discover the "biophilic phenotype" and the formative experiences that translate into a reverence for all living species.

5.4 Concluding Remarks

Encouraged by the biophilia hypothesis, this dissertation developed a new approach to quantify the short-term health impact of biophilic design in buildings. By using this method, this dissertation provides empirical evidence on how people response to different natural elements in diverse indoor settings, which could benefit architects, interior designers, and developers on better understanding, applying and promoting biophilic design in buildings.

APPENDIX 1 (For Chapter 2)

Survey A1.1 Baseline Survey for Study in Chapter 2

Q1.1 What is your participant ID?

Q1.2 How old are you? (please type age in years, e.g. 24)

Q1.3 What is your gender?

- ❍ Male
- ❍ Female

Q1.4 What is your occupation?

- ❍ Student at HSPH
- ❍ Staff at HSPH

Q1.5 Please specify your ethnicity

- ❍ White/Caucasian
- ❍ Black or African American
- ❍ Asian
- ❍ Native Hawaiian and other Pacific Islander
- ❍ American Indian or Alaska Native
- ❍ Latino
- ❍ Multiracial
- ❍ No response

Q2.1 In general, would you say your health is:

- ❍ Excellent
- ❍ Very good
- ❍ Good
- ❍ Fair
- ❍ Poor

Q2.2 In the past month, have you taken stress medicine or received stress treatment?

- ❍ Yes
- ❍ No

Q2.3 Did you have a good sleep last night?

- ❍ Yes
- ❍ Maybe
- ❍ No

Q2.4 Did you have any caffeinated beverages (e.g. coffee, tea, hot chocolate) before coming here today?

- ❍ Yes
- ❍ No

Q2.5 How would you rate your stress level TODAY? (On a scale of 1-5, with 1 being very little stress, and 5 being extreme stress)

- ❍ 1 (Very little)
- ❍ 2
- ❍ 3
- ❍ 4
- ❍ 5 (Extreme)

Q3.1 Have you ever heard biophilic design?

- ❍ Yes
- ❍ No

Q3.2 Please tell us how you define "biophilic design"? (if answer for Q3.1 is "Yes")

Survey A1.2 Space Survey for Study in Chapter 2

Q1 What is your participant ID?

Q2.1 In general, how would you describe your stress/relaxation today?

	Very Stressed	Stressed	Neither Stressed nor Relaxed	Relaxed	Very Relaxed
While IN THIS SPACE	❍	❍	❍	❍	❍
In the HOUR PRIOR to being in this space	❍	❍	❍	❍	❍

Q2.2 In general, how would you describe your engagement/boredom today?

	Very Engaged	Engaged	Neither Engaged nor Bored	Bored	Very Bored
While IN THIS SPACE	❍	❍	❍	❍	❍
In the HOUR PRIOR to being in this space	❍	❍	❍	❍	❍

Q2.3 In general, how would you describe your excitement today?

	Very Excited	Excited	Neither Excited nor Unexcited	Unexcited	Very Unexcited
While IN THIS SPACE	❍	❍	❍	❍	❍
In the HOUR PRIOR to being in this space	❍	❍	❍	❍	❍

Q2.4 In general, how would you describe your frustration/calmness today?

	Very Frustrated	Frustrated	Neither Frustrated nor Calm	Calm	Very Calm
While IN THIS SPACE	❍	❍	❍	❍	❍
In the HOUR PRIOR to being in this space	❍	❍	❍	❍	❍

Q3.1 Can you see any natural elements (e.g. plants, flowers, soil, water, etc.)?

- ❍ No, not at all
- ❍ Yes, a few
- ❍ Yes, a lot

Q3.2 Except for visual connection to nature, do you have some non-visual connections with nature? (e.g. hearing birds/water, smelling the natural scents of plants/flowers, touching the real plants/water, feeling the surface warm from sunlight, etc.)

- ❍ No, not at all
- ❍ Yes, a little
- ❍ Yes, very much

Q3.3 Do the natural elements (e.g. vegetation, birdsong, water-flow etc.) change dynamically? (If the answer for Q3.2 is not "No, not at all")

- ❍ No, not at all
- ❍ Yes, a little
- ❍ Yes, very much

Q3.4 Does this space has natural ventilation (i.e. operable windows, doors to the patio, etc.)?

- ❍ No, not at all
- ❍ Yes, a little
- ❍ Yes, a lot

Q3.5 Is there any water (e.g. water wall, fountain, pool, aquarium, etc.) in this space?

- ❍ No, not at all
- ❍ Yes, a little
- ❍ Yes, a lot

Q3.6 Does this space has dynamic light (e.g. natural daylight, ambient diffuse lighting on walls and ceilings)?

- ❍ No, not at all
- ❍ Yes, a little
- ❍ Yes, a lot

Q3.7 Do you think you can observe seasonal changes (light intensity and color, plant cycles, ambient scents) of natural view from this space?

- ❍ No, not at all
- ❍ Yes, a few
- ❍ Yes, a lot

Q3.8 Is there any biomorphic forms (e.g. fabric, carpet, wallpaper designs based on the imitation of nature elements, columns shaped like tress, etc.) in this space?

- ❍ No, not at all
- ❍ Yes, a few
- ❍ Yes, a lot

Q3.9 Does this space have material connections with nature (e.g. wood or stone furniture or building materials, etc.)?

- ❍ No, not at all
- ❍ Yes, a few
- ❍ Yes, a lot

Q3.10 How about the complexity in this space (e.g. material texture, figures in wallpaper and carpet, exposed building structure and mechanical system, etc.)?

- ❍ Nothing is complex
- ❍ There are a few things with complex patterns
- ❍ There are a lot of things with complex patterns

Q3.11 Do you have a long-distance view from this space?

- ❍ No, the focal length of major view is within 20 feet (6 meters)
- ❍ Yes, the focal length of major view is between 20 feet (6m) and 100 feet (30m)
- ❍ Yes, I can see views over 100 feet

Q3.12 Does this space have refuge places (i.e. a place for withdrawal from environmental conditions, in which the individual is protected from behind and overhead)? (e.g. seats with speech and visual privacy, spaces reserved for reflection, meditation, rest, relaxation, reading, etc.)

- ❍ No, not at all
- ❍ Yes, a few
- ❍ Yes, a lot

Q3.13 How about the mystery condition (i.e. obscuring of the boundaries and a portion of the focal subject, thereby enticing the user to anticipate the full extent of the subject and explore the space further) of this space?

- ❍ All the edges of this space are clear
- ❍ One edge of the focal subject is obscured
- ❍ Two or more edges of the focal subject are obscured

Q3.14 How about the risk condition (i.e. A present danger, which is inert and unable to cause harm due to a trusted element of safety) of this space? (Views from a higher room into the lower courtyard)

- ❍ Feel no risky
- ❍ High-level risk
- ❍ Low-level risk

Q4 Please add anything else you would like us to know about your experience feeling the natural elements in this building space?

Table A1.1 Biophilic I Biophilic Interior Design Index (BIDI)

		Biophilic Patterns	Weight	Level			Score
				Not at all (value=0)	A few/little (value=1)	A lot (value=2)	
Nature in the space	1	Visual connection with nature	3				
	2	Non-visual connection with nature	2				
	3	Non-rhythmic sensory stimuli	2				
	4	Thermal & Airflow variability	2				
	5	Presence of water	2				
	6	Dynamic & Diffuse light	2				
	7	Connection with natural system	1				
Natural analogues	8	Biomorphic form & patterns	1				
	9	Material connection with nature	1				
	10	Complexity & Order	2				
Nature of the space	11	Prospect	3				
	12	Refuge	3				
	13	Mystery	2				
	14	Risk/Peril	1				
						BIDI Score	

APPENDIX 2 (For Chapter 3)

Table A2.1 Baseline measures of physiological indicators of stress reaction among different environments and types of workspace (Mean ± SD)

	Systolic Blood Pressure (mmHg)	Diastolic Blood Pressure (mmHg)	Heart Rate (1/min)	RMSSD (ms)	Skin Conductance Level (µS)
Enclosed Space					
Non-biophilic/Control	106.4 ± 9.3	69.3 ± 9.1	70.9 ± 10.7	47.5 ± 26.3	5.3 ± 4.0
Natural elements	107.3 ± 8.5	69.8 ± 7.9	69.8 ± 10.7	45.0 ± 25.3	5.2 ± 3.4
Natural analogues	108.1 ±8.8	69.4 ± 8.1	70.2 ± 10.9	47.2 ± 25.6	5.4 ± 3.4
Combination	108.2 ± 9.9	70.3 ± 7.5	71.0 ± 11.8	48.3 ± 29.1	5.6 ± 3.7
Open Space					
Non-biophilic/Control	107.0 ± 10.2	68.8 ± 9.9	71.8 ± 11.3	49.2 ± 25.8	6.0 ± 4.1
Natural elements	109.8 ± 9.2	71.1 ± 9.3	73.0 ± 11.3	46.9 ± 23.7	6.3 ± 4.4
Natural analogues	107.5 ± 8.9	70.7 ± 7.8	72.1 ± 11.5	51.3 ± 30.9	5.7± 3.7
Combination	108.4 ± 9.5	69.8 ± 9.0	72.3 ± 11.4	48.0 ± 24.9	6.3 ± 3.9

Note: RMSSD, root mean square of successive differences of beat intervals; SD, standard deviation.

Table A2.2 Summary statistics of pre-post changes of physiological indicators of stress reaction among different environments and types of workspace (Mean ± SD)

	ΔSystolic Blood Pressure (mmHg)	ΔDiastolic Blood Pressure (mmHg)	ΔHeart Rate (1/min)	ΔRMSSD (ms)	ΔSkin Conductance Level (μS)
Enclosed Space					
Non-biophilic/Control	1.3 ± 6.1	1.2 ± 5.5	4.8 ± 3.7	-2.5 ± 8.5	0.9 ± 1.2
Natural elements	1.0 ± 5.0	-0.2 ± 4.6	4.3 ± 2.9	-1.5 ± 7.7	0.9 ± 1.1
Natural analogues	-0.5 ± 5.7	-0.2 ± 4.9	5.4 ± 3.9	-3.0 ± 9.0	0.8 ± 1.1
Combination	-0.3 ± 5.1	-1.6 ± 3.5	4.4 ± 4.4	-1.8 ± 12.8	0.7 ± 1.2
Open Space					
Non-biophilic/Control	1.4 ± 4.2	2.1 ± 4.9	5.2 ± 3.3	-5.3 ± 10.5	0.8 ± 1.2
Natural elements	-1.8 ± 5.0	-2.1 ± 3.9	3.9 ± 4.1	-3.3 ± 9.0	0.6 ± 1.5
Natural analogues	-1.2 ± 5.3	-1.2 ± 4.3	4.0 ± 4.1	-7.8 ± 11.5	0.8 ± 1.1
Combination	-1.0 ± 5.3	-0.6 ± 3.4	4.2 ± 3.3	-3.2 ± 9.9	0.7 ± 1.4

Note: Δ (delta) indicates the pre-post changes of physiological measures. RMSSD, root mean square of successive differences of beat intervals; SD, standard deviation.

Table A2.3 Summary statistics of cognitive outcomes among different environments and work modes (Mean ± SD)

	Creativity (Z score)	Reaction Time (ms)
Enclosed Space		
Non-biophilic/Control	-0.3 ± 0.8	1125 ± 332
Natural elements	0.1 ± 1.0	1164 ± 357
Natural analogues	0.0 ± 1.2	1116 ± 367
Combination	0.1 ±1.0	1153 ± 343
Open Space		
Non-biophilic/Control	0.0 ± 0.9	1116 ± 365
Natural elements	0.1 ± 1.1	1182 ± 379
Natural analogues	0.0 ± 1.0	1124 ± 345
Combination	0.0 ± 1.1	1143 ± 342

Note: SD, standard deviation.

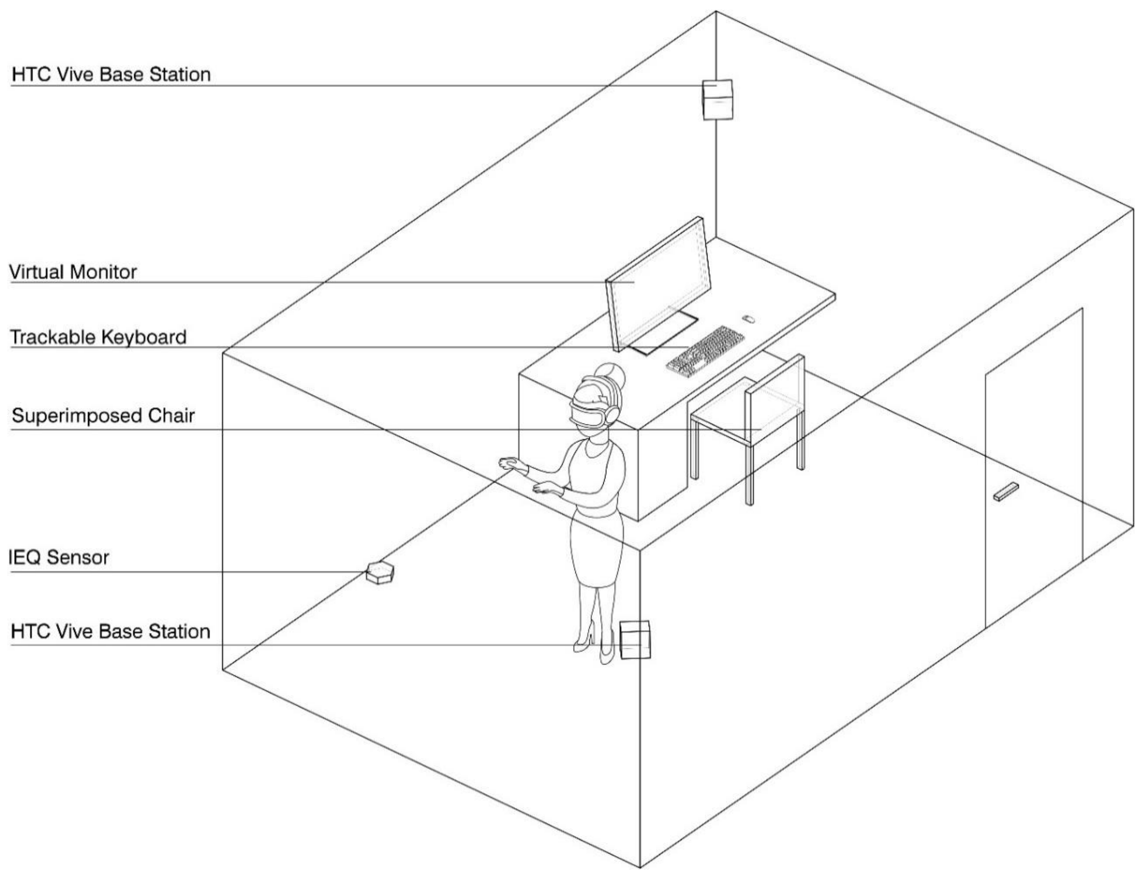


Figure A2.1 Experimental settings in the Virtual Reality Lab

Survey A2.1 Survey for Enclosed Space of Study in Chapter 3

Q1 How old are you? (please type age in years, e.g. 24)

Q2 What is your gender?

- Male
- Female

Q3 What is your occupation?

- Faculty
- Staff
- Student

Q4 Please specify your ethnicity

- White/Caucasian
- Black or African American
- Asian
- Native Hawaiian and other Pacific Islander
- American Indian or Alaska Native
- Latino
- Multiracial
- No response

Q5 Where you were raised?

- ❍ Urban area
- ❍ Suburban area
- ❍ Rural area

Q6 In general, do you like to go to natural spaces (e.g. go to park/riverside/forest)?

- ❍ Not at all
- ❍ Not very
- ❍ Neutral
- ❍ Some what
- ❍ Very much

Q7 In general, would you say your health is:

- ❍ Excellent
- ❍ Very good
- ❍ Good
- ❍ Fair
- ❍ Poor

Q8 Did you take stress medicine or received stress treatment during the past 24 hours?

- ❍ Yes
- ❍ No

Q9 Did you smoke during the past 24 hours?

- ❍ Yes
- ❍ No

Q10 Did you have alcohol during the past 24 hours?

- ❍ Yes
- ❍ No

Q11 Did you have a good sleep last night?

- ❍ Yes
- ❍ No

Q12 Did you participate in intensive exercise during the past 6 hours?

- ❍ Yes
- ❍ No

Q13 Did you have any caffeinated beverages (e.g. coffee, tea) during the past 6 hours?

- ❍ Yes
- ❍ No

Q14 How would you rate your stress level TODAY? (On a scale of 1-5, with 1 being very little stress, and 5 being extreme stress)

- ❍ 1 (Very little)
- ❍ 2
- ❍ 3
- ❍ 4
- ❍ 5 (Extreme)

Q15 Please rank the following 4 indoor environments in order of preference (most preferred environment at the top):


E1


E2


E3


E4

Q16 How much do you feel the connection with nature in the following 4 environments?

	0 1 2 3 4 5 6 7 8 9 10
	
	
	
	

Q17 Please rank the following biophilic patterns in order of preference (most preferred environment at the top):

_______ Indoor plants and living wall

_______ Natural light and view

_______ Biomorphic forms (leaf wallpaper, honeybee shape panel, natural shape furniture)

_______ Material connection with nature (wooden wall, floor, furniture)

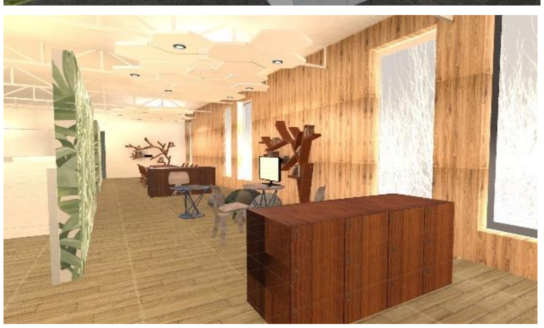
Survey A2.2 Survey for Open Space of Study in Chapter 3

Except for Q15 and Q16, all the questions in Survey A2.2 are the same as those in Survey A2.1

Q15 Please rank the following 4 indoor environments in order of preference (most preferred environment at the top):


O1


O2


O3


O4

Q16 How much do you feel the connection with nature in the following 4 environments?

	0 1 2 3 4 5 6 7 8 9 10
	
	
	
	

APPENDIX 3 (For Chapter 4)

Table A3.1 Summary of participants' physiological and psychological outcomes at baseline, pre-recovery and post-recovery stages.

	Baseline				Pre-recovery				Post-recovery			
	n	n (m)	Mean ±SD	Median (IQR)	n	n (m)	Mean ±SD	Median (IQR)	n	n (m)	Mean ±SD	Median (IQR)
HRV-RMSSD	-	-	-	-	-	-	-	-	-	-	-	-
Non-biophilic	22	3	51.4± 61.1	35.4 (16.9)	22	3	37.9± 20.0	34.1 (22.7)	22	3	43.6± 22.8	40.4 (23.1)
Indoor Green	24	1	45.1± 42.1	33.0 (20.1)	24	1	39.2± 27.2	33.1 (24.4)	23	2	50.8± 40.4	42.0 (24.2)
Outdoor View	24	1	39.2± 27.4	30.6 (22.4)	24	1	32.2± 18.3	25.7 (20.6)	24	1	40.6± 24.5	32.0 (26.1)
Combination	22	3	41.2± 19.7	44.4 (25.5)	21	4	36.7± 19.7	33.9 (22.7)	20	5	48.2± 26.7	49.4 (33.1)
HRV-LF/HF Ratio	-	-	-	-	-	-	-	-	-	-	-	-
Non-biophilic	22	3	1.8± 1.7	1.7 (1.5)	22	3	4.4± 4.5	3.4 (3.4)	22	3	1.8± 1.3	1.3 (1.9)
Indoor Green	24	1	1.9± 1.4	1.4 (1.7)	24	1	3.5± 2.5	3.2 (3.3)	23	2	2.4± 1.9	1.9 (2.2)
Outdoor View	24	1	2.1± 2.2	2.2 (1.5)	24	1	5.1± 5.3	2.4 (7.0)	24	1	2.1± 1.8	1.4 (1.7)
Combination	22	3	2.0± 1.9	1.9 (1.2)	21	4	3.0± 2.1	2.8 (3.1)	20	5	1.6± 0.9	1.2 (1.6)
Skin Conductance Level	-	-	-	-	-	-	-	-	-	-	-	-
Non-biophilic	25	0	4.2± 4.7	2.5 (4.6)	24	1	6.6± 5.1	5.6 (5.9)	23	2	6.3± 3.6	6.2 (5.5)
Indoor Green	24	1	3.8± 4.2	2.7 (4.2)	24	1	4.7± 5.2	2.8 (5.3)	24	1	5.1± 4.5	4.2 (4.2)
Outdoor View	23	2	2.1± 1.9	1.3 (2.6)	24	1	3.2± 3.0	1.9 (3.1)	24	1	4.4± 3.6	3.9 (4.4)
Combination	24	1	3.5± 3.3	2.3 (2.6)	23	2	5.9± 4.6	3.8 (7.3)	24	1	6.3± 5.2	4.3 (4.4)
Heart Rate	-	-	-	-	-	-	-	-	-	-	-	-
Non-biophilic	22	3	72.1± 14.0	72.7 (13.5)	22	3	79.4± 15.4	81.6 (20.5)	22	3	74.7± 12.9	76.8 (13.4)
Indoor Green	24	1	74.7± 14.6	77.4 (24.6)	24	1	80.6± 12.0	84.1 (13.5)	23	2	74.0± 12.6	76.3 (22.4)
Outdoor View	24	1	76.5± 16.8	72.8 (12.5)	24	1	78.7± 10.8	78.1 (16.3)	24	1	74.0± 10.1	72.2 (14.2)
Combination	22	3	74.5± 11.6	74.5 (13.7)	21	4	76.4± 11.1	74.8 (9.6)	20	5	73.1± 12.4	72.9 (11.1)
Systolic Blood Pressure	-	-	-	-	-	-	-	-	-	-	-	-
Non-biophilic	25	0	114.5 ±11.1	111.0 (13.0)	25	0	115.2 ±12.8	115.0 (18.0)	25	0	116.1 ±10.3	113.0 (17.0)

Table A3.1 (Continued)

Indoor Green	25	0	113.5 ±11.9	113.0 (14.0)	25	0	113.9 ±12.5	113.0 (14.0)	25	0	111.6 ±11.5	115.0 (15.0)
Outdoor View	25	0	116.2 ±13.3	113.0 (13.0)	25	0	118.0 ±14.6	116.0 (13.0)	25	0	116.0 ±14.0	115.0 (13.0)
Combination	25	0	115.5 ±13.1	112.0 (9.0)	25	0	114.7 ±9.9	112.0 (11.0)	25	0	114.3 ±10.0	114.0 (12.0)
Diastolic Blood Pressure	-	-	-	-	-	-	-	-	-	-	-	-
Non-biophilic	25	0	75.8± 9.7	76.0 (11.0)	25	0	75.5± 11.7	76.0 (8.0)	25	0	78.8± 10.4	80.0 (11.0)
Indoor Green	25	0	72.8± 10.1	75.0 (14.0)	25	0	73.6± 10.9	74.0 (12.0)	25	0	72.4± 10.9	73.0 (10.0)
Outdoor View	25	0	77.2± 11.5	75.0 (10.0)	25	0	79.4± 13.1	79.0 (13.0)	25	0	77.0± 11.3	77.0 (16.0)
Combination	25	0	72.7± 10.4	69.0 (13.0)	25	0	74.5± 9.8	72.0 (16.0)	25	0	76.6± 8.2	75.0 (8.0)
STAI	-	-	-	-	-	-	-	-	-	-	-	-
Non-biophilic	-	-	-	-	25	0	2.1± 0.5	2.2 (0.5)	25	0	1.7± 0.5	1.7 (0.5)
Indoor Green	-	-	-	-	25	0	2.1± 0.7	2.2 (1.2)	25	0	1.6± 0.5	1.7 (0.5)
Outdoor View	-	-	-	-	25	0	2.3± 0.6	2.3 (0.5)	25	0	1.6± 0.5	1.5 (0.7)
Combination	-	-	-	-	25	0	2.3± 0.6	2.5 (0.8)	25	0	1.6± 0.4	1.7 (0.7)

Note: HRV: Heart Rate Variability; RMSSD: Root mean square of the successive differences; LF/HF Ratio: Ratio of low frequency to high frequency; STAI: State-Trait Anxiety Inventory.

Table A3.2 Estimated pre-post changes in blood pressure (SBP & DBP) and state-trait anxiety inventory (STAI) score, recovery rates of heart rate, heart rate variability (HRV) and skin conductance level (SCL) in 6-minute recovery period among four environments

	Non-biophilic	***Indoor Green***	***Outdoor View***	***Combo***
Pre-post changes (95% confidence interval)				
Systolic Blood Pressure (mmHg)	0.8 (-2.1, 3.8)	**-2.3 (-4.5, -0.1)**	-0.2 (-2.8, 2.4)	-0.4 (-2.9, 2.0)
Diastolic Blood Pressure (mmHg)	3.3 (-0.1. 6.7)	-1.2 (-3.8, 1.5)	-0.6 (-3.6, 2.5)	2.1 (0.1, 4.0)
STAI	**-0.4 (-0.6, -0.2)**	-0.5 (-0.7, 0.2)	**-0.7 (-1.1, -0.4)**	**-0.7 (-0.9, -0.4)**
Recovery rates (95% confidence interval)				
Heart Rate ($1/min^2$)	**-1.1 (-1.4, -0.7)**	**-1.2 (-1.5, -0.9)**	**-1.0 (-1.3, -0.7)**	**-0.9 (-1.3, -0.5)**
Log(HRV-RMSSD) (ms/min)	**0.05 (0.03, 0.07)**	**0.07 (0.06, 0.08)**	**0.05 (0.04, 0.07)**	**0.06 (0.04, 0.07)**
Log(HRV-LF/HF) ratio	**-0.13 (-0.16, -0.09)**	**-0.12 (-0.15, -0.09)**	**-0.12 (-0.16, -0.09)**	**-0.12 (-0.15, -0.09)**
Log(SCL) (μS/min)	0.00 (-0.02, 0.03)	0.01 (-0.02, 0.04)	**0.02 (0.01, 0.03)**	**0.01 (0.00, 0.03)**

Note: SRMSSD: Root mean square of the successive differences; LF/HF ratio: Ratio of low frequency to high frequency; We log transformed HRV, SCL data in the regression model. Significant results were bolded.

Table A3.3 Estimated recovery rates of heart rate (HR), heart rate variability (HRV) and skin conductance level (SCL) in three stages (2-minute for each stage) of recovery period.

		Recovery rate (95% confidence interval)		
	Environment	**1-2 minutes (Start Stage)**	**3-4 minutes (Middle Stage)**	**5-6 minutes (End Stage)**
Heart Rate ($1/min^2$)	*Non-biophilic*	0.5 (-0.8, 1.7)	0.4 (-0.2, 0.9)	**-0.8 (-1.2, -0.5)**
	Indoor Green	-0.1 (-1.3, 1.1)	0.1 (-0.5, 0.7)	**-1.0 (-1.4, -0.7)**
	Outdoor View	0.8 (-0.3, 1.9)	0.4 (-0.2, 0.9)	**-0.7 (-1.0, -0.3)**
	Combination	0.9 (-0.6, 2.3)	**0.7 (0.0, 1.4)**	**-0.7 (-1.1, -0.2)**
Log(HRV -RMSDD) (ms/min)	*Non-biophilic*	-0.06 (-0.14, 0.01)	**-0.03 (-0.07, 0.00)**	**0.03 (0.01, 0.05)**
	Indoor Green	-0.03 (-0.08, 0.02)	0.01 (-0.01, 0.04)	**0.05 (0.04, 0.07)**
	Outdoor View	-0.05 (-0.10, 0.00)	0.01 (-0.02, 0.03)	**0.04 (0.02, 0.05)**
	Combination	-0.04 (-0.09, 0.02)	0.00 (-0.03, 0.03)	**0.04 (0.02, 0.06)**
Log(HRV -LF/HF)	*Non-biophilic*	0.01 (-0.12, 0.14)	-0.02 (-0.08, 0.05)	**-0.10 (-0.15, -0.06)**
	Indoor Green	0.05 (-0.07, 0.16)	0.02 (-0.04, 0.07)	**-0.09 (-0.13, -0.06)**
	Outdoor View	-0.01 (-0.14, 0.11)	**-0.07 (-0.13, -0.02)**	**-0.10 (-0.14, -0.07)**
	Combination	0.03 (-0.10, 0.15)	-0.01 (-0.08, 0.05)	**-0.10 (-0.14, -0.06)**
Log(SCL) (uS/min)	*Non-biophilic*	**0.11 (0.01, 0.22)**	0.03 (-0.02, 0.08)	0.03 (-0.01, 0.06)
	Indoor Green	0.07 (-0.05, 0.18)	0.00 (-0.05, 0.06)	0.02 (-0.01, 0.06)
	Outdoor View	**0.09 (0.05, 0.14)**	**0.05 (0.03, 0.07)**	**0.03 (0.02, 0.05)**
	Combination	0.03 (-0.04, 0.09)	0.02 (-0.02, 0.05)	**0.02 (0.00, 0.04)**

Note: RMSSD: Root mean square of the successive differences; LF/HF: Heart Rate Variability-Ratio of low frequency to high frequency; We log transformed HRV, SCL data in the regression model. Significant results were bolded.

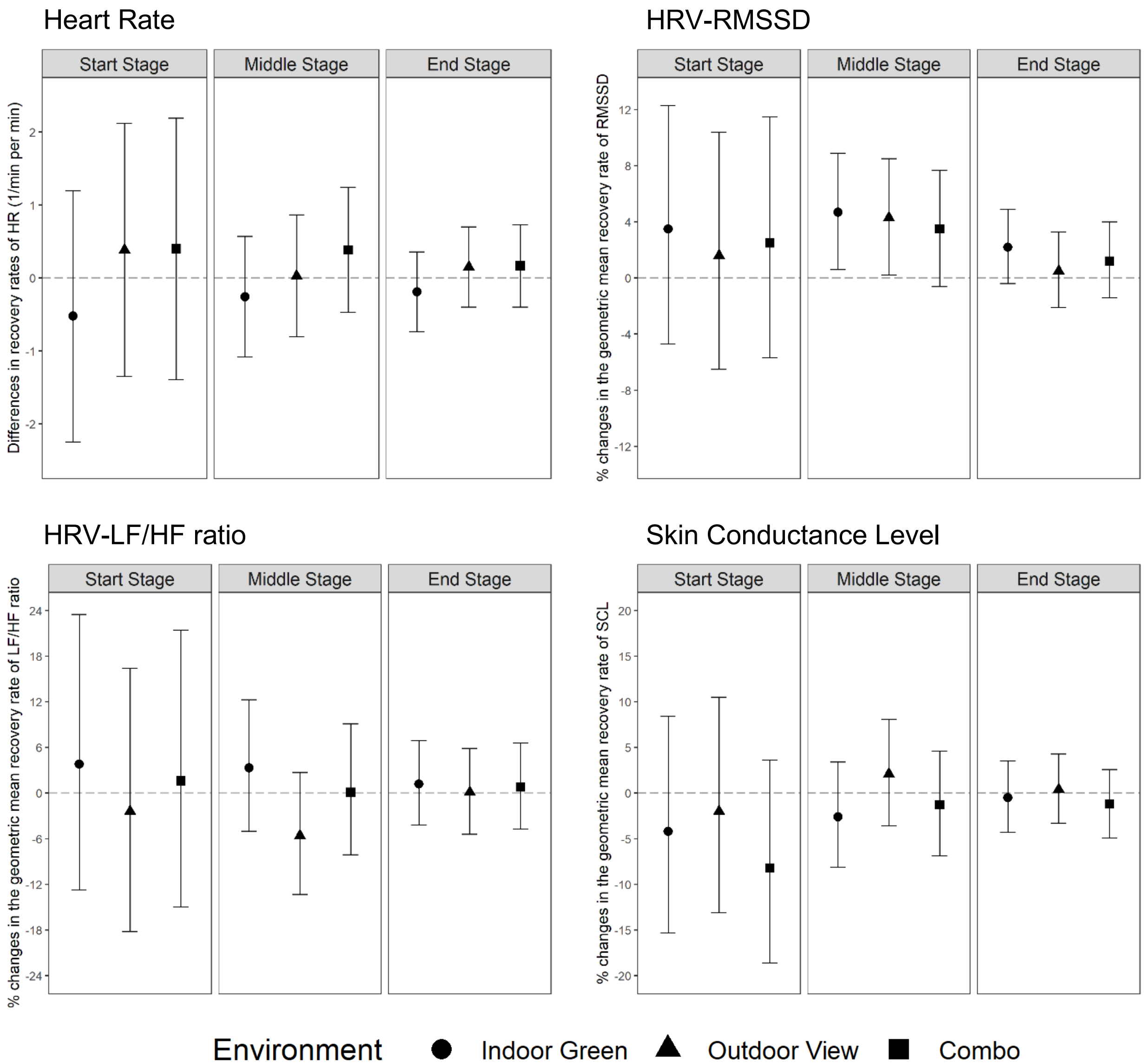


Figure A3.1 Estimated differences in recovery rates of heart rate (HR), percentage changes in the geometric mean recovery rate of heart rate variability (HRV) and skin conductance level (SCL), in biophilic environments versus those in non-biophilic in three stages (2 minutes for each stage) of recovery period.

Note: RMSSD: Root mean square of the successive differences; LF/HF: Ratio of low frequency to high frequency. We log transformed HRV, SCL data in the regression model. Error bars depict 95% confidence interval.

Survey A3.1 Baseline Survey for Study in Chapter 4

Q1.1 What is your participant ID?

Q1.2 How old are you? (please type age in years, e.g. 24)

Q1.3 What is your gender?

- ❍ Male
- ❍ Female

Q1.4 Please specify your ethnicity

- ❍ White/Caucasian
- ❍ Black or African American
- ❍ Asian
- ❍ Native Hawaiian and other Pacific Islander
- ❍ American Indian or Alaska Native
- ❍ Latino
- ❍ Multiracial
- ❍ No response

Q2.1 In general, you would say your health is:

- ❍ Excellent
- ❍ Very good
- ❍ Good
- ❍ Fair
- ❍ Poor

Q2.2 Did you have a good sleep last night?

- ❍ Yes
- ❍ No

Q2.3 Did you have any caffeinated beverages (e.g. coffee, tea, hot chocolate) before coming here today?

- ❍ Yes
- ❍ No

Q2.4 How would you rate your stress level TODAY? (On a scale of 1-5, with 1 not stressful at all, and 5 extremely stressful)

- ❍ 1 (Not Stressful)
- ❍ 2
- ❍ 3
- ❍ 4
- ❍ 5 (Extreme Stressful)

Short-form of State-Trait Anxiety Inventory (STAI)

Sample of short STAI before 6-minute recovery (after stressor)

	Not at all	Somewhat	Moderately	Very much
I feel calm	❍	❍	❍	❍
I am tense	❍	❍	❍	❍
I feel upset	❍	❍	❍	❍
I am relaxed	❍	❍	❍	❍
I feel content	❍	❍	❍	❍
I am worried	❍	❍	❍	❍

Sample of short STAI after 6-minute recovery (after stressor)

	Not at all	Somewhat	Moderately	Very much
I feel secure	❍	❍	❍	❍
I am satisfied	❍	❍	❍	❍
I feel strained	❍	❍	❍	❍
I am nervous	❍	❍	❍	❍
I feel pleasant	❍	❍	❍	❍
I feel confused	❍	❍	❍	❍

BIBLIOGRAPHY

1. Florian L, Peter K, Leila H, et al. City living and urban upbringing affect neural social stress processing in humans. *Nature.* 2011;474(7352):498.

2. Frumkin H, Bratman GN, Breslow SJ, et al. Nature contact and human health: a research agenda. *Environmental Health Perspectives.* 2017;125(7):75001.

3. MacNaughton P, Eitland E, Kloog I, Schwartz J, Allen J. Impact of Particulate Matter Exposure and Surrounding "Greenness" on Chronic Absenteeism in Massachusetts Public Schools. *Int J Environ Res Public Health.* 2017;14(2).

4. Wu CD, McNeely E, Cedeno-Laurent JG, et al. Linking student performance in Massachusetts elementary schools with the "greenness" of school surroundings using remote sensing. *PLoS One.* 2014;9(10):e108548.

5. Dadvand P, Pujol J, Macia D, et al. The Association between Lifelong Greenspace Exposure and 3-Dimensional Brain Magnetic Resonance Imaging in Barcelona Schoolchildren. *Environ Health Perspect.* 2018;126(2):027012.

6. James P, Banay RF, Hart JE, Laden F. A Review of the Health Benefits of Greenness. *Current epidemiology reports.* 2015;2(2):131-142.

7. 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.

8. Berto R. The role of nature in coping with psycho-physiological stress: a literature review on restorativeness. *Behavioral sciences (Basel, Switzerland).* 2014;4(4):394.

9. Bratman GN, Daily GC, Levy BJ, Gross JJ. The benefits of nature experience: Improved affect and cognition. *Landscape and Urban Planning.* 2015;138:41-50.

10. Kuo M. How might contact with nature promote human health? Exploring promising mechanisms and a possible central pathway. *Frontiers in psychology.* 2015;6.

11. Park B, Tsunetsugu Y, Kasetani T, Kagawa T, Miyazaki Y. The physiological effects of Shinrin-yoku (taking in the forest atmosphere or forest bathing): evidence from field experiments in 24 forests across Japan. *Environ Health Prev Med.* 2010;15(1):18-26.

12. Fromm E. *The heart of man : its genius for good and evil.* 1st ed. ed. New York: Harper & Row; 1964.

13. Wilson EO. *Biophilia.* Cambridge, Mass.1984.

14. Ulrich RS, Simons RF, Losito BD, Fiorito E, Miles MA, Zelson M. Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology.* 1991;11(3):201-230.

15. Kaplan S. The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology.* 1995;15(3):169-182.

16. Kellert SR, Heerwagen J, Mador M. *Biophilic design : the theory, science, and practice of bringing buildings to life.* Hoboken, N.J.2008.

17. 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. *International Journal of Architectural Research.* 2014;8(2):62-76.

18. Kaitlyn G, Birgitta G. A Review of Psychological Literature on the Health and Wellbeing Benefits of Biophilic Design. *Buildings.* 2015;5(3):948-963.

19. Bringslimark T, Hartig T, Patil GG. The psychological benefits of indoor plants: A critical review of the experimental literature. *Journal of Environmental Psychology.* 2009;29(4):422-433.

20. Ulrich RS. View through a Window May Influence Recovery from Surgery. *Science.* 1984;224(4647):420-421.

21. Zhang X, Lian Z, Wu Y. Human physiological responses to wooden indoor environment. *Physiology & behavior.* 2017;174:27-34.

22. Allen J, MacNaughton P, Laurent J, Flanigan S, Eitland E, Spengler J. Green Buildings and Health. *Curr Envir Health Rpt.* 2015;2(3):250-258.

23. Cedeño-Laurent JG, Williams A, Macnaughton P, et al. Building Evidence for Health: Green Buildings, Current Science, and Future Challenges. *Annual review of public health.* 2018.

24. International-WELL-Building-Institute. *The WELL Building Standard: V1 with Q1 2018 addenda.* 2018.

25. International Living Future Institute. *Living Building Challenge 3.0.* 2014.

26. Higuera-Trujillo JL, López-Tarruella Maldonado J, Llinares Millán C. Psychological and physiological human responses to simulated and real environments: A comparison between Photographs, 360° Panoramas, and Virtual Reality. *Applied Ergonomics.* 2017.

27. Kellert SR. *Nature by Design: the Practice of Biophilic Design.* New Haven & London: Yale University Press; 2018.

28. Yin J, Zhu S, Macnaughton P, Allen JG, Spengler JD. Physiological and cognitive performance of exposure to biophilic indoor environment. *Building and Environment.* 2018.

29. Turner WR, Nakamura T, Dinetti M. Global Urbanization and the Separation of Humans from Nature. *BioScience.* 2004;54(6):585-590.

30. Klepeis NE, Nelson WC, Ott WR, et al. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of Exposure Analysis and Environmental Epidemiology.* 2001;11(3):231.

31. Peen J, Schoevers RA, Beekman AT, Dekker J. The current status of urban‐rural differences in psychiatric disorders. In. Vol 121. Oxford, UK2010:84-93.

32. Jim Van O, Gunter K, Bart PFR. The environment and schizophrenia. *Nature.* 2010;468(7321):203.

33. Frumkin H. Beyond toxicity: human health and the natural environment. *American journal of preventive medicine.* 2001;20(3):234-240.

34. Hartig T, Mitchell R, Vries dS, Frumkin H. Nature and Health. *Annual Review of Public Health.* 2014;35:207-228.

35. Bedimo-Rung AL, Mowen AJ, Cohen DA. The significance of parks to physical activity and public health: A conceptual model. *American journal of preventive medicine.* 2005;28(2):159-168.

36. Alcock I, White MP, Wheeler BW, Fleming LE, Depledge MH. Longitudinal effects on mental health of moving to greener and less green urban areas. *Environmental science & technology.* 2014;48(2):1247.

37. White MP, Alcock I, Wheeler BW, Depledge MH. Would You Be Happier Living in a Greener Urban Area? A Fixed-Effects Analysis of Panel Data. *Psychological Science.* 2013;24(6):920-928.

38. Pereira G, Foster S, Martin K, et al. The association between neighborhood greenness and cardiovascular disease: an observational study. *BMC Public Health.* 2012;12:466.

39. Mitchell R, Popham F. Effect of exposure to natural environment on health inequalities: an observational population study. *The Lancet.* 2008;372(9650):1655-1660.

40. James P, Hart JE, Banay RF, Laden F. Exposure to Greenness and Mortality in a Nationwide Prospective Cohort Study of Women. *Environmental Health Perspectives.* 2016;124(9).

41. Berman MG, Kross E, Krpan KM, et al. Interacting with nature improves cognition and affect for individuals with depression. *Journal of Affective Disorders.* 2012;140(3):300-305.

42. Lohr VI, Pearson-Mims CH, Goodwin GK. Interior plants may improve worker productivity and reduce stress in a windowless environment. *Journal of environmental horticulture.* 1996;14(2):97-100.

43. Joye Y. Architectural Lessons From Environmental Psychology: The Case of Biophilic Architecture. *Review of General Psychology.* 2007;11(4):305-328.

44. Newman P, Soderlund J. Biophilic architecture: a review of the rationale and outcomes. *AIMS Environmental Science.* 2015;2(4):950-969.

45. Berto R. Exposure to restorative environments helps restore attentional capacity. *Journal of Environmental Psychology.* 2005;25(3):249-259.

46. Brown DK, Barton JL, Gladwell VF. Viewing nature scenes positively affects recovery of autonomic function following acute-mental stress. *Environmental science & technology.* 2013;47(11):5562.

47. Kahn PH, Friedman B, Gill B, et al. A plasma display window?—The shifting baseline problem in a technologically mediated natural world. *Journal of Environmental Psychology.* 2008;28(2):192-199.

48. Jiang B, Chang C-Y, Sullivan WC. A dose of nature: Tree cover, stress reduction, and gender differences. *Landscape and Urban Planning.* 2014;132:26-36.

49. Jiang B, Li D, Larsen L, Sullivan WC. A Dose-Response Curve Describing the Relationship Between Urban Tree Cover Density and Self-Reported Stress Recovery. *Environment and Behavior.* 2016;48(4):607-629.

50. Valtchanov D, Barton KR, Ellard C. Restorative effects of virtual nature settings. *Cyberpsychology, behavior and social networking.* 2010;13(5):503.

51. Zhang X, Lian Z, Ding Q. Investigation variance in human psychological responses to wooden indoor environments. *Building and Environment.* 2016;109:58-67.

52. Kjellgren A, Buhrkall H. A comparison of the restorative effect of a natural environment with that of a simulated natural environment. *Journal of Environmental Psychology.* 2010;30(4):464-472.

53. Berman MG, Jonides J, Kaplan S. The cognitive benefits of interacting with nature. *Psychological science.* 2008;19(12):1207.

54. van den Berg M, Maas J, Mulder R, et al. Autonomic nervous system responses to viewing green and built settings: differentiating between sympathetic and parasympathetic activity. *International Journal of Environmental Research and Public Health.* 2015;12(12):15860-15874.

55. Barton J, Pretty J. What is the Best Dose of Nature and Green Exercise for Improving Mental Health? A Multi-Study Analysis. *Environmental Science & Technology.* 2010;44(10):3947.

56. Krupski A, Boyle P. An Observational Analysis of Children's Behavior during a Simple-Reaction-Time Task: The Role of Attention. *Child Development.* 1978;49(2):340.

57. Deary I, Liewald D, Nissan J. A free, easy-to-use, computer-based simple and four-choice reaction time programme: The Deary-Liewald reaction time task. *Behav Res.* 2011;43(1):258-268.

58. Woods DL, Wyma JM, Yund EW, Herron TJ, Reed B. Factors influencing the latency of simple reaction time. *Frontiers in Human Neuroscience.* 2015;9.

59. Stroop JR. Studies of interference in serial verbal reactions. *Journal of Experimental Psychology.* 1935;18(6):643-662.

60. Scarpina F, Tagini S. The Stroop Color and Word Test.(Report). *Frontiers in psychology.* 2017;8.

61. Jonides J, Lewis RL, Nee DE, Lustig CA, Berman MG, Moore KS. The mind and brain of short-term memory. *Annual review of psychology.* 2008;59:193.

62. Ulrich RS. Aesthetic and affective response to natural environment. *Human Behaviour and Environment Advances in Theory and Research.* 1983;6:85-125.

63. Largo-Wight E, Chen W, Dodd V, Weiler R. Healthy Workplaces: The Effects of Nature Contact at Work on Employee Stress and Health. *Public Health Reports.* 2011;126:124.

64. Li Q, Otsuka T, Kobayashi M, et al. Acute effects of walking in forest environments on cardiovascular and metabolic parameters. *Eur J Appl Physiol.* 2011;111(11):2845-2853.

65. Verkuil BB, J. F.; Tollenaar, M. S.; Lane, R. D.; Thayer, J. F. Prolonged Non-metabolic Heart Rate Variability Reduction as a Physiological Marker of Psychological Stress in Daily Life. *Annals of behavioral medicine : a publication of the Society of Behavioral Medicine.* 2016;50(5):704-714.

66. Samet J, Spengler J. Indoor environments and health: moving into the 21st century. *American Journal of Public Health.* 2003;93(9):1489-1493.

67. Centers for Disease Contol and Prevention. Workplace Health Model. 2016; https://www.cdc.gov/workplacehealthpromotion/model/index.html. Accessed April 13, 2019.

68. 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.

69. 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.

70. Loftness V, Hakkinen B, Adan O, Nevalainen A. Elements that contribute to healthy building design. *Environ Health Perspect.* 2007;115(6):965-970.

71. Kellert SR, Wilson EO. *The Biophilia hypothesis.* Washington, D.C.1993.

72. Yin J, Spengler JD. Going Biophilic: Living and Working in Biophilic Buildings. In: Galea S, Ettman CK, Vlahov D, eds. *Urban Health.* New York: Oxford University Press; 2019:369-374.

73. Twohig-Bennett C, Jones A. The health benefits of the great outdoors: A systematic review and meta-analysis of greenspace exposure and health outcomes. *Environmental Research.* 2018;166:628-637.

74. van Den Bosch M, Ode Sang Å. Urban natural environments as nature-based solutions for improved public health – A systematic review of reviews. *Environmental Research.* 2017;158:373-384.

75. McSweeney J, Rainham D, Johnson SA, Sherry SB, Singleton J. Indoor nature exposure (INE): a health-promotion framework. *Health Promotion International.* 2015;30(1):126-139.

76. Dijkstra K, Pieterse ME, Pruyn A. Stress-reducing effects of indoor plants in the built healthcare environment: The mediating role of perceived attractiveness. *Preventive Medicine.* 2008;47(3):279-283.

77. Choi J-H, Beltran LO, Kim H-S. Impacts of indoor daylight environments on patient average length of stay (ALOS) in a healthcare facility. *Building and Environment.* 2012;50(Supplement C):65-75.

78. Li D, Sullivan CW. Impact of views to school landscapes on recovery from stress and mental fatigue. *Landscape and Urban Planning.* 2016;148:149-158.

79. Raanaas RK, Evensen KH, Rich D, Sjøstrøm G, Patil G. Benefits of indoor plants on attention capacity in an office setting. *Journal of Environmental Psychology.* 2011;31(1):99-105.

80. Smolders KCHJ, de Kort YAW, van den Berg SM. Daytime light exposure and feelings of vitality: Results of a field study during regular weekdays. *Journal of Environmental Psychology.* 2013;36(Supplement C):270-279.

81. 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. *Journal of clinical sleep medicine : JCSM : official publication of the American Academy of Sleep Medicine.* 2014;10(6):603.

82. Burnard M, Kutnar A. Wood and human stress in the built indoor environment: a review. *Wood Sci Technol.* 2015;49(5):969-986.

83. Ikei H, Song C, Miyazaki Y. Physiological Effects of Touching Wood. *International journal of environmental research and public health.* 2017;14(7).

84. 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. *Frontiers in psychology.* 2018;9.

85. Vischer JC. Towards an Environmental Psychology of Workspace: How People are Affected by Environments for Work. *Architectural Science Review.* 2008;51(2):97-108.

86. 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. *Computers, Environment and Urban Systems.* 2015;54:363-375.

87. Tabrizian P, Baran PK, Smith WR, Meentemeyer RK. Exploring perceived restoration potential of urban green enclosure through immersive virtual environments. *Journal of Environmental Psychology.* 2018;55:99-109.

88. Salvucci D, Goldberg J. Identifying fixations and saccades in eye-tracking protocols. In: ACM; 2000:71-78.

89. Diaz G, Cooper J, Kit D, Hayhoe M. Real-time recording and classification of eye movements in an immersive virtual environment. *Journal of vision.* 2013;13(12).

90. McCraty R, Shaffer F. Heart Rate Variability: New Perspectives on Physiological Mechanisms, Assessment of Self-regulatory Capacity, and Health Risk. *Global Advances in Health and Medicine.* 2015;4(1):46-61.

91. 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. *Frontiers in psychology.* 2014;5.

92. Kim J, Cha S, Koo C, Tang S-K. The effects of indoor plants and artificial windows in an underground environment. *Building and Environment.* 2018;138:53.

93. Parsons TD, Rizzo AA. Initial Validation of a Virtual Environment for Assessment of Memory Functioning: Virtual Reality Cognitive Performance Assessment Test. *CyberPsychology & Behavior.* 2008;11(1):17-25.

94. 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.

95. Guilford JP. *The nature of human intelligence.* New York1967.

96. 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. *Thinking Skills and Creativity.* 2015;18:32-42.

97. van den Berg MMHE, Maas J, Muller R, et al. Autonomic Nervous System Responses to Viewing Green and Built Settings: Differentiating Between Sympathetic and Parasympathetic Activity. *International Journal of Environmental Research and Public Health.* 2015;12(12):15860-15874.

98. 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.

99. *gamm4: Generalized Additive Mixed Models using 'mgcv' and 'lme4'* [computer program]. 2017.

100. *R: A Language and Environment for Statistical Computing* [computer program]. Vienna, Austria: R Foundation for Statistical Computing; 2018.

101. Zadeh RS, Shepley MM, Williams G, Chung SSE. The Impact of Windows and Daylight on Acute-Care Nurses' Physiological, Psychological, and Behavioral Health. *HERD: Health Environments Research & Design Journal.* 2014;7(4):35-61.

102. Park S-H, Mattson RH. Ornamental indoor plants in hospital rooms enhanced health outcomes of patients recovering from surgery. *Journal of alternative and complementary medicine (New York, NY).* 2009;15(9):975.

103. Gladwell V, Brown D, Barton J, et al. The effects of views of nature on autonomic control. *Eur J Appl Physiol.* 2012;112(9):3379-3386.

104. Shibata S, Suzuki N. EFFECTS OF THE FOLIAGE PLANT ON TASK PERFORMANCE AND MOOD. *Journal of Environmental Psychology.* 2002;22(3):265-272.

105. 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. *Environment and behavior.* 1998;30(3):261-281.

106. Stone NJ, Irvine JM. Direct or indirect window access, task type, and performance. *Journal of Environmental Psychology.* 1994;14(1):57-63.

107. Isen AM. Positive Affect and Decision Making. In: Lewis M, Haviland-Jones JM, eds. *Handbook of emotions.* New York: Guilford Press; 1993:261-277.

108. 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.

109. Lopez RP. *The built environment and public health.* 1st ed. San Francisco: Jossey-Bass; 2012.

110. Facey AD, Tallentire V, Selzer RM, Rotstein L. Understanding and reducing work-related psychological distress in interns: a systematic review. In. Vol 452015:995-1004.

111. Stansfeld S, Candy B. Psychosocial work environment and mental health--a meta-analytic review. *Scandinavian journal of work, environment & health.* 2006;32(6):443-462.

112. Wadsworth EJK, Chaplin KS, Smith AP. The work environment, stress and well-being. *Occupational Medicine.* 2010;60(8):635-639.

113. Tost H, Champagne FA, Meyer-Lindenberg A. Environmental influence in the brain, human welfare and mental health. *Nature Neuroscience.* 2015;18(10):1421-1431.

114. Van Os J. Does the urban environment cause psychosis? *British Journal Of Psychiatry.* 2004;184:287-288.

115. Whiteford HA, Degenhardt L, Rehm J, et al. Global burden of disease attributable to mental and substance use disorders: findings from the Global Burden of Disease Study 2010. *The Lancet.* 2013;382(9904):1575-1586.

116. Substance Abuse and Mental Health Services Administration. *Key substance use and mental health indicators in the United States: Results from the 2017 National Survey on Drug Use and Health.* Rockville, MD: Center for Behavioral Health Statistics and Quality, Substance Abuse and Mental Health Services Administration;2018.

117. Danielsson M, Heimerson I, Lundberg U, Perski A, Stefansson C-G, Åkerstedt T. Psychosocial stress and health problems: Health in Sweden: The National Public Health Report 2012. Chapter 6. *Scandinavian Journal of Public Health.* 2012;40(9_suppl):121-134.

118. Hartig T, Kahn PH. Living in cities, naturally. *Science (New York, NY).* 2016;352(6288):938.

119. Bratman GN, Anderson CB, Berman MG, et al. Nature and mental health: An ecosystem service perspective. *Science Advances.* 2019;5(7):eaax0903.

120. Kaplan R, Kaplan S. Restorative experience: The healing power of nearby nature. In: Francis M, Hester Jr. RT, eds. *The meaning of gardens : idea, place, and action.* Cambridge, MA: MIT Press; 1990:238-243.

121. United Nations. World Population Prospects. 2018; https://population.un.org/wup/. Accessed July 12, 2019.

122. Allen J, et al. *The 9 Foundations of a Healthy Building.* Center for Health and Global Environment, Harvard T.H. Chan School of Public Health;2017.

123. Shaffer F, Ginsberg JP. An Overview of Heart Rate variability Metrics and Norms. *Frontiers In Public Health.* 2017;5.

124. Marteau TM, Bekker H. The development of a six-item short-form of the state scale of the Spielberger State-Trait Anxiety Inventory (STAI). *The British journal of clinical psychology.* 1992;31 (Pt 3):301.

125. Spielberger CD, Gorsuch RL, Lushene RE. *Manual for the State-Trait Anxiety Inventory.* 1970.

126. Marteau TM, Bekker H. The development of a six‐item short‐form of the state scale of the Spielberger State—Trait Anxiety Inventory (STAI. *British Journal of Clinical Psychology.* 1992;31(3):301-306.

127. Kirschbaum C, Pirke KM, Hellhammer DH. The 'Trier Social Stress Test'--a tool for investigating psychobiological stress responses in a laboratory setting. *Neuropsychobiology.* 1993;28(1-2):76.

128. Dickerson SS, Kemeny ME. Acute Stressors and Cortisol Responses: A Theoretical Integration and Synthesis of Laboratory Research. *Psychological Bulletin.* 2004;130(3):355-391.

129. Kudielka B, Hellhammer D, Kirschbaum C. *Ten years of research with the Trier Social Stress Test (TSST) revisited shared substrates.* 2007.

130. Spruance SL, Reid JE, Grace M, Samore M. Hazard Ratio in Clinical Trials. *Antimicrobial Agents and Chemotherapy.* 2004;48(8):2787.

131. Shoemaker CA, Randall K, Relf PD, Geller ES. Relationships between plants, behavior, and attitudes in an office environment. *HortTechnology.* 1992;2(2):205-206.

132. Gray T, Birrell C. Are biophilic-designed site office buildings linked to health benefits and high performing occupants? *International journal of environmental research and public health.* 2014;11(12):12204.

133. Sop Shin W. The influence of forest view through a window on job satisfaction and job stress. *Scandinavian Journal of Forest Research.* 2007;22(3):248-253.

134. Wooller JJ, Rogerson M, Barton J, Micklewright D, Gladwell V. Can Simulated Green Exercise Improve Recovery From Acute Mental Stress? *Frontiers in psychology.* 2018;9.

135. Oiamo TH, Luginaah IN, Baxter J. Cumulative effects of noise and odour annoyances on environmental and health related quality of life. *Social Science & Medicine.* 2015;146:191-203.

136. Gaoua N. Cognitive function in hot environments: a question of methodology. *Scandinavian Journal of Medicine & Science in Sports.* 2010;20(3):60-70.

137. Matsuoka RH. Student performance and high school landscapes: Examining the links. *Landscape and Urban Planning.* 2010;97(4):273-282.

138. Wooller J-J, Barton J, Gladwell VF, Micklewright D. Occlusion of sight, sound and smell during Green Exercise influences mood, perceived exertion and heart rate. *International Journal of Environmental Health Research.* 2015;26(3):1-14.

139. Grunwald M. *Human Haptic Perception: Basics and Applications.* Vol 9783764376123. Basel: Birkhäuser Basel; 2008.

140. Allen J. Global COGfx Study – Healthy Buildings. https://forhealth.org/globalbuildings/. Accessed July 12, 2019.

141. BRE. Biophilic Design: The Biophilic Office. https://www.bregroup.com/services/research/the-biophilic-office/. Accessed July 12, 2019.