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Effects of biophilic indoor environment on stress and anxiety recovery: A between-subjects experiment in virtual reality

Jie Yin[a,b,*,1], Jing Yuan[a,1], Nastaran Arfaei[a], Paul J. Catalano[c,d], Joseph G. Allen[a,2], John D. Spengler[a,2]

[a] Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, MA, USA
[b] Population Health Sciences Program, Harvard Graduate School of Arts and Sciences, Cambridge, MA, USA
[c] Department of Data Sciences, Dana-Farber Cancer Institute, Boston, MA, USA
[d] Department of Biostatistics, Harvard T.H. Chan School of Public Health, Boston, MA, USA

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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 bio-monitoring sensors. Their anxiety level was measured by 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.

1. Introduction

Human health and well-being have been affected by the quality of environments that people live in (Lopez, 2012). Urban living is usually related to long working hours, heavy workload, tight deadline and unsatisfied working environments (Facey et al., 2015). Concurrently, the risk of mental disorders has been increased in the population bearing psychosocial work stressors in their working environments (Stansfeld and Candy, 2006; Wadsworth et al., 2010). Previous studies have shown that city living and urban upbringing could affect people's neural social stress processing (Florian et al., 2011; Tost et al., 2015) and are associated with higher rates of psychosis (Van Os, 2004), anxiety disorders and depression (Peen et al., 2010) than those growing up in rural areas. Moreover, mental disorders have already become one of largest factors in global disease burden (Whiteford et al., 2013). 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 (Substance Abuse and Mental Health Services Administration, 2018). Better understanding of interventions that ameliorate stress and anxiety are needed given their negative consequences on human health (Danielsson et al., 2012).

Contacting with outdoor natural elements, settings and process has become a frequently used approach to seek relief from stressful urban lives (Hartig and Kahn, 2016), which could be explained by people's innate affinity with nature since we were primarily exposed to nature

* Corresponding author at: Harvard T.H. Chan School of Public Health, 401 Park Drive, Landmark Center 4th floor West, Boston, MA 02215, USA.
E-mail address: jieyin@hsph.harvard.edu (J. Yin).
[1] Both authors are joint first author.
[2] Both authors are joint last author.

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during our evolutionary process (Ulrich et al., 1991; Wilson, 1984). 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 (Bratman et al., 2019). The effects of exposure to natural environments on restorative benefits have been explored through many pathways with two dominant theories from environmental psychology perspective (Browning and Alvarez, 2019): attention restoration theory (ART) (Kaplan and Kaplan, 1990; Kaplan, 1995) and stress reduction theory (SRT) (Ulrich et al., 1991). 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 (Kaplan, 1995). 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 (Ulrich et al., 1991). Although these two theories are debating the mechanisms of how nature affect human health, they both emphasized that exposure to natural environments could improve restoring capacities, including attention restoration and psychophysiological stress recovery (Markevych et al., 2017). Nowadays, we are living in a rapidly urbanizing world where accessibility to nature is typically limited (Turner et al., 2004; United Nations, 2018). Moreover, based on the statistic from the National Human Activity Pattern Survey (NHAPS), people spend almost 90% of their time indoors (Klepeis et al., 2001), 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 (Kellert, 2018; Kellert et al., 2008; Kellert and Wilson, 1993; Wilson, 1984). By bringing nature into living and working building spaces, people could increase their time and frequency of connecting with natural elements while being indoors (Yin and Spengler, 2019). Recently, building evaluating system, such as the *WELL* (International WELL Building Institute, 2018), *Living Building Challenge* (International Living Future Institute, 2014), and *The 9 Foundations of a Healthy Building* (Allen et al., 2017) 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 (Bringslimark et al., 2009; Ryan et al., 2014; Ulrich, 1984). Generally, although the effect of biophilic design on psychological responses had been previously summarized (Kaitlyn and Birgitta, 2015), study investigating how it affects the physiological response in stress recovery process is limited (Li and Sullivan, 2016), 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 (Gillis and Gatersleben, 2015; Yin et al., 2019). 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 subjectively. 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 (Chandrasekera et al., 2019; Kuliga et al., 2015). 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 scripting different types of biophilic elements in a convenient way, to estimate the impact of a particular design strategy (Chamilothori et al., 2019; Yin et al., 2019). Moreover, for patients who experience reduced mobility, VR natural environment could be used as therapy for improving their mental well-being during therapy (White et al., 2018).

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 stressor. 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.

2. Method

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 behavioral 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 pre-screening 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.

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 (Fig. 1).

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) (Fig. 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, the *indoor green* condition indicated that we incorporated living walls and potted plants, water (fish tank), natural materials and biomorphic shapes, which were frequently used in interior design practice, into indoor space; the *outdoor view* condition represented long-distance natural view of trees, grass, water and daylight through windows, which shared the same size and location of the living walls in the *indoor green* condition. 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. We kept the same size and similar layout for those four conditions to maximize the comparability.

Fig. 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. Videos for better demonstrating these four indoor environments are available in the "Data availability" sections. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Except for biophilic design interventions, all four offices were identical in terms of all other elements.

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 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 (Shaffer and Ginsberg, 2017). LF/HF ratio is the ratio between the low frequency band power (0.04–0.15 Hz) 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 (Shaffer and Ginsberg, 2017). The calculations of HRV indicators (RMSSD and LF/HF ratio) were performed internally every 30 s, which is the minimal time interval to calculate HRV of this sensor. HR output [1/min] was the mean heart rate for each 30-sec interval. 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 (Ulrich et al., 1991). To match the 30-sec output interval of ECG sensor, the EDA sensor also averaged the SCL data every 30 s. 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)). 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) (Fig. 2).

Additionally, we measured psychological indicator of anxiety level by using the six-item short-form of State-Trait Anxiety Inventory (STAI) (Marteau and Bekker, 1992; Spielberger et al., 1970). 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 (Marteau and Bekker, 1992). 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.

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 from Academia Sinica. Specifically, temperature [°C] and relative humidity [%] were measured by HTU21d sensor; CO_2 [ppm] was measured by SenseAir S8 sensor; $PM_{2.5}$ [μg/m3] was measured by Plantower 5003 sensor. Those IEQ indicators were collected every 5 min.

The experiment includes three parts: preparation and baseline, stressor, and recovery (Fig. 2). In the preparation and baseline period, participants signed the informed written consent. Then, they wore HTC Vive VR headset and bio-monitoring sensors 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) (Dickerson and Kemeny, 2004; Kirschbaum et al., 1993). In the two-minute memory

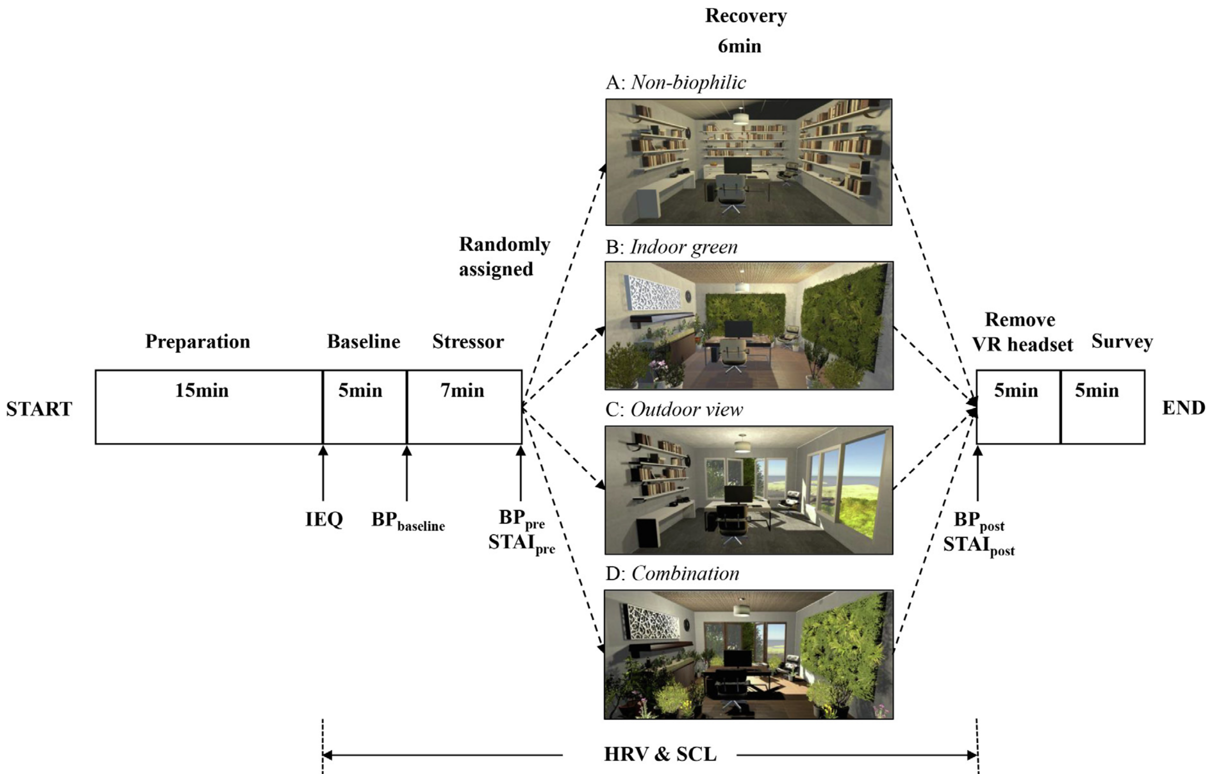

Fig. 2. Experimental procedure. Note: IEQ: indoor environmental quality; BP: blood pressure; STAI: State-Trait Anxiety Inventory; HRV: heart rate variability; SCL: skin conductance level.

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 s 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 (Kudielka et al., 2007). 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 (Barton and Pretty, 2010; Brown et al., 2013; van den Berg et al., 2015; Yin et al., 2018). 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). We administered these questions at the end of the experiment to avoid disclosing study objectives that was to compare stress recovery of participants among different indoor environments. The whole experiment lasted around 45 min.

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. A two-side alpha level of 0.05 was used to determine statistical significance. 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, for the pre-post stressor physiological measures to determine if participants' physiological stress levels after the stress-induction tasks were significantly higher than their baseline measures. A one-side alpha level of 0.05 was used to determine statistical significance.

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 1).

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

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 2) (R package 'gamm4',

Table 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 ± 12	28 ± 11	27 ± 8	31 ± 12	30 ± 15
Gender	–	–	–	–	–
Female	63(63)	16(64)	15(60)	16(64)	16(64)
Male	37(37)	9(36)	10(40)	9(36)	9(36)
Ethnicity	–	–	–	–	–
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)
Self-reported stress level (1-lowest to 5-highest)	2.2 ± 0.9	2.0 ± 0.6	2.4 ± 1.2	2.8 ± 1.0	2.2 ± 0.8
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 (°C)	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	717 ± 115	689 ± 143	740 ± 143	719 ± 117

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.

$$(log)Y_{ij} = \beta_0 + \beta_{1\sim3} environment + \beta_4 time + \beta_{5\sim7} environment * time + e_{ij} + \mu_i \quad (2)$$

where:

- $(log)Y_{ij}$ = HR, log scale of HRV or SCL for participant i at time j
- $time$ = number of 30-second interval after stressor
- $(exp)\beta_{5\sim7}$ = 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* has the same meaning as that in Model (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 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) (Spruance et al., 2004). All analyses were conducted in the open-source statistical package R (v.3.5.1)

$$\lambda(t; environment) = \lambda_0(t) exp(\beta_{1\sim3} environment) \quad (3)$$

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

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.

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 1. Participants had an average age of 29.2 ± 11.8 year, 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. Most of them were not stressed and the average score of self-reported stress level was 2.2 ± 0.9. 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 $\mu g/m^3$, 716 ± 121 ppm, 21.3 ± 1.2 °C, and 36.7 ± 10.0%, respectively. There were no statistically significant differences of demographics and most IEQ among four conditions after randomization (Table S1). One exception is that the average relative humidity was lower in the non-biophilic environment compare with those in the biophilic environments (Table 1). In addition, the baseline physiological measures were similar among four conditions with no significant differences (Table S1). The absence of differences across baseline measures among four groups indicated the success of the randomization.

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 Fig. 3 and Table S3. Our results from paired *t*-tests and Wilcoxon signed-rank tests suggest that participants' physiological stress level increased significantly after experiencing stressor (Table S2). In addition, our ANOVA results suggest that effect sizes for between group differences in BP, STAI, SCL HR, and HRV are not significant (Table S1). Therefore, there were no significant differences in stress and anxiety level after stressor among four groups.

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) (Fig. 4 and Table S4). 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 (Fig. 3 and Table S4). 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 (Fig. 4 and Table S4). However, the difference of STAI decreases between *indoor green* condition and non-biophilic environment was close to the null and not statistically significant.

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 Fig. 4. 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. 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 S1** and Table S5). However, we did not find significant difference of recovery rates of LF/HF ratio, HR and SCL between biophilic and non-biophilic environments.

3.4. Effect of biophilic environments on time to complete recovery

Estimated hazard ratio of complete recovery for physiological

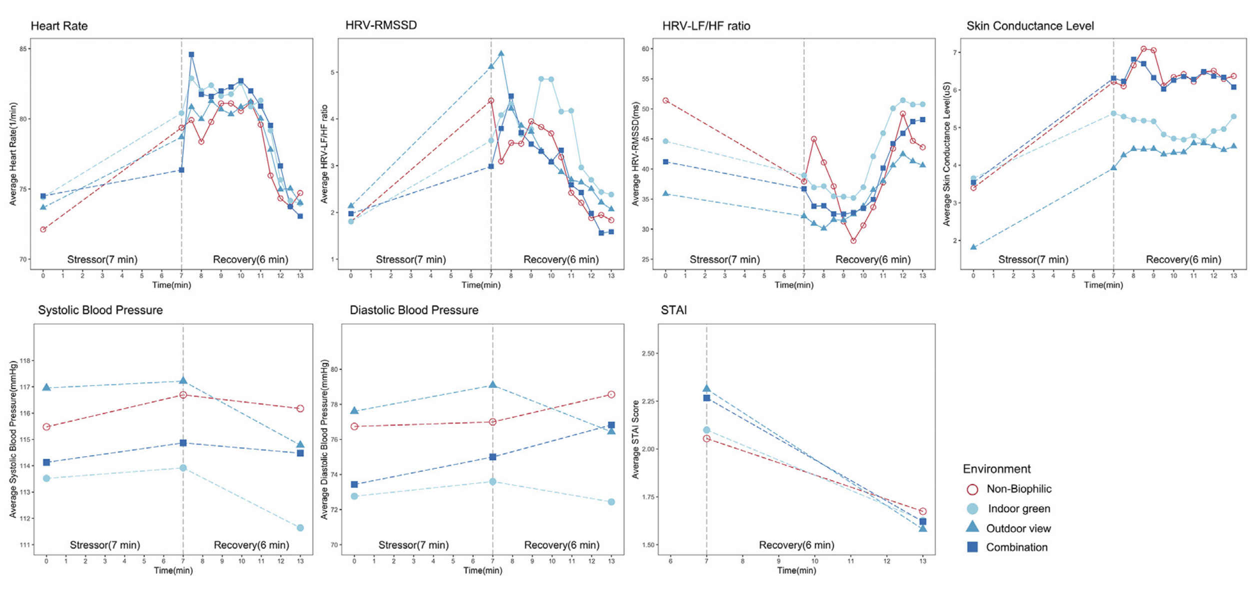

Fig. 3. Average physiological and psychological outcomes in baseline, after stressor and during the recovery period among four environments. Note: HRV: Heart Rate Variability; RMSSD: Root mean square of the successive differences; LF/HF Ratio: Low to high frequency ratio. STAI: State-Trait Anxiety Inventory. High RMSSD and low LF/HF indicate low stress level.

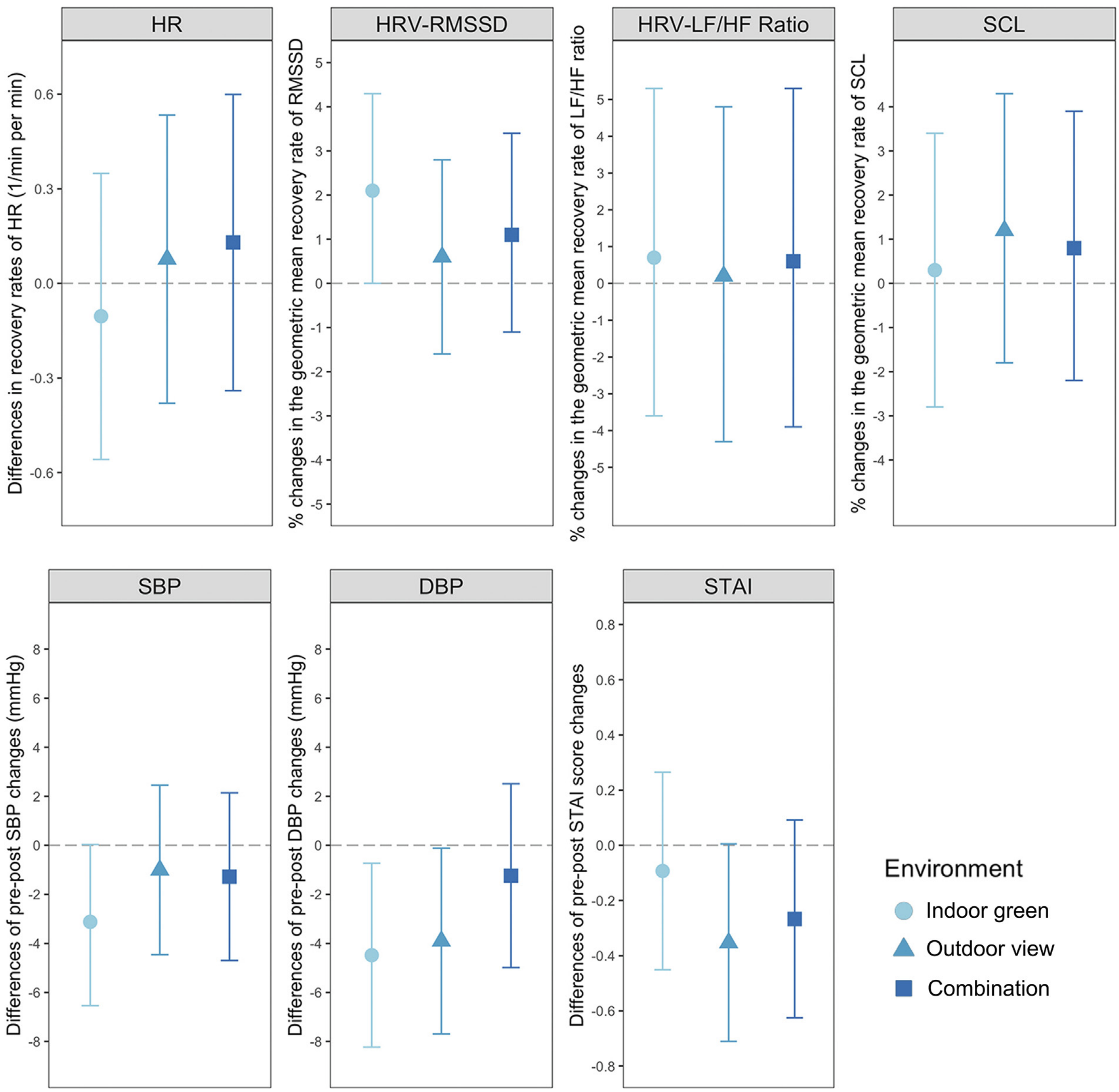

Fig. 4. Estimated differences in recovery rates of heart rate (HR), percentage changes in the geometric mean recovery rate of heart rate variability (HRV) and skin conductance level (SCL), and differences in pre-post changes in blood pressure (SBP & DBP) and state-trait anxiety inventory (STAI) score 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.

measures in biophilic environments compare to non-biophilic environment in 6-minute recovery period are shown in Fig. 5. Since SCL measure in four groups kept stable during recovery period rather than reduced back to baseline, we excluded 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 suggested that throughout the recovery period, the participants in biophilic environments recovered faster.

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. For most physiological and psychological measures, the effects of the *combination* condition were between those of *indoor green* and *outdoor view* conditions, although the differences were not significant. Within the recovery period, we also found the biophilic environments had the

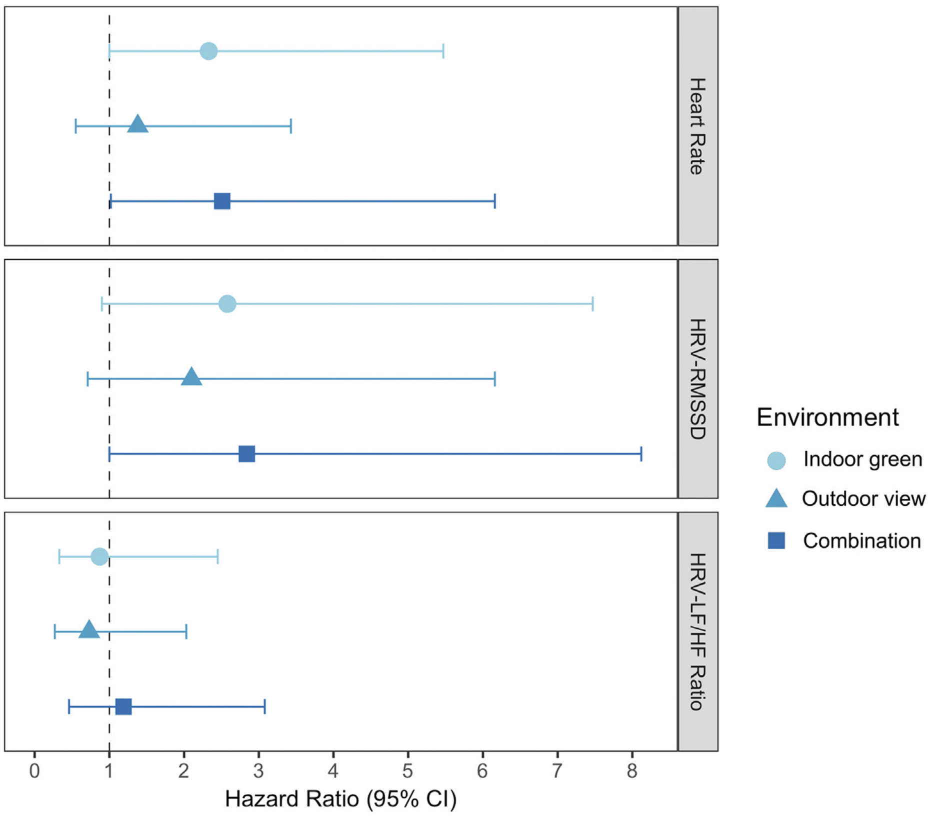

Fig. 5. Estimated hazard ratio of complete recovery for physiological measures in biophilic environments compare to non-biophilic environment in 6-minute recovery period. Note: HRV: Heart Rate Variability; RMSSD: Root mean square of the successive differences; LF/HF: Ratio of low frequency to high frequency. 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.

largest effect on reducing physiological stress in the first four minutes of the six-minute recovery process.

4.1. Benefits of biophilic environments on restoration

Our physiological results from linear model, mixed effect model and Cox model indicated that participants in biophilic environments had consistently better recovery from stress. This findings was consistent with previous studies, which 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 (Ulrich et al., 1991). Our findings also indicate that the biophilic environments, especially the *indoor green* condition, have improved participants' blood pressure, which was partially consistent with our previous findings that visual exposure to indoor biophilic environments could improve participants' blood pressure, especially for diastolic blood pressure (Yin et al., 2019). Consistently, a systematic review paper also mentioned that outdoor greenspace exposure, rather than indoor biophilic environments, was associated with decreased diastolic blood pressure ($p = 0.009$) and systolic blood pressure ($p = 0.13$) (Twohig-Bennett and Jones, 2018). 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 (Li and Sullivan, 2016). 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 (Ulrich et al., 1991). 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 Fig. 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.

4.2. Different effects among three biophilic environments

In this study, we found different restorative effects on physiological stress indicators and anxiety level 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 (Gray and Birrell, 2014; Lohr et al., 1996; Shoemaker et al., 1992). 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 (Li and Sullivan, 2016; Sop Shin, 2007).

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.

4.3. 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 (Higuera-Trujillo et al., 2017; Valtchanov et al., 2010). 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, olfactory, thermal comfort, or people's interaction with the surroundings (Gaoua, 2010; Hedblom et al., 2019; Matsuoka, 2010; Wooller et al., 2018). 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 (Yin et al., 2018). 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 (Wooller et al., 2015; Wooller et al., 2018). 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.

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.

CRediT authorship contribution statement

Jie Yin: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Project administration, Funding acquisition. **Jing Yuan:** Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Nastaran Arfaei:** Methodology, Software, Writing - review & editing, Visualization. **Paul J. Catalano:** Methodology, Writing - review & editing. **Joseph G. Allen:** Conceptualization, Writing - review & editing, Supervision. **John D. Spengler:** Conceptualization, Writing - review & editing, Supervision.

Data availability

The data support the findings of this study is available at http://dx.doi.org/10.17632/zsh5hkdjhh.2.

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Declaration of Competing Interest

The authors declare no competing interests.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.105427.

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