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Physiological and psychological responses to transitions between urban built and natural environments using the cave automated virtual environment

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HIGHLIGHTS

- Transition from built to natural environments could improve mood and reduce anxiety.
- Transition from natural to built environments has the reverse effects.
- Participants showed more emotional responses to natural environments.
- Individual characteristics and contextual factors differentiate restorative effects.

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ABSTRACT

Observational and experimental studies have illustrated that exposure to greenness is beneficial to long-term health and well-being. In the urban context, however, more evidence is needed for a better understanding of the short-term health impacts of nearby nature. To address this limitation, we investigated the dynamic influence of transitions between built and natural environments on urban residents using Cave Automated Virtual Environment (CAVE) immersive virtual reality technology. In this experiment, we filmed two pairs of 360° 8K videos of geographically adjacent built and natural environments in Boston, MA to mimic real-life environmental exposure of urban residents, and created virtual immersive stimuli with an 8K-resolution curved panoramic screen accompanied with a 7.2 Dolby Surround 360° audio system. We recruited 171 participants in a randomized crossover experiment to evaluate physiological and psychological responses to transitions between urban built and natural environments. Our psychological results indicate significant reductions in negative mood dimensions, total mood disturbance, and transient anxiety, during the transition from built to natural environments; and increases during the transition from natural to built environments. In addition, we observed participants showed more emotional responses to nature through physiological measures. Lastly, we found that contextual factors that were rarely tested in previous studies, including differential physical health conditions, underlying stress levels, formative experience with nature, and growth environments, might influence the extent of stress recovery. This study provided empirical evidence from the health perspective for promoting nearby nature in urban built environments.

1. Introduction

Urbanization characterizes the growth of cities and urban populations due to industrialization and economic development (Turan & Beşirli, 2008). Indeed, it is not only simply a demographic shift, but also comprises environmental, social, economic, and psychological

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changes within that population transition. As people now spend almost 90% of their time indoors (Klepeis et al., 2001; Turner, Nakamura, & Dinetti, 2004), one of the inevitable consequences of rapid urbanization is the compromised physiological and psychological health of urban dwellers as a result of limited access to nature and thus accumulation of urban stress (Lederbogen et al., 2011; Peen, Schoevers, Beekman, & Dekker, 2010; van Os, Kenis, & Rutten, 2010). As proposed by Harvard biologist E. O. Wilson in *Biophilia*, humans possess an innate connection with nature and other forms of life (Wilson, 1986). Based on this hypothesis, emerging scientific evidence has shown that exposure to nature has significant benefits for health and well-being, including stress recovery (Ulrich, 1983; Ulrich et al., 1991), improvement of cognitive functions (Berman, Jonides, & Kaplan, 2008; Berto, 2005; Staats, Kieviet, & Hartig, 2003), and increase in positive affect (Berman et al., 2008; Hartig, Mitchell, De Vries, & Frumkin, 2014). Practically, however, access to distant outdoor nature is usually limited for urban residents due to transportation, concentration of urban greenspace to limited areas, or lack of time. For urban residents, small parks and green spaces are more accessible than distant outdoor nature for stress relief in the city, yet the potential benefits of urban green spaces have not yet been adequately quantified, making it difficult to incorporate green spaces into urban planning and design processes efficiently to maximize their health benefits.

Recent observational studies have found that exposure to green space in urban areas is positively associated with physical activities (Bedimo-Rung, Mowen, & Cohen, 2005), stress reduction and recovery (Thompson et al., 2012; Van den Berg, Maas, Verheij, & Groenewegen, 2010), positive workplace attitude (Lottrup, Grahn, & Stigsdotter, 2013), and negatively associated with cardiovascular disease (Pereira et al., 2012), morbidity, and mortality (James, Hart, Banay, & Laden, 2016; Maas et al., 2009; Mitchell & Popham, 2008). Experimental studies have also demonstrated similar health benefits of urban green space using two main approaches: field experiment and virtual simulation (Beil & Hanes, 2013; Rodiek, 2002; Tyrväinen et al., 2014). The former is typically conducted through site visits to different urban built and natural environments paired with physiological measurements and subjective evaluations. Previous field experiments found that exposure to urban nature has positive effects on perceived restoration from stress, vitality, positive affect, and self-reported creativity (Tyrväinen et al., 2014), as well as pre-to-post changes in salivary amylase (Beil & Hanes, 2013). Virtual stimuli, on the other hand, originally represented exposure to urban nature through photographs (Berto, 2005; Nordh & Østby, 2013; Ulrich, 1979), plasma display windows (Kahn Jr et al., 2008), and 3-D videos (Jiang, Chang, & Sullivan, 2014; Jiang, Li, Larsen, & Sullivan, 2016). More recently, emerging virtual reality (VR) technology provides the potential to improve the previous methods by allowing researchers to customize and create virtual environmental exposures and providing participants with more immersive experiences. This method has been applied and validated in previous VR experiments, which have been proved to have similar physiological and psychological responses compared to the physical stimuli in the real environment (Yin et al., 2019; Yin et al., 2020; Yin, Zhu, MacNaughton, Allen, & Spengler, 2018; Annerstedt et al., 2013; Tabrizian, Baran, Smith, & Meentemeyer, 2018; Valtchanov, Barton, & Ellard, 2010).

Using virtual stimuli in simulation experiments can address the limitation of field experiments which usually suffer from uncontrollable environmental factors such as temperature, light, sounds, and smells that may bias the results (Browning, Saeidi-Rizi, McAnirlin, Yoon, & Pei, 2021), as they need to bring participants to the actual sites and engage them in the same activities, such as walking tours across multiple sites. Commonly used virtual stimuli such as images and videos were limited by the 2D presentation by which participants were not able to see the surroundings and thus may raise questions about the validity of their responses. VR technology, on the other hand, allows for a more immersive experience of environmental exposures of interest. Individual VR headsets are so far the most commonly applied among all VR equipment in simulation experiments. We noticed that most previous studies have been carried out in a between-subject design with small to moderate sample sizes, which resulted in the lack of statistical power to detect the effect of short-term exposures. In this study, we instead used a within-subject experimental design to control for inter-subject variability. We also proposed to offer a novel application of an enhanced room-based, rather than head-based, virtual reality system – Cave Automated Virtual Environment (CAVE) (Muhanna, 2015). The technical components of CAVE include two rear projectors displaying 8K 3D videos of environmental stimuli on a curved panoramic screen and a 7.2 Dolby Surround 360° audio system. This VR technology not only provides at least an equivalent level of immersion but also allows simultaneous data collection of groups of participants in real-time, achieving a larger sample size and thus enhanced statistical power.

Studying the dynamic influence of transitions between adjacent built and natural environments in an urban environment can provide empirical evidence for promoting health in urban designs. However, existing literature either evaluated the health impacts of urban green space alone or compared responses in irrelevant built and natural environments separately; there is yet no study that focused on the dynamic influence of transition between adjacent built and natural environments that represent true exposure of environments in an urban setting. To fill in this gap, we recorded two pairs of 360° 8K videos of densely populated built and natural environments in the Boston urban area, with geographic proximity to mimic urban dwellers' daily commuting patterns. The aim was to evaluate the physiological and psychological responses to virtual transitions of these environments in a controlled lab space.

2. Methods

2.1. Study design

We used the randomized crossover study design, in which participants served as their own control, to minimize potential time-invariant confounding factors and to increase statistical power (Fig. 1**A**). All participants experienced two pairs of virtual urban environments (i.e. a total of four: two built (B1, B2) and two natural (N1, N2) environments) in a randomized order within a single visit, with each pair consisting of one built and one natural environment (Fig. 1**B**). Their physiological and psychological responses were measured repeatedly during the experiment.

2.2. Study population

We enrolled 173 healthy adults in the Boston area via the recruitment system of the Harvard Decision Science Lab (a university-wide facility for behavioral research). The facility hosts a subject pool of over 10,000 people from the Boston area that is open for university researchers to conduct experiments. People who are in this pool could see our study recruitment and choose a time slot to participate. During the prescreening process, we excluded participants who self-reported taking stress recovery medicine, such as Buspirone and selective serotonin reuptake inhibitors (SSRI). We also excluded candidates who seek treatments for stress including both mental health care and physical therapy. We used this exclusion criterion, because people with severe stress levels and under medical supervision may have different responses to nature than people with average stress levels. Eligible participants voluntarily signed up for the experiment with a $25 gift card as compensation. The study was approved by the Institutional Review Board of Harvard T.H. Chan School of Public Health and all participants signed a consent form before starting the experiment.

2.3. Environmental stimuli and test site

We recorded two pairs of virtual environments in the Boston area:

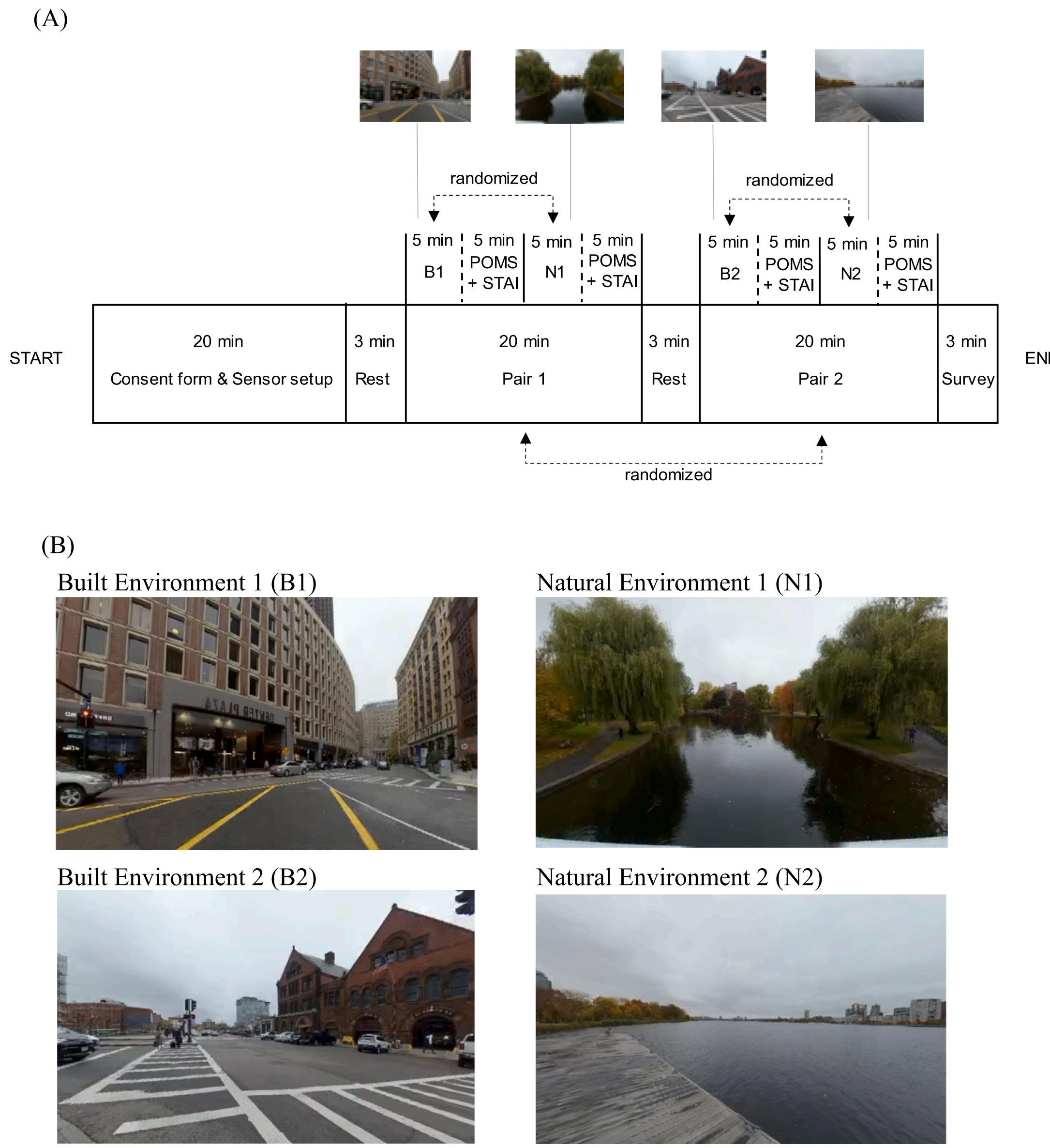

Fig. 1. (A) Timeline of the experimental design and data collection. Participants were randomly assigned to a viewing order (for example, B1 to N1 then B2 to N2 in this figure) after initial rest upon their consent. POMS and STAI were administered immediately after each viewing window. Participants were given a three-minute rest to reset between two pairs of scenes. (B) Representations of each virtual stimulus. The built environment in Pair 1 (B1) was filmed from an office district in Downtown Boston; the natural environment in Pair 1 (N1) was filmed from an adjacent urban park Boston Common. The built environment in Pair 2 (B2) was filmed from a business street Boylston Street in Boston city; the natural environment in Pair 2 (N2) was filmed from an adjacent urban green space Charles River Esplanade. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Pair 1 consisted of built environment 1 (B1) and natural environment 1 (N1), which were filmed from an office district in Downtown Boston and a nearby urban park Boston Common, respectively; Pair 2 consisted of built environment 2 (B2) and natural environment 2 (N2), which were filmed by a business street Boylston Street in Boston city and an adjacent urban green space Charles River Esplanade, respectively (Fig. 1**B**). Each virtual environment was sourced from field filming of three representative scenes and consisted of three 100-second footages from two different angles, 50s for each angle. Each pair of environments was selected based on their geographic proximity to mimic the real-life experience of urban residents. The scenes were filmed using the Insta360 Pro camera (Insta360 Inc), which directly records 360° 8K video that suits the curved panoramic screen as well as real-time audio. The six pieces of filmed footage for each virtual environment were then stitched together continuously into a five-minute video to be projected onto the screen, and no modifications or effects were added to the video or audio. The 8K video rendering was done using Adobe Premiere Pro CC 2019 (version 14.0).

2.4. Outcome measures

We first measured participants' acute stress reactions through real-time physiological indicators, including heart rate variability (HRV), heart rate (HR), and skin conductance level (SCL). Specifically, HRV is an indicator of autonomic nervous system activities in emotional responses (Appelhans & Luecken, 2006; Cacioppo, Klein, Berntson, & Hatfield, 1993; Choi et al., 2017; Rommel, Nandrino, Jeanne, & Logier, 2012). Choi et al. suggest its use when high levels of motion are induced by visual stimulation (Choi et al., 2017). SCL changes are caused by sweat gland secretions, which are controlled by the sympathetic nervous system activity (Ulrich et al., 1991). Participants wore NeuroLynQ biometric sensors (Shimmer Research Ltd, Ireland) on the wrist of their non-dominant hands and four electrodes were connected to the sensor (Fig. 2**A**).

We obtained HRV and HR from electrocardiography (ECG) signals captured by two electrodes placed across the heart and SCL from two electrodes placed on their index and middle fingers. HR output was beats per minute (bpm) for the mean heart rate in each 30-second interval. HRV was calculated internally based on the R-R interval (i.e., the interval between successive heartbeats) range every 10-second epochs using the estimated breadth cycle (EBC) metric (Dandu, Gill, Americas, & Siefert; Goss & Miller, 2013). An HRV response was detected if the EBC was not within a certain range. HRV at resting was non-zero, so a constant HR signal for an interval of time (low HRV) indicated that the participant was paying attention or engaged in the task, whereas if the HR varied more than when at rest (high HRV) then the participant was aroused (Dandu et al., n.d.). In this study, an HRV close to zero or above a certain threshold was labeled an HRV response to the environmental stimuli. We used the fraction of participants' total HRV response during each five-minute exposure window to quantify the level of emotional response to the stimuli. All physiological measurements were collected only during each five-minute time window of viewing, and no further noise filtering was applied.

The second outcome was measurements of psychological indicators of transient anxiety level and distinct mood states using the six-item short form of the State-Trait Anxiety Inventory (STAI) (Marteau & Bekker, 1992; Spielberger, 1970) and the 37-item short form of Profile of Mood States (POMS-SF) (Curran, Andrykowski, & Studts, 1995; McNair,

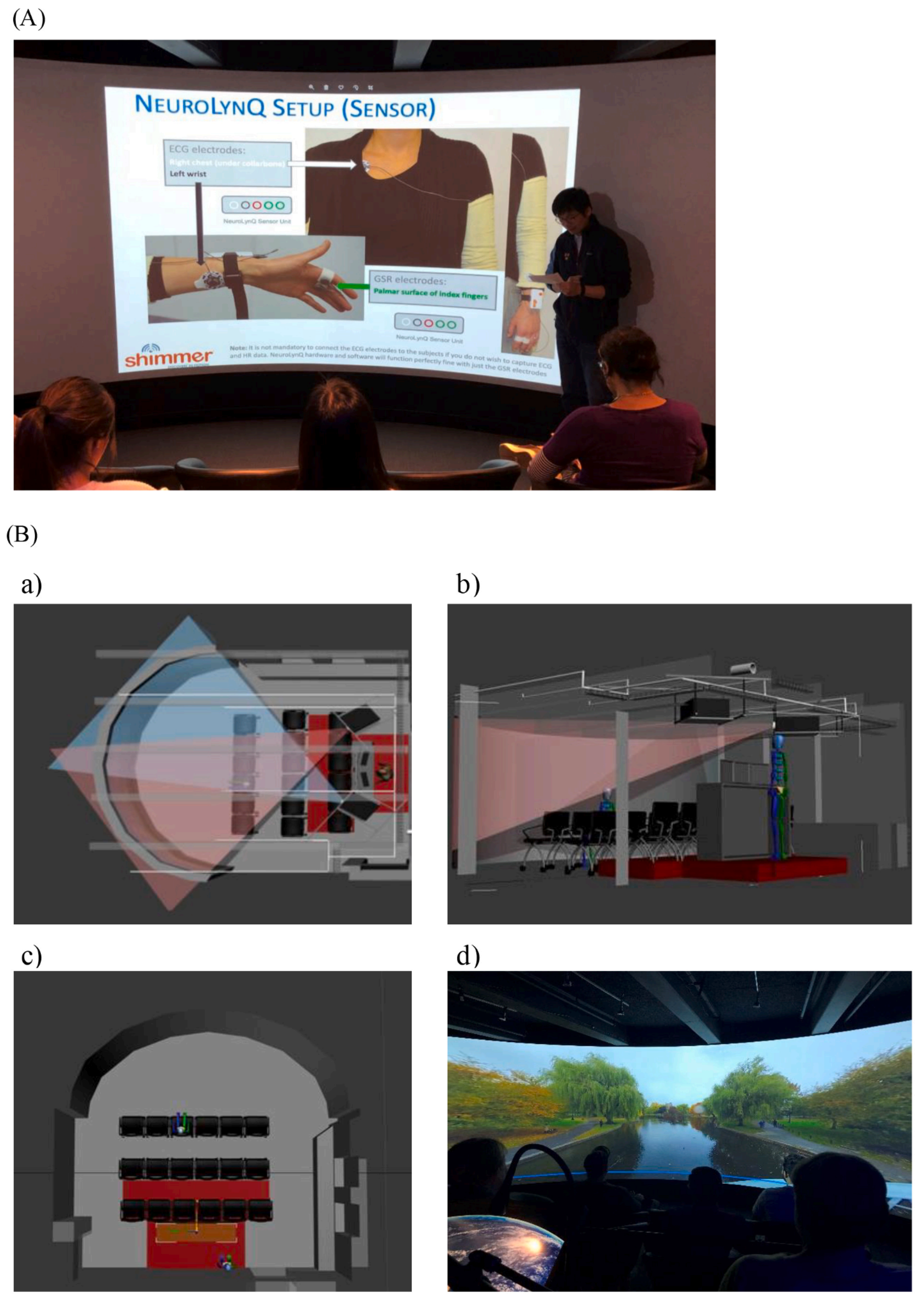

Fig. 2. (A) Physiological measurements were set up with two electrodes placed across the heart to capture the electrocardiography (ECG) signal and the other two placed on the index and middle fingers to measure the skin conductance level (SCL). A total of four electrodes were connected to the sensor for streaming data to storage in real-time. (B) Schematic representation of the research laboratory CAVE system setup. a) The immersive CAVE utilizes two rear projectors for 2 K-4 K-8 K 3D data sources displayed on the curved panoramic screen. b) A researcher was in charge at the monitoring desk for video control. c) a maximum of 15 participants were allowed for each experiment, with a room capacity of 18. d) a site picture of the experiment. Courtesy of the Harvard Visualization Research and Teaching Lab.

Lorr, & Droppleman, 1989; Shacham, 1983), respectively. The short-form STAI consists of 6 questions and is highly correlated with the full 20-item form (internal reliability consistency was greater than 0.90) (Marteau & Bekker, 1992). The short version of STAI includes 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 asked participants how they felt at the test moment and were rated on a four-level scale (e.g., "Not at all", "Moderately", "Somewhat" and "Very Much"), which were scored from one to four. Higher scores indicated greater anxiety for anxiety-positive items and reversely for anxiety-negative items. Mean scores of six questions were used as an index of degrees of anxiety.

The POMS-SF is an adjective list of 37 mood-related items rated on a five-point scale ranging from "not at all" to "extremely." These items are categorized into six dimensions that summarize participants' transient mood states: depression, vigor, confusion, tension, anger, and fatigue. The results of short-form POMS have been tested highly comparable (r greater than 0.95) with those of the full form of POMS that includes 65 items (Curran et al., 1995; Shacham, 1983). Six scores for each dimension and a total mood disturbance (TMD) score were calculated for each participant. TMD scores for the POMS-SF were computed using the formula 1 (Curran et al., 1995):

$$\mathrm{TMD} = \mathrm{Depression} + \mathrm{Tension} + \mathrm{Anger} + \mathrm{Fatigue} + \mathrm{Confusion} - \mathrm{Vigor} \quad (1)$$

2.5. Experimental procedure

The experiments were conducted in the Harvard Visualization Research and Teaching Lab. The schematic representation of the lab room orientation is shown in Fig. 2**B**. Experiments were conducted in groups with a maximum capacity of 15 participants each time. Grouped participants experienced the same randomly assigned ordering of the two pairs of transition environments. Each experiment included three parts: preparation, immersive virtual exposure, and evaluation (Fig. 1**A**). During the preparation phase, participants provided their written consent and were then instructed to wear the biometric sensors with assistance from researchers. After the sensor signals of all participants had been successfully detected, they were given a three-minute break. In the virtual exposure period, each group of participants was randomly assigned to one of the two video viewing orders (pair 1 followed by pair 2, vice versa) (Fig. 1**A**). Within each video pair, the two virtual environments were also randomly assigned to transition groups. A transition group is either built to natural or natural to built environment (hereinafter referred to as B-to-N and N-to-B, respectively). This generated four randomly assigned transition groups in total: B1-to-N1, B2-to-N2, N1-to-B1, and N2-to-B2. Each virtual environment was projected for five minutes, after which STAI and POMS tests were immediately administered to the participants. When all participants finished the tests, they stayed seated and researchers collected the questionnaires. They were given a three-minute break between the two pairs of virtual environments. Finally, all the devices were removed from participants, and each participant completed a paper survey about their demographic information (age, gender, and ethnicity), self-reported general health condition (excellent, very good, good, fair, or poor), caffeinated beverage drinking within six hours before the experiment (yes/no), good sleep quality of the night before (yes/no), and current stress level (Likert scales from 1 to 5: with 1 being very little stress, and 5 being extreme stress). The entire experiment lasted around 70 min.

2.6. Statistical analysis

To evaluate the effect of transitions between built and natural environments, we used the Wilcoxon signed-rank test to determine whether physiological and psychological responses were significantly different between the two types of virtual environments for each video pair. A two-sided alpha level of 0.05 was used to determine statistical significance. We also compared the mean differences among changes in physiological and psychological measures with estimated 95% confidence intervals across four transition groups.

We also examined the differential effect of individual and contextual factors on the physiological and psychological differences during transitions, including age, gender, self-reported physical health status, self-reported mental health status, self-reported stress level, and the existence of positive and/or formative experience with nature. Limited literature has found that participants with different physical and mental health conditions experienced differential benefits from nature (Barton and Pretty, 2010). Some also alluded to a phenomenon that prior experience with nature (Collado, Staats and Corraliza, 2013; De Dominicis et al., 2017; Duerden and Witt, 2010; Evans et al., 2007) and the growth environment of whether rural or urban (Hinds and Sparks, 2008) can influence restorative benefits from nature. We assumed linearity of effect and used univariable linear mixed effect models with each of these variables, and used mean differences in percent change of HR, HRV response fraction, SCL, and mean differences in STAI and POMS scores between the built and natural environments in each video pair as dependent variables. Each participant was treated as a random intercept to control for the variability across individuals. Lastly, we aggregated four transition groups into two (i.e., B-to-N and N-to-B) and analyzed each transition group separately using formula 2.

$$\Delta Y_i = \beta_0 + \beta_1(\textit{individual or contextual factors}) + e_i \quad (2)$$

where:

- ΔY_i = mean differences in percent change of HR, HRV response fraction, SCL, and mean differences in STAI, POMS individual dimension scores, and TMD between the two environments in each video pair for participant *i*
- *individual or contextual factors*: age, gender, self-reported physical health status, self-reported mental health status, self-reported stress level, and the existence of positive and/or formative experience with nature
- β_1 = effect of individual or contextual factors on the physiological and psychological measures

3. Results

3.1. Demographics and experimental conditions

The overall characteristics of the 173 participants are presented in Table 1. Participants mean age was 37 years old, with a standard deviation (SD) of 17 years old. Among 94% of people who responded, 43% were female and 49% were male, with 1% of other genders. 50% of the participants who responded their ethnicity were white. More than 80% of participants self-reported good, very good, or excellent physical and mental health status, 64% reported good sleep quality the previous night, and 48% had a caffeinated drink within six hours before the experiment. The mean self-reported stress level on a one (lowest) to five (highest) basis was 2.4, with an SD of 0.9.

3.2. Differences in physiological and psychological responses to urban built and natural environments

Participants' mean and median physiological and psychological measures for each transition group are shown in Fig. 3 and **Table S1**. In the two B-to-N groups, participants' HRV response fractions in two natural environments did not differ much from in built environments, but in the two N-to-B groups, a significant reverse trend was observed (both $p < 0.001$). However, regardless of whether the second visual stimuli were the built or natural environment, lower HR and higher SCL during the second environment were observed as non-significant and consistent for each transition group.

For psychological measures, POMS results showed a similar trend

Table 1
Characteristics of study participants at baseline. The population consisted of 173 residents in the Boston area recruited.

Baseline characteristics	Mean ± SD or n (%)
Number of Participants	173
Age	37 ± 17
Gender	
Female	75 (43)
Male	85 (49)
Other	2 (1)
No response	11 (6)
Ethnicity	
White/Caucasian	87 (50)
Black/African American	21 (12)
Asian	32 (18)
Latino	10 (6)
Multiracial	10 (6)
No response	13 (8)
Self-reported physical health	
Excellent	38 (22)
Very good	70 (40)
Good	46 (27)
Fair	15 (9)
No response	4 (2)
Self-reported mental health	
Excellent	23 (13)
Very good	58 (34)
Good	60 (35)
Fair	26 (15)
Poor	2 (1)
No response	4 (2)
Rest from overnight sleep	
Yes	110 (64)
No	59 (34)
No response	4 (2)
Caffeinated drink intake 6 h before the experiment	
Yes	83 (48)
No	86 (50)
No response	4 (2)
Self-reported stress level (1-lowest to 5-highest)	2.4 ± 0.9
Indoor environmental quality	
$PM_{2.5}$ (μg/m^3)	2.2 ± 2.7
Temperature (°C)	27.6 ± 3.8
Relative Humidity (%)	14.6 ± 4.3
CO_2 (%)	0.1 ± 0.1

across most negative mood dimensions. The two B-to-N groups reported significantly lower mean scores for depression ($p = 0.042$ and $p < 0.001$, respectively), tension (both $p < 0.001$), and anger ($p = 0.073$ and 0.002, respectively) in the natural environments. Similarly, significantly higher mean scores in tension (both $p < 0.001$) and anger ($p < 0.001$ and $p = 0.004$, respectively) dimensions were observed among the two N-to-B groups. The mean score of the positive dimension vigor increased from built to natural environments ($p = 0.661$ for B1-to-N1, $p = 0.407$ for B2-to-N2) and decreased from natural to built environments ($p = 0.258$ for N1-to-B1, $p = 0.270$ for N2-to-B2) but with no statistical significance. The aggregated measure, TMD, summarized scores for six dimensions and showed a significant reduction of mood disturbance in natural environments ($p = 0.013$ for B1-to-N1 and $p = 0.001$ for B2-to-N2) and, reversely, a significant increase in built environments ($p = 0.009$ for N1-to-B1, $p = 0.002$ for N2-to-B2). Meanwhile, the STAI scores exhibited similar patterns in which participants reported significantly lower scores in natural environments ($p = 0.009$ for B1-to-N1 and $p < 0.001$ for B2-to-N2) and higher in built environments ($p < 0.001$ for both N1-to-B1 and N2-to-B2).

3.3. Effect of transitions between urban built and natural environments on changes in physiological and psychological measures

Comparing the trend of between-transition physiological and psychological changes between B-to-N and N-to-B groups within each video pair (Fig. 4 and **Table S2**), there was no significant trend for HR, HRV response fraction, and SCL except in video pair 2 ($p < 0.035$) (Fig. 4**A**). However, the psychological responses of the B-to-N transition showed significant and consistent lower scores in POMS negative dimensions than those of N-to-B transitions, including depression ($p = 0.010$ for video pair 1, $p < 0.001$ for video pair 2), confusion ($p = 0.023$, $p < 0.001$, respectively), tension (both $p < 0.001$), anger (both $p < 0.001$), and aggregated TMD score ($p = 0.003$, $p < 0.001$, respectively), as well as STAI scores (both $p < 0.001$). The positive dimension vigor indicated a consistent reduction for both N-to-B groups ($p = 0.178$, $p = 0.033$, respectively) (Fig. 4**B**).

3.4. Differential physiological and psychological effects of individual and contextual factors

We conducted stratified analyses separately for two transition groups, B-to-N and N-to-B (Table 2). We found that compared to male participants, females presented a significant increase in SCL by 11.6 % (95% CI: 1.1%, 22.0%) during transitions from natural to built environment. With regard to psychological effects, female participants experienced a greater reduction in mood disturbance (Δ: −6.0, 95% CI: −10.4, −1.7) and STAI score (Δ: −0.2, 95% CI: −0.3, 0.0) from built into natural environments compared to males.

In the transition from a built to a natural environment, better self-reported physical health was overall significantly associated with less reduction in mood disturbance, especially among participants who self-reported very good and excellent physical health status. However, participants with higher self-reported stress levels reported a higher reduction in total mood disturbance (Δ: −2.8, 95% CI: −5.0, −0.6).

The contextual factors included whether participants have positive and/or negative formative experiences with nature and their growth environment. In B-to-N groups, among participants with positive formative experience with nature compared to those without, we observed a greater reduction in HR (Δ: −3.8%, 95% CI: −11.5%, 4.0%) but less reduction in mood disturbance (Δ: 2.8, 95% CI: −10.2, 15.9) and STAI score (Δ: 0.1, 95% CI: −0.4, 0.7). Participants who self-reported negative formative experiences showed significantly less reduction in STAI score (Δ: 0.2, 95% CI: 0.0, 0.4). In N-to-B groups, we only observed a significant increase in TMD (Δ: 4.9, 95% CI: 0.5, 9.4) among participants with negative formative experience compared to those without, while greater TMD scores were shown among those with positive formative experience compared to those without.

Though the growth environment was not overall associated with significant changes in physiological and psychological measures. Interestingly, there was a pattern across different types of growth environments. For example, compared to participants growing up in large city urban areas (Δ: −0.7, 95% CI: −2.6, 1.1) in the B-to-N group, participants growing up in suburban and rural areas tend to experience less reduction in mood disturbance (Δ: 2.5, 95% CI: −2.7, 7.7; Δ: 3.1, 95% CI: −5.8, 12.1, respectively) in comparison with those growing in large or small city urban environments (Δ: −5.5, 95% CI: −9.5, −1.5; Δ: −0.7, 95% CI: −6.6, 5.1, respectively). A similar trend was observed for the STAI score as well.

4. Discussion

4.1. Physiological and psychological effect of transitions between built and natural environments

The psychological results, on one hand, strongly supported our hypothesis that participants may experience a restorative effect on mood disturbance and transient anxiety from built to natural environments, but elevated mood disturbance and anxiety, rather than a lasting calming effect, from natural to built environments. On the other hand, the physiological measures during transitions were not significantly changed. The perceived benefits of mood restoration and stress recovery in urban natural environments were consistent with literature

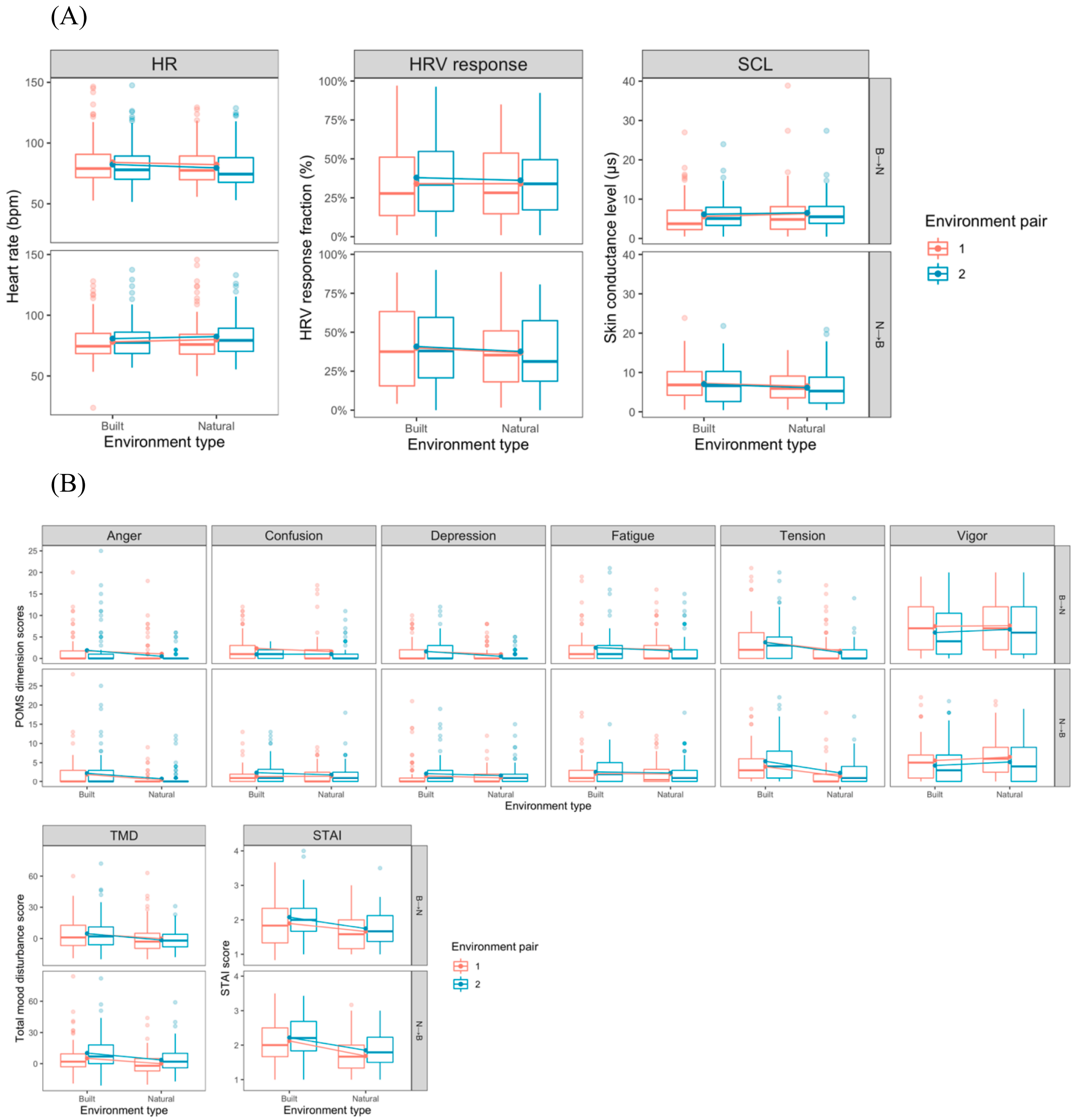

Fig. 3. Distribution of physiological (A) and psychological (B) measurements of each viewed environment during the five-minute viewing window for four transition groups. Physiological measurements include heart rate (HR), heart rate variability (HRV) response, and skin conductance level (SCL). Psychological measurements include six dimensions of the Profile of the Mood States (POMS): depression, vigor, confusion, tension, anger, and fatigue, an aggregated POMS total mood disturbance (TMD), and the State-Trait Anxiety Inventory (STAI) score.

conducting both field and virtual experiments. For example, Tyrväinen et al. found that field visits to urban natural areas have positive effects on perceived restoration, vitality, positive affect, and feelings of creativity measured by several psychological scales, compared to the built city center (Tyrväinen et al., 2014). Another field study with a randomized crossover design concluded significant restorative effects of exposure to natural settings as measured by pre-to-post changes in self-reported stress levels (Beil & Hanes, 2013). Studies using virtual stimuli such as images and immersive visualization consistently reported that exposure to natural environments in urban areas was associated with an increase in perceived mental restoration (Berto, 2005; Nordh & Østby, 2013; Tabrizian et al., 2018; Ulrich, 1979). Our observation of elevated mood disturbance and transient anxiety from natural to built environment, however, was novel. To the best of our knowledge, few previous experiments have tested the reverse direction of exposing participants to natural environments, followed by built city environments or stressors. Further research could investigate this hypothesis in field experiments, other virtual settings, or using other types of natural environments such

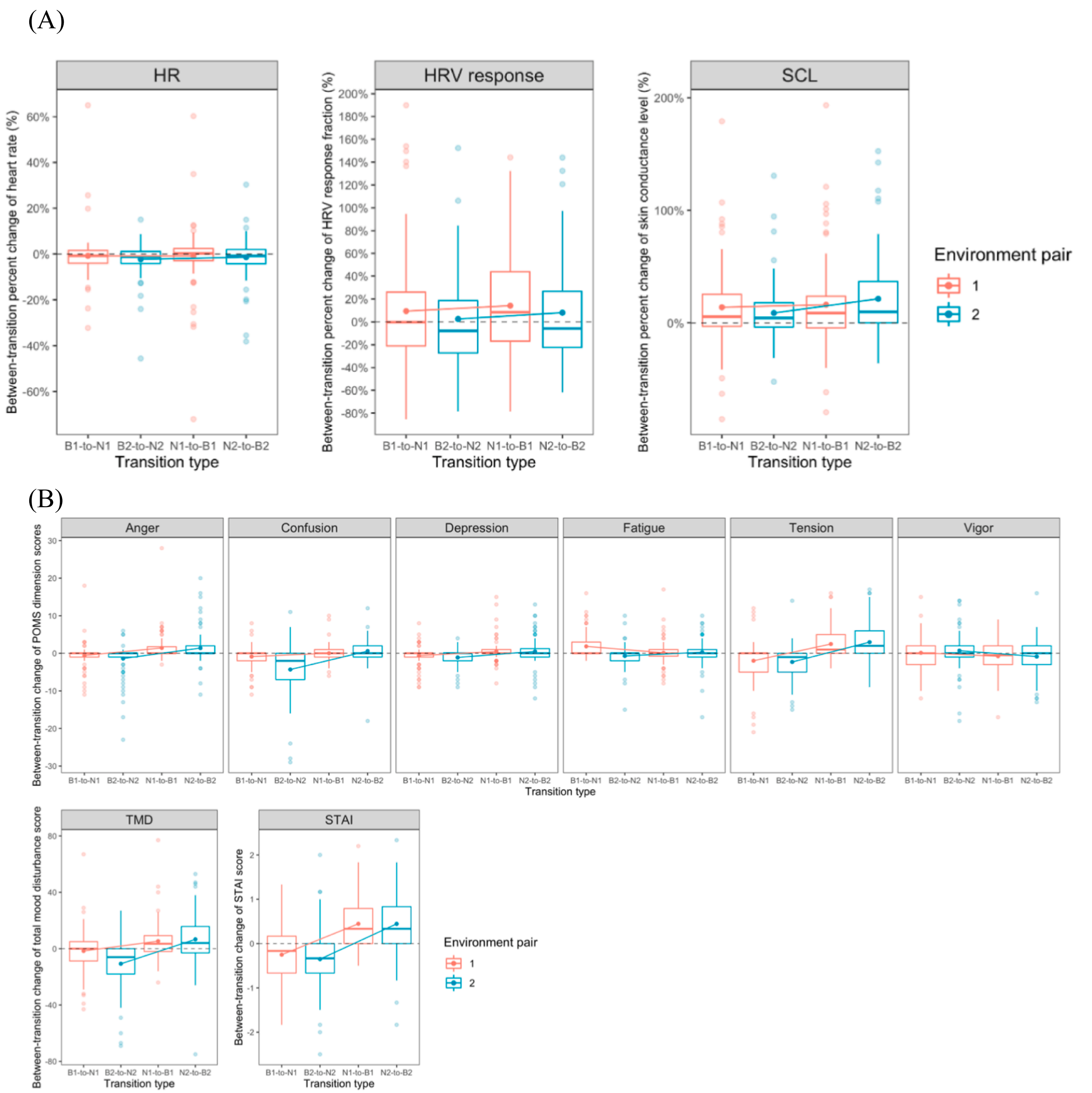

Fig. 4. Mean differences in physiological (A) and psychological (B) responses during the five-minute viewing window of each environment in four transition groups. Differences in physiological responses include percentage changes in heart rate (HR), heart rate variability (HRV) response fraction, and skin conductance level (SCL). Differences in psychological responses include six scores for six dimensions of the Profile of the Mood States (POMS): depression, vigor, confusion, tension, anger, and fatigue, an aggregated POMS total mood disturbance (TMD) score, and the State-Trait Anxiety Inventory (STAI) score.

as wild nature.

For the physiological measurements, significantly higher HRV response observed in two natural environments in both transition groups suggested that participants showed more emotional response to nature, but HR and SCL results were inconsistent. Percent change of HR and SCL exhibited a consistent pattern of negative and positive differences across all four transition groups, respectively, suggesting a time-dependent effect that may have masked the true physiological effect of the second environment. Previous studies using videotapes (Ulrich et al., 1991) and recent VR studies (Yin et al., 2019; Yin et al., 2020) with different experimental designs observed greater physiological recovery following a stressor, as measured by SCL, HR, and HRV when participants were viewing natural or biophilic environments, compared to built environments. One study by Browning et al. adopted the same sensors as ours and found that SCL similarly increased with exposure to nature as we observed, although their experimental design was to experience the control environment followed by exposure to nature in VR (Browning, Mimnaugh, Van Riper, Laurent, & LaValle, 2020). Therefore, we suspect that the overall null result in our experimental setting might be due to a stabilization of participants' physiological response as they moved on to the second environment, regardless of whether the second was the built or natural environment. Another contributing factor might be the

Table 2
Estimated difference (β and 95% confidence intervals) of physiological and psychological measures by individual and contextual factors of participants in built-to-natural environments (B-to-N) and natural-to-built environments (N-to-B) groups. Boldface indicates statistical significance (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$).

	Δ % change of HR (%)	**Δ % change of HRV response fraction (%)**	**Δ % change of SCL (%)**	**Δ Total mood disturbance**	**Δ STAI**
B-to-N					
Age	−0.1 (-0.1, 0.0)	−0.3 (-1.1, 0.4)	0.0001 (-0.004, 0.004)	**0.1 (0.0, 0.3)***	0.001 (-0.005, 0.006)
Gender					
Male (reference)	–	–	–	–	–
Female	0.2 (-1.8, 2.3)	4.1 (-21.2, 29.4)	2.9 (-11.6, 17.3)	**−6.0 (-10.4, −1.7)****	−0.2 (-0.3, 0.0)
Self-reported physical health					
Fair (reference)	–	–	–	–	–
Good	−1.4 (-5.7, 3.0)	24.8 (-25.5, 75.1)	14.8 (-10.3, 39.9)	7.1 (-0.4, 14.6)	0.1 (-0.2, 0.5)
Very good	−2.5 (-6.6, 1.6)	−12.4 (-59.7, 35.0)	19.1 (-5.0, 43.2)	**13.0 (5.7, 20.3)*****	**0.4 (0.1, 0.7)***
Excellent	−1.0 (-5.5, 3.6)	17.2 (−33.8, 68.3)	22.9 (-3.2, 50.1)	**12.9 (5.0, 20.8)****	0.3 (0.0, 0.7)
Self-reported mental health					
Fair (reference)	–	–	–	–	–
Good	1.1 (-2.7, 4.7)	1.1 (-43.5, 45.7)	15.3 (-6.1, 36.7)	3.1 (-3.5, 9.7)	0.1 (-0.2, 0.3)
Very good	−1.1 (-4.8, 2.5)	−13.3 (-56.8, 30.1)	6.6 (-14.5, 27.8)	1.8 (-4.7, 8.4)	0.0 (-0.3, 0.2)
Excellent	0.2 (-4.2, 4.7)	−4.9 (-54.8, 45.0)	11.3 (-13.5, 36.2)	3.0 (-4.7, 10.7)	0.1 (-0.2, 0.4)
Self-reported stress level	0.4 (-0.9, 1.6)	−2.8 (-20.0, 14.4)	−3.3 (-10.6, 3.9)	**−2.8 (-5.0, −0.6)***	−0.1 (-0.2, 0.0)
Positive formative experience					
No (reference)	–	–	–	–	–
Yes	−3.8 (-11.5, 4.0)	14.7 (-48.5, 77.9)	15.4 (-26.7, 57.5)	2.8 (-10.2, 15.9)	0.1 (-0.4, 0.7)
Negative formative experience					
No (reference)	–	–	–	–	–
Yes	0.3 (-2.1, 2.9)	−9.1 (-31.3, 13.0)	9.3 (-4.3, 23.0)	3.7 (-0.6, 8.0)	0.2 (0.0, 0.4)
Growth environment					
Large city urban (reference)	–	–	–	–	–
Small city urban	−1.1 (-3.7, 1.5)	**−49.6 (-83.6, −15.7)****	−6.0 (-24.8, 12.7)	−0.7 (-6.6, 5.1)	−0.1 (-0.3, 0.2)
Suburban	−0.7 (-3.0, 1.7)	−19.1 (-49.2, 10.9)	6.3 (-10.3, 22.9)	2.5 (-2.7, 7.7)	0.1 (-0.2, 0.3)
Rural	0.0 (-4.2, 4.2)	−36.4 (-89.8, 17.0)	**63.1 (34.2, 91.9)*****	3.1 (-5.8, 12.1)	0.3 (-0.1, 0.6)
N-to-B					
Age	−0.1 (-0.1, 0.0)	−0.4 (-1.3, 0.5)	0.0 (-0.3, 0.3)	0.0 (-0.1, 0.2)	−0.002 (-0.008, 0.003)
Gender					
Male (reference)	–	–	–	–	–
Female	−0.7 (-3.5, 2.1)	−16.3 (-41.2. 8.5)	**11.6 (1.1, 22.0)***	0.6 (-3.7, 4.9)	0.0 (-0.1, 0.2)
Self-reported physical health					
Fair (reference)	–	–	–	–	–
Good	**−6.9 (-12.3, −1.4)***	−6.5 (−22.1, 101.5)	10.6 (-10.2, 31.5)	4.7 (-4.2, 13.7)	0.1 (-0.3, 0.4)
Very good	**−7.8 (-13.0, −2.5)** **	9.0 (-50.3, 68.2)	6.9 (-12.7, 26.6)	6.0 (-2.5, 14.5)	0.0 (-0.3, 0.4)
Excellent	−3.5 (-9.1, 2.2)	1.9 (-60.9, 64.7)	17.4 (-3.8, 38.6)	5.4 (-3.8, 14.5)	0.0 (-0.3, 0.4)
Self-reported mental health					
Fair (reference)	–	–	–	–	–
Good	−1.4 (-5.2, 2.4)	–32.2 (-68.6, 4.2)	11.2 (-3.6, 26.0)	1.4 (-4.8, 7.6)	0.1 (-0.1, 0.4)
Very good	**−4.1 (-8.0, −0.3)***	**−44.0 (-81.2, −6.9)***	−1.0 (-16.2, 14.2)	3.6 (-2.7, 9.9)	0.0 (-0.2, 0.3)
Excellent	−0.1 (-5.0, 4.8)	**−55.1 (-103.3, −7.0)***	8.3 (-10.6, 27.2)	1.3 (-6.6, 9.1)	0.0 (-0.3, 0.4)
Self-reported stress level	0.6 (-0.9, 2.1)	−6.0 (-20.7, 8.8)	−0.2 (-5.8, 5.5)	1.3 (-1.0, 3.6)	0.0 (-0.1, 0.1)
Positive formative experience					
No (reference)	–	–	–	–	–
Yes	0.1 (-11.9, 12.0)	−11.4 (-75.5, 98.4)	14.3 (-29.1, 57.6)	5.4 (-13.0, 23.7)	0.0 (-0.8, 0.8)
Negative formative experience					
No (reference)	–	–	–	–	–
Yes	−1.5 (-4.4, 1.4)	10.4 (-14.5, 35.4)	−0.2 (-10.6, 10.3)	**4.9 (0.5, 9.4)***	0.0 (-0.2, 0.2)
Growth environment					
Large city urban (reference)	–	–	–	–	–
Small city urban	−0.9 (-4.7, 3.0)	15.9 (−22.2, 54.0)	0.6 (-14.9, 16.1)	−1.4 (-7.6, 4.8)	−0.1 (-0.3, 0.2)
Suburban	0.0 (-3.3, 3.4)	−45.5(-34.9, 24.0)	4.4 (-17.4, 8.6)	−1.2 (-6.4, 4.1)	−0.1 (-0.3, 0.2)
Rural	4.8 (-0.4, 10.0)	−6.4 (-60.0, 47.3)	1.7 (-18.4, 21.9)	−5.2 (-13.3, 2.9)	−0.1 (-0.4, 0.3)

hydrogel pads to electrodes attached to participants' fingers, which may cause the skin to sweat after wearing it for minutes in a comfortable indoor space. Sweat secretion increases moisture on the epidermis and, therefore, increases its conductance potential, which may partly explain the consistent increase of SCL across all groups over time during the experiment, regardless of the order of the environments experienced.

4.2. Differential effects by individual and contextual factors

Regarding differential effects of environmental transitions by individual factors, we found that gender, self-reported physical health, and self-reported baseline stress were significantly associated with response changes. Males experienced a significant reduction in HR and an increase in SCL from built to natural environments, whereas females experienced a significant increase in SCL from natural to built environments. Females also experienced more reduction in mood disturbance and transient anxiety than males during the transition from built to natural environments. This confirms the observations of differences in mental health benefits stratified by gender in many previous research studies as summarized in several recent systematic reviews (Bolte, Nanninga, & Dandolo, 2019; Núñez et al., 2022; Sillman, Rigolon, Browning, Yoon, & McAnirlin, 2022), which consistently points to women experiencing stronger beneficial effects of urban greenness than men. Several arguments for such phenomenon include the marginalization of women in society resulting in more to gain from exposure and access to greenness due to worse life and health than men (Sillman, Rigolon, Browning, Yoon, & McAnirlin, 2022), safety concerns, and societal roles carried by women (Bolte, Nanninga, & Dandolo, 2019; Núñez et al., 2022).

In addition, we observed an overall negative trend between self-reported physical health status and reduction in mood disturbance and transient anxiety level. This may imply that participants with better physical conditions are more psychologically resilient and therefore experienced fewer negative effects. This is consistent with foundings from previous studies that physical fitness can confer resilience (Meredith et al., 2011; Perna et al., 2012; Silverman & Deuster, 2014; Skrove, Romundstad, & Indredavik, 2013), defined as "the ability to withstand, recover, and grow in the face of stressors and changing demands" (Deuster & Silverman, 2013) through multiple biological pathways, such as serving as a stress buffer (Huang, Webb, Zourdos, & Acevedo, 2013; Li & He, 2009), mobilizing neuroendocrine and physiological responses to stressors (Forcier et al., 2006; Fragala et al., 2011; Stranahan, Lee, & Mattson, 2008), promoting an anti-inflammatory internal environment (Gleeson et al., 2011; Hamer, 2007), and enhancing neuroplasticity and grow factor regulation (Cotman, Berchtold, & Christie, 2007; Dishman et al., 2006; Knaepen, Goekint, Heyman, & Meeusen, 2010). We also proposed that this may be mediated directly by nature connectedness, as people with poorer physical health tend to be less physically active and, therefore, less exposed to nature and its restorative effects.

Moreover, participants with higher self-reported baseline stress were found to experience a significantly greater reduction in mood disturbance when entering natural from built environments. This implies that people with higher underlying stress might be more psychologically sensitive to natural exposure, or environmental change in general, leading to differentially higher restorative effects from nature. This is consistent with the suggestion by Wohlwill that people with higher levels of arousal, an emotion triggered by stress, are more likely to immerse themselves in nature (Wohlwill, 1976), in which case people with higher underlying stress experience a higher level of immersiveness and greater capacity for stress recovery.

Among contextual factors, we observed interesting patterns in the effects of positive and negative formative experiences with nature as well as the growth environment. During the transition from built to natural environments, HR, and HRV response fractions indicated that participants who had positive formative experiences with nature felt restful and paid more attention in natural environments, respectively. During the transition from natural to built environments, HR, HRV response fraction, and SCL indicated they felt less restful, showed decreased attention to built environments, and more transient stress, respectively. On the other hand, participants with negative experiences felt less restful, paid less attention, and experienced more transient stress in natural environments after viewing built environments. They also felt less restful but paid more attention and experienced less stress from natural to built environments. For psychological measurements, perceived mood disturbance decreased in B-to-N transition groups and increased in N-to-B transition groups similarly, regardless of whether individuals ever had positive and/or negative formative experiences with nature. This phenomenon seemed to suggest that exposure to nature can bring benefits in perceived restorativeness even among people who previously had negative interactions with nature, but physiologically still reflected the influence of former negative affect in nature compared to the positive. Although the direct link between previous positive or negative experience of nature and potential difference in health benefits is not adequately proved yet, many previous findings have demonstrated that experience of nature, especially during childhood, is one of the major determinants in one's environmental attitude and behaviors that are strongly linked to adulthood nature relatedness (Chawla, 1999; Hinds & Sparks, 2008). This can partially explain the observation in physiological responses for which participants having negative previous experience with nature revealed less restfulness in natural environments and less stress in built environments, but the underlying mechanism remains to be explored.

Lastly, we observed differential effects of the growth environment on mood disturbance and STAI scores. Participants growing up in large or small city urban areas seem to experience greater effects in reducing mood disturbance and transient anxiety than those growing up in suburban or rural areas. The interpretation could be bi-directional: one being that people growing up in wild nature regions may be more mentally resilient to potential stress arising from built environments, while the other being that their perception of nature is highly shaped by their growth environment, in which case individual emotional response may differ by whether the natural environment viewed was indeed considered "nature." To date, there has been no study that explored this relationship, and more environmental psychosocial research is needed to understand this phenomenon.

4.3. Strengths and limitations

Our study had a few limitations. First, because of the design nature of the curved screen, our videos with the 16:9 aspect ratio had slight distortion on the vertical edges. However, we anticipate that these distortions may not substantially influence our results as people tend to focus on the center. On the other hand, the wideness provided an immersive experience for participants, and the curved screen also allowed us to simultaneously collect physiological measurements of groups of participants, largely increasing the sample size and efficiency of such experiments. Second, the application of real-time monitoring sensors required hydrogel pads for measuring HR and SCL, which may get loose after wearing for a certain period when the attached skin started to sweat. This may result in an underestimation of physiological measurements in later stages and might have contributed to our findings of non-significant physiological effects. However, because the duration of wearing monitoring sensors was $<$40 min and the room temperature was maintained at a thermal comfort level, we do not anticipate this to have led to large errors in measurement. Third, we acknowledge that the virtual environments as shown in representative shots in Fig. 1 were all collected on a cloudy day, which was not a common practice in previous experiments. The environmental stimuli were filmed during October in Boston. Such an environment represents very typical local weather during the filming period, and filming was carried out on a predetermined date based on the weather forecast in order to assure that all virtual stimuli were collected on the same day while avoiding extreme weather such as rain or snow. We anticipate that filming in other seasons such as summer when built and natural scenes differ more drastically may result in differences in observations of these same measurements, which is worth comparison in future experiments. The virtual environments used in this experiment, however, did mimic the real environmental exposure for the specific time and location, although compromising the generalizability of the observed results. Lastly, the repeated filling of the same questionnaires four times throughout the experiment may diminish the validity of reported results in later responses. To minimize the potential bias, we chose the shortest possible versions of both questionnaires to reduce the filling time. We also randomized the viewing orders within each pair of virtual stimuli and allocated 3-min for rest to dilute the potential effects of later responses being more biased.

A key innovation of our study is that it was the first to incorporate the dynamics of transition between urban built and natural environments by randomly assigning consecutive exposure to built and natural environments to participants while measuring their real-time physiological responses and transient psychological responses. This allowed us to closely mimic the real-life experience of urban residents. Among the important strengths of our study is the 8K immersive CAVE system – allowing simultaneous experience by groups of participants while providing equivalent if not higher level of immersiveness. The randomized crossover study design was a key strength, in which participants acted as their own control, minimizing potential time-invariant confounding and increasing statistical power. Lastly, our study had a larger sample size compared to similar studies and our study population reflected a wide range of individual characteristics, which allowed us to explore discernible effects of different transition groups and differential effects of individual characteristics and contextual factors.

5. Conclusion

We conducted a randomized crossover study using CAVE immersive technology to evaluate physiological and psychological responses to transitions between built and natural environments in urban areas. Psychological responses indicated significant reductions in negative mood dimensions, total mood disturbance, and transient anxiety, during the transition from built to natural environments; and increases during the transition from nature to built environments. The analysis of individual characteristics and contextual factors suggested that people with differential physical health conditions and underlying stress levels may experience different extents of stress recovery. Formative experience with nature and growth environments, as a manifest of nature connectedness, also differentiated perceived restorative effects. We did not find consistently significant results in our physiological measurements, but it might be due to time-dependent effects caused by the wearing of personal sensors. Our study provided scientific evidence for urban planners to consider accessibility to and the quality of built and natural landscapes in urban areas, as well as the potential health benefits of shifting places for urban residents in their daily life.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2023.104919.

References

Annerstedt, M., Jönsson, P., Wallergård, M., Johansson, G., Karlson, B., Grahn, P., Hansen, A. M., & Währborg, P. (2013). Inducing physiological stress recovery with sounds of nature in a virtual reality forest—Results from a pilot study. *Physiology & Behavior, 118*, 240–250.
Appelhans, B. M., & Luecken, L. J. (2006). Heart rate variability as an index of regulated emotional responding. *Review of General Psychology, 10*(3), 229–240.
Barton, J., & Pretty, J. (2010). What is the best dose of nature and green exercise for improving mental health? A multi-study analysis. *Environmental Science & Technology, 44*(10), 3947–3955.
Bedimo-Rung, A. L., Mowen, A. J., & Cohen, D. A. (2005). The significance of parks to physical activity and public health: A conceptual model. *American Journal of Preventive Medicine, 28*(2), 159–168.
Beil, K., & Hanes, D. (2013). The influence of urban natural and built environments on physiological and psychological measures of stress—A pilot study. *International Journal of Environmental Research and Public Health, 10*(4), 1250–1267.
Berman, M. G., Jonides, J., & Kaplan, S. (2008). The cognitive benefits of interacting with nature. *Psychological Science, 19*(12), 1207–1212.
Berto, R. (2005). Exposure to restorative environments helps restore attentional capacity. *Journal of Environmental Psychology, 25*(3), 249–259.
Bolte, G., Nanninga, S., & Dandolo, L. (2019). Sex/gender differences in the association between residential green space and self-rated health—A sex/gender-focused systematic review. *International Journal of Environmental Research and Public Health, 16*(23), 4818.
Browning, M. H., Mimnaugh, K. J., Van Riper, C. J., Laurent, H. K., & LaValle, S. M. (2020). Can simulated nature support mental health? Comparing short, single-doses of 360-degree nature videos in virtual reality with the outdoors. *Frontiers in Psychology, 10*, 2667.
Browning, M. H., Saeidi-Rizi, F., McAnirlin, O., Yoon, H., & Pei, Y. (2021). The role of methodological choices in the effects of experimental exposure to simulated natural landscapes on human health and cognitive performance: A systematic review. *Environment and Behavior, 53*(7), 687–731.
Cacioppo, J. T., Klein, D. J., Berntson, G. G., & Hatfield, E. (1993). *The psychophysiology of emotion*. New York: Guilford.
Chawla, L. (1999). Life paths into effective environmental action. *The Journal of Environmental Education, 31*(1), 15–26.
Choi, K.-H., Kim, J., Kwon, O. S., Kim, M. J., Ryu, Y. H., & Park, J.-E. (2017). Is heart rate variability (HRV) an adequate tool for evaluating human emotions?–A focus on the use of the International Affective Picture System (IAPS). *Psychiatry Research, 251*, 192–196.
Collado, S., Staats, H., & Corraliza, J. A. (2013). Experiencing nature in children's summer camps: Affective, cognitive and behavioural consequences. *Journal of Environmental Psychology, 33*, 37–44.
Cotman, C. W., Berchtold, N. C., & Christie, L.-A. (2007). Exercise builds brain health: Key roles of growth factor cascades and inflammation. *Trends in Neurosciences, 30*(9), 464–472.
Curran, S. L., Andrykowski, M. A., & Studts, J. L. (1995). Short form of the profile of mood states (POMS-SF): Psychometric information. *Psychological Assessment, 7*(1), 80.
Dandu, S. R., Gill, G., Americas, S., & Siefert, C. Quantifying Emotional Responses of Viewers based on Physiological Signals. n.d.
De Dominicis, S., Bonaiuto, M., Carrus, G., Passafaro, P., Perucchini, P., & Bonnes, M. (2017). Evaluating the role of protected natural areas for environmental education in Italy. *Applied Environmental Education & Communication, 16*(3), 171–185.
Dishman, R. K., Berthoud, H. R., Booth, F. W., Cotman, C. W., Edgerton, V. R., Fleshner, M. R., … Hillman, C. H. (2006). Neurobiology of exercise. *Obesity, 14*(3), 345–356.
Duerden, M. D., & Witt, P. A. (2010). The impact of direct and indirect experiences on the development of environmental knowledge, attitudes, and behavior. *Journal of Environmental Psychology, 30*(4), 379–392.
Evans, G. W., Brauchle, G., Haq, A., Stecker, R., Wong, K., & Shapiro, E. (2007). Young children's environmental attitudes and behaviors. *Environment and Behavior, 39*(5), 635–658.
Forcier, K., Stroud, L. R., Papandonatos, G. D., Hitsman, B., Reiches, M., Krishnamoorthy, J., & Niaura, R. (2006). Links between physical fitness and cardiovascular reactivity and recovery to psychological stressors: A meta-analysis. *Health Psychology, 25*(6), 723.
Fragala, M. S., Kraemer, W. J., Denegar, C. R., Maresh, C. M., Mastro, A. M., & Volek, J. S. (2011). Neuroendocrine-immune interactions and responses to exercise. *Sports Medicine, 41*(8), 621–639.
Gleeson, M., Bishop, N. C., Stensel, D. J., Lindley, M. R., Mastana, S. S., & Nimmo, M. A. (2011). The anti-inflammatory effects of exercise: Mechanisms and implications for the prevention and treatment of disease. *Nature Reviews Immunology, 11*(9), 607–615.

Goss, C. F., & Miller, E. B. (2013). Dynamic metrics of heart rate variability. *arXiv preprint arXiv:1308.6018*.

Hamer, M. (2007). The relative influences of fitness and fatness on inflammatory factors. *Preventive Medicine, 44*(1), 3–11.

Hartig, T., Mitchell, R., De Vries, S., & Frumkin, H. (2014). Nature and health. *Annual Review of Public Health, 35*, 207–228.

Hinds, J., & Sparks, P. (2008). Engaging with the natural environment: The role of affective connection and identity. *Journal of Environmental Psychology, 28*(2), 109–120.

Huang, C.-J., Webb, H. E., Zourdos, M. C., & Acevedo, E. O. (2013). Cardiovascular reactivity, stress, and physical activity. *Frontiers in Physiology, 4*, 314.

Deuster, P. A., & Silverman, M. N. (2013). Physical fitness: a pathway to health and resilience. *U.S. Army Medical Department journal*, 24–35.

James, P., Hart, J. E., Banay, R. F., & Laden, F. (2016). Exposure to greenness and mortality in a nationwide prospective cohort study of women. *Environmental Health Perspectives, 124*(9), 1344–1352.

Jiang, B., Chang, C.-Y., & Sullivan, W. C. (2014). A dose of nature: Tree cover, stress reduction, and gender differences. *Landscape and Urban Planning, 132*, 26–36.

Jiang, B., Li, D., Larsen, L., & Sullivan, W. C. (2016). A dose-response curve describing the relationship between urban tree cover density and self-reported stress recovery. *Environment and Behavior, 48*(4), 607–629.

Kahn, P. H., Jr, Friedman, B., Gill, B., Hagman, J., Severson, R. L., Freier, N. G., … Stolyar, A. (2008). A plasma display window?—The shifting baseline problem in a technologically mediated natural world. *Journal of Environmental Psychology, 28*(2), 192–199.

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., … Engelmann, W. H. (2001). The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants. *Journal of Exposure Science & Environmental Epidemiology, 11*(3), 231–252. https://doi.org/10.1038/sj.jea.7500165

Knaepen, K., Goekint, M., Heyman, E. M., & Meeusen, R. (2010). Neuroplasticity—exercise-induced response of peripheral brain-derived neurotrophic factor. *Sports Medicine, 40*(9), 765–801.

Lederbogen, F., Kirsch, P., Haddad, L., Streit, F., Tost, H., Schuch, P., … Meyer-Lindenberg, A. (2011). City living and urban upbringing affect neural social stress processing in humans. *Nature, 474*, 498–501. https://doi.org/10.1038/nature10190

Li, G., & He, H. (2009). Hormesis, allostatic buffering capacity and physiological mechanism of physical activity: A new theoretic framework. *Medical Hypotheses, 72*(5), 527–532.

Lottrup, L., Grahn, P., & Stigsdotter, U. K. (2013). Workplace greenery and perceived level of stress: Benefits of access to a green outdoor environment at the workplace. *Landscape and Urban Planning, 110*, 5–11.

Maas, J., Verheij, R. A., de Vries, S., Spreeuwenberg, P., Schellevis, F. G., & Groenewegen, P. P. (2009). Morbidity is related to a green living environment. *Journal of Epidemiology & Community Health, 63*(12), 967–973.

Marteau, T. M., & Bekker, H. (1992). 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, 31*(3), 301–306.

McNair, D., Lorr, M., & Droppleman, L. (1989). Profile of mood states (POMS).

Meredith, L. S., Sherbourne, C. D., Gaillot, S. J., Hansell, L., Ritschard, H. V., Parker, A. M., & Wrenn, G. (2011). Promoting psychological resilience in the US military. *Rand Health Quarterly, 1*(2).

Mitchell, R., & Popham, F. (2008). Effect of exposure to natural environment on health inequalities: An observational population study. *The lancet, 372*(9650), 1655–1660.

Muhanna, M. A. (2015). Virtual reality and the CAVE: Taxonomy, interaction challenges and research directions. *Journal of King Saud University-Computer and Information Sciences, 27*(3), 344–361.

Nordh, H., & Østby, K. (2013). Pocket parks for people–A study of park design and use. *Urban Forestry & Urban Greening, 12*(1), 12–17.

Núñez, M., Suzman, L., Maneja, R., Bach, A., Marquet, O., Anguelovski, I., & Knobel, P. (2022). Gender and sex differences in urban greenness' mental health benefits: A systematic review. *Health & Place, 76*, Article 102864.

Peen, J., Schoevers, R. A., Beekman, A. T., & Dekker, J. (2010). The current status of urban-rural differences in psychiatric disorders. *Acta Psychiatrica Scandinavica, 121*(2), 84–93. https://doi.org/10.1111/j.1600-0447.2009.01438.x

Pereira, G., Foster, S., Martin, K., Christian, H., Boruff, B. J., Knuiman, M., & Giles-Corti, B. (2012). The association between neighborhood greenness and cardiovascular disease: An observational study. *BMC Public Health, 12*(1), 1–9.

Perna, L., Mielck, A., Lacruz, M. E., Emeny, R. T., Holle, R., Breitfelder, A., & Ladwig, K. H. (2012). Socioeconomic position, resilience, and health behaviour among elderly people. *International Journal of Public Health, 57*(2), 341–349.

Rodiek, S. (2002). Influence of an outdoor garden on mood and stress in older persons. *Journal of Therapeutic Horticulture, 13*(1), 13–21.

Rommel, D., Nandrino, J., Jeanne, M., & Logier, R. (2012). *Heart rate variability analysis as an index of emotion regulation processes: interest of the Analgesia Nociception Index (ANI)*. Paper presented at the 2012 Annual international conference of the IEEE engineering in medicine and biology society.

Shacham, S. (1983). A shortened version of the Profile of Mood States. *Journal of Personality Assessment*.

Sillman, D., Rigolon, A., Browning, M. H., & McAnirlin, O. (2022). Do sex and gender modify the association between green space and physical health? A systematic review. *Environmental Research, 209*, Article 112869.

Silverman, M. N., & Deuster, P. A. (2014). Biological mechanisms underlying the role of physical fitness in health and resilience. *Interface Focus, 4*(5), 20140040.

Skrove, M., Romundstad, P., & Indredavik, M. S. (2013). Resilience, lifestyle and symptoms of anxiety and depression in adolescence: The Young-HUNT study. *Social Psychiatry and Psychiatric Epidemiology, 48*(3), 407–416.

Spielberger, C. D. (1970). Manual for the state-trait anxietry, inventory. *Consulting Psychologist*.

Staats, H., Kieviet, A., & Hartig, T. (2003). Where to recover from attentional fatigue: An expectancy-value analysis of environmental preference. *Journal of Environmental Psychology, 23*(2), 147–157.

Stranahan, A. M., Lee, K., & Mattson, M. P. (2008). Central mechanisms of HPA axis regulation by voluntary exercise. *Neuromolecular medicine, 10*(2), 118–127.

Tabrizian, P., Baran, P. K., Smith, W. R., & Meentemeyer, R. K. (2018). Exploring perceived restoration potential of urban green enclosure through immersive virtual environments. *Journal of Environmental Psychology, 55*, 99–109.

Thompson, C. W., Roe, J., Aspinall, P., Mitchell, R., Clow, A., & Miller, D. (2012). More green space is linked to less stress in deprived communities: Evidence from salivary cortisol patterns. *Landscape and urban planning, 105*(3), 221–229.

Turan, M., & Beşirli, A. (2008). Impacts of urbanization process on mental health. *Anadolu Psikiyatri Dergisi, 9*, 238–243.

Turner, W. R., Nakamura, T., & Dinetti, M. (2004). Global urbanization and the separation of humans from nature. *Bioscience, 54*(6), 585–590.

Tyrväinen, L., Ojala, A., Korpela, K., Lanki, T., Tsunetsugu, Y., & Kagawa, T. (2014). The influence of urban green environments on stress relief measures: A field experiment. *Journal of Environmental Psychology, 38*, 1–9.

Ulrich, R. S. (1979). Visual landscapes and psychological well-being. *Landscape research, 4*(1), 17–23.

Ulrich, R. S. (1983). Aesthetic and affective response to natural environment. In *Behavior and the Natural Environment* (pp. 85–125). Springer.

Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology, 11*(3), 201–230. https://doi.org/10.1016/S0272-4944(05)80184-7

Valtchanov, D., Barton, K. R., & Ellard, C. (2010). Restorative effects of virtual nature settings. *Cyberpsychology, Behavior, and Social Networking, 13*(5), 503–512.

Van den Berg, A. E., Maas, J., Verheij, R. A., & Groenewegen, P. P. (2010). Green space as a buffer between stressful life events and health. *Social science & medicine, 70*(8), 1203–1210.

van Os, J., Kenis, G., & Rutten, B. P. F. (2010). The environment and schizophrenia. *Nature, 468*(7321), 203–212. https://doi.org/10.1038/nature09563

Wilson, E. O. (1986). *Cambridge*. MA and London, England: Harvard University Press.

Wohlwill, J. F. (1976). Environmental aesthetics: The environment as a source of affect. In *Human behavior and environment* (pp. 37–86). Springer.

Yin, J., Arfaei, N., MacNaughton, P., Catalano, P. J., Allen, J. G., & Spengler, J. D. (2019). Effects of biophilic interventions in office on stress reaction and cognitive function: A randomized crossover study in virtual reality. *Indoor Air, 29*(6), 1028–1039.

Yin, J., Yuan, J., Arfaei, N., Catalano, P. J., Allen, J. G., & Spengler, J. D. (2020). Effects of biophilic indoor environment on stress and anxiety recovery: A between-subjects experiment in virtual reality. *Environment International, 136*, Article 105427.

Yin, J., Zhu, S., MacNaughton, P., Allen, J. G., & Spengler, J. D. (2018). Physiological and cognitive performance of exposure to biophilic indoor environment. *Building and Environment, 132*, 255–262.