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Research Paper

Vertical greenery buffers against stress: Evidence from psychophysiological responses in virtual reality

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HIGHLIGHTS

- We used VR to examine the buffering effects of vertical greenery against stressors.
- Self-report measures show vertical greenery prevented reduction in positive affect.
- Heart rate variability suggests vertical greenery prevented increase in stress.
- Our results indicate that vertical greenery can be used to buffer stress.

1. Introduction

Rapid urbanization has been associated with decreased nature exposure (Cox, Hudson, Shanahan, Fuller, & Gaston, 2017; Turner, Nakamura, & Dinetti, 2004) and increased environmental stressors like traffic noise and pollution (Verheij, Maas, & Groenewegen, 2008). Given that nature can combat stress and promote wellbeing (Bertram & Rehdanz, 2015; Hartig, Mitchell, de Vries, & Frumkin, 2014), there has been tremendous interests and collective efforts across the globe to increase urban greenspace such as trees, parks, and community gardens over the past few decades. It has been reported that from 1989 to 2009, 286 cities in China increased their average green space from 17% to 37% (Zhao et al., 2013), while 202 cities in Europe had an average annual increase of 0.54% in green space between 2000 and 2006 (Kabisch & Haase, 2013).

Vertical greenery refers to the integration of vegetation onto the vertical structures of buildings, which differs from green roofs that utilize the flat horizontal space atop buildings (Pérez, Coma, Martorell, & Cabeza, 2014). In the past, vertical greenery mainly consisted of self-climbing plants like vines that spread over buildings' facades. However, recent contemporary structural systems have been developed that enable a wide variety of plants to be grown on and incorporated within vertical surfaces (Pérez-Urrestarazu, Fernández-Cañero, Franco-Salas, & Egea, 2015). Vertical greenery offers the potential to increase greenspace above-ground, thereby overcoming land constraints common in high-density urban areas (Jim, 2004). Vertical greenery provides important ecosystem services including the lowering of ambient temperature which reduces energy consumption from cooling systems (Alexandri & Jones, 2008), sound absorption which decreases noise pollution (Wong, Kwang Tan, Tan, Chiang, & Wong, 2010), and absorption of harmful pollutants which mitigates air pollution (Pandey, Pandey, & Tripathi, 2015). It further contributes to human health and wellbeing by providing exposure to nature in urban landscapes (Gillis & Gatersleben, 2015). Existing research on nature's effects on emotion and stress has been dominated by natural environments such as parks and forests (Haluza, Schönbauer, & Cervinka, 2014; Hartig et al., 2014). Although there is growing research interest in urban forms of nature such as green roofs (e.g., Lee, Williams, Sargent, Williams, & Johnson, 2015), indoor plants and window views (e.g., Evensen, Raanaas, Hagerhall, Johansson, & Patil, 2013), no experimental study has been done to examine the psycho-physiological benefits of having a row of buildings covered in vertical greenery. We seek to fill this research gap by examining how concerted efforts to increase greenery among a cluster of buildings may benefit the psychological wellbeing of building occupants and passers-by.

Therefore, in this study we examined how vertical greenery on the exterior of buildings can affect emotion and buffer against stress. Our study extends current literature on nature exposure by investigating urban nature that spans across a row of buildings, and focuses on the understudied buffering effect of nature. We used virtual reality (VR) to conduct immersive and well-controlled experiments, avoiding confounding variables in field studies and teasing out the unique effect of nature. Past research has shown that the color green may produce anxiety-reducing effects (Kaya & Helena, 2004). We thus used green

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color walls instead of simply no vertical greenery in the control condition to show that nature can produce positive psychological effects beyond the effects of the color green. Our study aims to generate evidence suggesting that growing plants on a wall can result in better stress-buffering effects than simply painting a wall green.

1.1. *Effects of nature on emotion and stress*

Nature has been found to have beneficial effects on cognition (for a review, see Ohly et al., 2016), stress (for a review, see Mygind et al., 2019) and emotion (for a review, see McMahan & Estes, 2015). The stress reduction theory (Ulrich et al., 1991; Ulrich, 1983) argues that as a result of our evolutionary past, humans are predisposed to respond positively to cues (e.g., vegetation) that signal better chance of survival for our ancestors. A large body of literature shows that nature exposure is associated with improved emotion and lower stress in correlational (e.g., Bertram & Rehdanz, 2015; White, Alcock, Wheeler, & Depledge, 2013) and experimental studies (e.g., Berman, Jonides, & Kaplan, 2008; Hartig, Mang, & Evans, 1991). A meta-analysis of 32 studies reported a moderate effect size between nature exposure and increased positive affect ($r = 0.31$) and a corresponding smaller effect size between nature exposure and decreased negative affect ($r = -0.12$) (McMahan & Estes, 2015). The beneficial effects of nature on stress levels have been consistently found across a diverse range of measures. For example, participants reported lower anxiety on the state version of the State-Trait Anxiety Inventory after walking in a natural environment compared to an urban one (Bratman, Daily, Levy, & Gross, 2015). Lower stress levels following a nature exposure, compared to a corresponding control condition, have also been reflected in measurements of physiological indicators like heart rate variability (Annerstedt et al., 2013), salivary cortisol level (Park, Tsunetsugu, Kasetani, Kagawa, & Miyazaki, 2010), and skin-conductance level (Valtchanov, Barton, & Ellard, 2010). These findings are further corroborated by brain imaging results from an fMRI study which showed that neural activity associated with behavioral stress-related response varied as a function of the amount of greenery in urban landscapes viewed by participants (Chang et al., 2021).

We differentiate between three main types of effects studied in previous research on how nature influences emotion and stress, namely restorative, instorative, and buffering effects. Table 1 summarizes the differences among these effects and highlights sample studies for each type. To examine nature's *restorative* effects, participants are first exposed to a stressor before experiencing nature. For example, after stress levels were raised by viewing a stressful video about work accidents, participants that watched a nature video demonstrated quicker and fuller stress recovery compared to those that watched an urban video (Ulrich et al., 1991). In another study, participants completed a directed-forgetting task to deplete cognitive resources, before taking a walk in a park or downtown area, and were found to have better mood recovery after the park walk (study 1; Berman et al., 2008).

Table 1
Three main types of nature effects studied.

Type	Experimental paradigm	Effect	Sample studies
Restorative	Stressor or cognitive depletion task first, then nature exposure	Psychological states recover back to baseline	Annerstedt et al. (2013), Berman et al. (2008), Ulrich et al. (1991)
Instorative	No antecedent stressor or cognitive depletion, just nature exposure	Psychological states improve beyond baseline	Beute and de Kort (2014), Gidlow et al. (2016), Hartig et al. (1991)
Buffering	Experience nature simultaneously with a stressor or cognitive depletion task	Psychological states remain at baseline, or worsen but to a smaller extent compared to a control condition	Kweon et al. (2007)

Studies on *instorative* effects measure the effects of nature without using a prior stressor. For example, viewing a slideshow of nature scenes, compared to urban scenes, was found to improve mood without participants undergoing a prior depletion task (study 2; Beute & de Kort, 2014). Similarly, a walk through a country park without a stressor improved mood from baseline and reduced stress levels reflected by salivary cortisol changes (Gidlow et al., 2016).

In contrast to restorative and instorative effects, *buffering* effects refer to nature extenuating adverse consequences during the experience of a stressor. Very few experimental studies have directly tested how nature can buffer adverse consequences of a stressor experienced simultaneously. One such study was done by Kweon, Ulrich, Walker, and Tassinary (2007) who investigated the effects of nature landscape posters in an office setting and found that males reported less anger and stress in the office with (vs. without) nature posters after completing computer tasks that were meant to provoke anger and stress. To the best of our knowledge, no experimental study has been conducted to examine the buffering effects of vertical greenery while being exposed to a stressor.

Many existing studies have taken comparative approaches contrasting natural environments (e.g., nature reserves, parks) with predominantly urban environments (e.g., downtown, residential street), leaving behind a paucity of research examining nature that is integrated into built environments. A handful of studies have showcased the benefits of indoor plants (Bringslimark, Hartig, & Patil, 2009; Evensen et al., 2013), window views of nature (Kahn et al., 2008; Leather, Pyrgas, Beale, & Lawrence, 1998), roadside trees (Cackowski & Nasar, 2003; Lindal & Hartig, 2015), green rooftops (Lee et al., 2015), a green façade on a single building (Elsadek, Liu, & Lian, 2019), and a courtyard with vegetation (Huang, Yang, Jane, Li, & Bauer, 2020). Our study extends these findings by examining vertical greenery on the exteriors of a row of city buildings, which is a much larger area of the city.

A final issue that deserves attention concerns the color green as a confounding variable. Green is associated with the qualities of calmness and peacefulness (Clarke & Costall, 2008). Exposure to the color green evokes lower anxiety and higher relaxation and comfort (Kaya & Helena, 2004). Akers et al. (2012) showed that participants had lower ratings of total mood disturbance and perceived exertion while watching a video of cycling in a rural natural environment that featured much greenery during a cycling exercise, compared to viewing the video with an achromatic or red filter. Most studies on the effects of nature examined green vegetation and it could be possible that simply the color green as a primitive visual feature resulted in the effect. Therefore, to overcome this problem, our study used a control condition which matched vertical greenery with green color, to control for the effect of color.

1.2. *VR as a tool to study nature effects*

VR offers several important methodological advantages for conducting psychological studies (Blascovich et al., 2002; Hardiess, Mallot, & Meilinger, 2015; Roberts et al., 2019). Firstly, it enables researchers to have precise control over the design and development of environmental settings – addressing limitations of field studies that cannot control for many potential confounding variables (e.g., temperature, crowd, traffic). Second, immersive VR provides a compelling sense of presence which is defined as the subjective experience of feeling like one is actually in the virtual environment (Witmer & Singer, 1998). This provides greater ecological validity over traditional lab studies that use images or videos of real natural landscapes to simulate nature exposure. Thirdly, VR can be used to create experimental settings where comparable real-life environments are not available (e.g., identical residential area with vs. without roadside trees). Fourth, codes for the construction of VR environments can be easily shared among researchers so long as compatible VR systems and devices are used (e.g., VR with head-mounted displays), increasing the possibility of precise replication which is a major challenge in today's psychological research (Open Science Collaboration, 2015).

VR has been implemented using a flat screen display (e.g., de Kort, Meijnders, Sponselee, & Ijsselsteijn, 2006), a projection-based cube room commonly referred to as a computer automatic virtual environment (CAVE) (e.g., Annerstedt et al., 2013), or a head-mounted display (HMD) (e.g., Valtchanov et al., 2010). A key improvement from flat screen displays to the other two visualization systems is the provision of an immersive experience such that the user is completely surrounded by the virtual environment. This provides an experience more similar to real-life. Supporting this, research has shown that VR with HMD induces greater immersion and spatial presence compared to flat screen displays (Seibert & Shafer, 2018; Shu, Huang, Chang, & Chen, 2019). Compared to CAVE, HMD is a much more cost-effective system which offers the added advantage of being portable. Comparing VR in CAVE and HMD, Juan and Pérez (2009) found that standing over a deep hole on the ground in CAVE induced greater presence and anxiety, compared to the same experience in HMD. However, the study used an older version of HMD that provided a field-of-view of only 40° (vs. the HTC VIVE Pro's 110° which we use in this study). More recent studies that utilize the latest HMD technology have shown that HMD is comparable and can even outperform a CAVE system. Cordeil et al. (2017) compared performance on a collaborative task in CAVE and HMD, and showed that while both systems produced similarly high task accuracy, participants were significantly faster in HMD compared to CAVE. Elor et al. (2020) compared an exercise game in CAVE and HMD and found that participants performed better and reported greater immersion and engagement in HMD than CAVE. Recent VR studies that employ the latest HMD technology have been shown to elicit similar psycho-physiological effects to those in real-life (Roberts et al., 2019; Wiederhold & Rizzo, 2005). For example, in a study examining the physiological effects of presence in a stressful VR, participants showed significant heart rate changes when they stood over a virtual pit that fell 20 feet below them, which correlated well with a self-report measure of presence (Meehan, Insko, Whitton, & Brooks, 2002). In another study, participants' heart rate and heart rate variability predicted their self-reported measures of stress in a job interview simulation in VR (Villani et al., 2017). Similarly, participants displayed stress-related physiological responses (e.g., increased heart rate, electrodermal activity) and self-reported distress when giving a speech to a virtual audience in VR (Owens & Beidel, 2015). At the same time, it is also important to acknowledge the limitations of VR in HMD. Compared to flat screen displays and CAVE, VR with HMD has been associated with increased motion sickness (Kim, Rosenthal, Zielinski, & Brady, 2012; Weidner, Hoesch, Poeschl, & Broll, 2017). To address this, we utilized a simple tracking program to synchronize participants' visual senses with their body movements – a key feature shown to reduce motion sickness (Llorach, Evans, & Blat, 2014; Ng, Chan, & Lau, 2019). Another limitation is that effects found in VR may be smaller compared to those in real-life (Owens & Beidel, 2015).

A few studies have used HMD VR to examine the effects of nature exposure. In the studies conducted by Valtchanov and Ellard (2010) and Valtchanov et al. (2010), participants first completed an arithmetic stressor before being immersed in a virtual nature environment (forest; island) or corresponding control environment (urban; geometric shapes). Results showed improved mood and reduced stress level following the nature immersion compared to the control immersion. Another study also employed the use of a mental stressor before participants were immersed in VR, and showed that participants reported greater vigor and less negative emotions after experiencing a 360° video-recordings of forests in VR, while they reported greater fatigue and lower self-esteem when they experienced a 360° video-recording of bustling urban environments (Yu, Lee, & Luo, 2018). Huang et al. (2020) exposed participants to an arithmetic stressor before randomly assigning them to a virtual courtyard that differed in the presence of vegetation. They showed that viewing a VR courtyard with vegetation resulted in improved positive affect and lower physiological stress, compared to a courtyard without vegetation. Similarly, Yin et al. (2020) examined the restorative effects of biophilic design following a couple of stress tasks, and showed that virtual offices with natural elements (e.g., potted plants, fish tank, window view of nature) reduced anxiety levels and physiological stress more in comparison to a virtual office without any natural elements.

Our study differs from the previous VR studies in several important ways. First, all existing VR studies examined nature's restorative effects by exposing their participants to a stressor before the nature immersion, while our study focused on nature's buffering effects during a stressor. Second, existing VR studies have focused on forests (Valtchanov et al., 2010; Yu et al., 2018), islands (Valtchanov & Ellard, 2010), courtyards (Huang et al., 2020), and indoor offices (Yin et al., 2020), while our study examined vertical greenery on the exterior of buildings in a downtown area. Third, all studies had participants remain seated throughout the VR immersion, with most involving passive viewing. In contrast, our study allowed participants to physically walk and experience walking through the street, making the VR experience more comparable to the real-life.

1.3. Present study

To investigate the stress buffering effect of vertical greenery, we conducted a between-subject experiment to compare participants' changes in positive affect, negative affect, anxiety, and stress level, while they were stressed by heavy traffic noise and walked along a virtual street with building walls covered by green plants (plant condition) vs. green color (color condition). We collected participants' self-report data before and after the VR experience and recorded their cardiovascular responses continuously with a portable electrocardiogram (ECG) device.

We hypothesized that vertical greenery buffers the adverse effects of a stressor such that participants in the plant condition will have a smaller decrease in positive affect, smaller increase in negative affect, smaller increase in anxiety, and smaller increase in stress, compared to the color condition.

2. Methodology

2.1. Participants

A power analysis was performed using G*Power 3.1. (Faul, Erdfelder, Buchner, & Lang, 2009) with alpha = 0.05, power = 0.95, and an effect size of $\eta_p^2 = 0.113$ that was based on research by Valtchanov and Ellard (2010) which showed effects of VR nature on self-reported stress. Results indicated a sample size of 106. We recruited 119 undergraduate students from a large university who participated in exchange for course credits. Eight participants had to be excluded due to data collection failures in VR or surveys. This resulted in a final sample of 111 participants (females = 71; age: M = 21.63, SD = 1.81). Experiments were completed on an individual basis and participants were randomly assigned to either the plant condition (n = 56) or the color condition (n = 55).

2.2. Virtual environment

A virtual cityscape was developed using the Unity platform (http://www.unity.com). It featured a straight path in-between two rows of buildings in a downtown area. In the plant condition, vertical greenery covered the balconies, walls, and pillars of buildings (see Fig. 1). In the color condition, the plants were replaced with corresponding shades of green (see Fig. 2). The scene was accompanied by continuous heavy traffic noise which was used to induce stress. Demo

Fig. 1. A sample of participants' view in the plant condition.

Fig. 2. A sample of participants' view in the color condition.

videos of the VR scenes are available online (plant condition: https://www.youtube.com/watch?v=YqQfIslpAM8; color condition: https://www.youtube.com/watch?v=y68tu7JOYgE). We chose not to include pedestrians in the environment because realistic human avatars are difficult to build with the current technology, and we did not want participants to interact with avatars while they are walking. We created a cover story and told participants that they would be walking along an empty street in the city that is next to a busy main road. This cover story also explains why participants would hear traffic noise but do not see cars. Participants wore the HTC VIVE Pro headset with full auditory and visual immersion. We developed a program to track the movement of the two wireless controllers which were attached to participants' knees, and enabled participants to move in the virtual environment when they walked on the spot while holding onto fixed handlebars (see Fig. 3). This setup was created to provide a natural way of navigating in the virtual space, and facilitate synchronization of a user's visual senses and body movement which has been shown to reduce motion sickness induced by VR (Llorach et al., 2014; Ng et al., 2019). We chose this method over a VR treadmill as it is much more cost-effective compared to the latter. Moreover, VR treadmills that are currently available on the market involve slight resistance when walking, which makes it feel less natural.

2.3. *Stressor*

Participants heard heavy traffic noise when they walked in VR. Traffic noise has been used in past research to induce stress (e.g., Valtchanov & Ellard, 2010; Yin et al., 2020) and naturally matched our setting. We used the Audacity software (https://www.audacityteam.org/) to create a 1-minute traffic noise audio clip which contains a neutral white noise background with 10 incidents of noise – 6 vehicles speeding by and 4 honks, with an average of 5–7 s in-between. These sound effects were freely available on the Internet (https://www.soundbible.com/). The 1-minute audio clip was looped throughout the 5-minute VR task.

Fig. 3. A researcher wearing the VR headset and wireless controllers on his knees for movement tracking.

2.4. *Measures*

To assess emotion, we used the Positive and Negative Affect Schedule (PANAS; Watson, Clark, & Tellegen, 1988). There are 10 items that measure positive affect (e.g., interested, excited) and another 10 items that measure negative affect (e.g., upset, hostile). Participants indicated the extent they felt each emotion on a 5-point Likert scale (1 = very slightly or not at all, 5 = extremely). The scale showed good reliability with Cronbach's α = 0.89 for positive affect at both pre-test and post-test, and Cronbach's α = 0.81 at pre-test and Cronbach's α = 0.92 at post-test for negative affect.

To assess anxiety, we used the short state version of the State-Trait Anxiety Inventory (Marteau & Bekker, 1992; Spielberger, 1983). There are 6 items (e.g., "I am relaxed"), and participants indicated the extent that each statement described their present feelings on a 4-point Likert scale (1 = not at all, 4 = very much so). The scale showed good reliability with Cronbach's α = 0.79 at pre-test and Cronbach's α = 0.87 at post-test.

To assess physiological stress, cardiovascular activity was continuously measured using a portable ECG device from BITalino (https://bitalino.com/en/) with three disposable electrodes attached under participants' left and right collarbones, and lower left ribcage at a sampling rate of 1000 Hz. ECG measurements have been shown to be a valid reflection of participants' physiological states in virtual environments (Guger, Edlinger, Leeb, Pfurtscheller, & Antley, 2004). From the ECG recordings, customized algorithms generated with *Python* code were used to extract heart rate variability (HRV) (Bizzego, Battisti, Gabrieli, Esposito, & Furlanello, 2019; Gabrieli, Azhari, & Esposito, 2020). This was done by first pre-processing the ECG data with the application of a high-pass filter and a low-pass filter to clear noise in the signal. Next, R peaks were detected and used to determine the inter-beat interval (IBI) which is the time between 2 successive R peaks (Task Force of the European Society of Cardiology, & North American Society of Pacing and Electrophysiology, 1996). From IBI, two time-domain HRV measures were computed – the standard deviation of R-R intervals (SDRR) and root mean square of successive differences (RMSSD). Higher HRV is associated with better functioning of our automatic nervous system (ANS) which increases a person's ability to cope with stressors (Kim, Cheon, Bai, Lee, & Koo, 2018). The ANS responds to stressors through its sympathetic and parasympathetic branches (Ulrich-Lai & Herman, 2009). The sympathetic branch ("fight-or-flight") mainly controls activation and mobilization, whereas the parasympathetic branch ("rest-and-digest") mainly controls restoration and relaxation (Andreassi, 2010). SDRR was chosen to reflect overall ANS contributed by both parasympathetic and sympathetic activity (Brennan, Palaniswami, & Kamen, 2001) while RMSSD was chosen to reflect parasympathetic activity more specifically (Shaffer & Ginsberg, 2017; Task Force of the European Society of Cardiology, & North American Society of Pacing and Electrophysiology, 1996). For both SDRR and RMSSD, a higher value corresponds to lower stress (Delaney & Brodie, 2000). Following standard practice in cardiology studies (Task Force of the European Society of Cardiology, & North American Society of Pacing and Electrophysiology, 1996), a 5-minute duration was used to compute the indices for baseline and VR respectively.

At the end of the study, participants completed a measure of noise sensitivity (Weinstein, 1978; Worthington, 2017) which was rated on a scale of 1 (strongly agree) to 6 (strongly disagree). It included 21 items (e.g., "I get used to most noises without much difficulty", $\alpha = 0.85$). They also indicated if they had tried VR with a head-mounted display before the study (0 = no, 1 = yes), and their age and gender. An additional item was included in the post-test survey asking participants to rate their level of discomfort on a 5-point Likert scale (1 = very slightly or not at all, 5 = extremely).

2.5. *Procedure*

Upon the participant's arrival at the lab, a researcher explained the experimental procedure and provided clear instructions to the participant on the correct way of attaching the ECG electrodes. Participants were reminded that they could inform the researcher at any point in time to end the experiment without repercussions should they feel uncomfortable. A fitting room in the lab was provided to ensure privacy and comfort. Once an ECG signal was detected, the participant was directed to complete the pre-test survey on the computer.

Next, a researcher of the same gender helped the participant put on knee pads for tracking movement in VR, and demonstrated the action required (walking on the spot while holding onto handlebars). The participant was then instructed to walk on the spot for 5 min to obtain a baseline measure of heart rate. After this, the same researcher helped the participant put on the VR headset. The participants were told that they would be walking along an empty street in the city that is next to a busy main road, which created a cover story for why there was heavy traffic noise and no pedestrians or cars around. After 5 min walking, the VR scene was terminated. The number of steps that participants made during the VR walk was recorded.

Then, participants returned to the computer and completed the post-test survey. Finally, participants were debriefed and probed, and none of the participants correctly guessed the study aims. The same two researchers (one female and one male) were present for all experiments. They followed a standard script that was read out to participants (see Supplemental Materials). The study protocol was approved by the University ethics committee (IRB-2018-05-053-01), and informed consent was obtained from all participants.

2.6. *Data analysis*

Independent samples t tests were ran to examine differences between noise sensitivity, number of steps taken in VR, and ratings of post-VR discomfort. Chi-square tests were ran on gender distribution, and whether participants had tried VR before to test if there were differences between conditions. We expected that there would be no differences for all the aforementioned variables.

To test our primary hypotheses, a mixed factorial ANOVA with time (pre vs. post) as a within-subject factor and condition (plant vs. color) as a between-subject factor was conducted for each self-report measure. Planned paired t tests were then run to determine the simple effects of time in each condition. For cardiovascular activity, SDRR and RMSSD were extracted for every 10 s, with 5 s overlapping with the preceding data point. We computed the mean over the 5-minute baseline walk, and the mean over the 5-minute walk in VR. A mixed factorial ANOVA with period (baseline vs. VR) as a within-subject factor and condition (plant vs. color) as a between-subject factor was conducted for SDRR and RMSSD separately, with follow-up planned paired t tests to determine changes from baseline in each condition.

3. Results

3.1. *Preliminary analyses*

There were no significant differences between conditions for noise sensitivity (plant: M = 4.31, SD = 0.74; color: M = 4.14, SD = 0.62; $t(109) = -1.31$, $p = .19$, $d = -0.25$), and number of steps taken in the VR environment (plant: M = 461.50, SD = 96.37; color: M = 477.80, SD = 80.23; $t(109) = 0.97$, $p = .34$, $d = 0.18$). None of the participants reported feeling unwell after the VR tasks, and the ratings of post-VR discomfort was low (plant: M = 1.95, SD = 1.05; color: M = 1.98, SD = 1.15; $t(109) = 0.17$, $p = .87$, $d = -0.03$). There were also no differences between conditions in distribution of gender (plant: 60.7% female; color: 67.3% female; $\chi^2(1) = 0.52$, $p = .47$) and whether participants had tried VR before (plant: 32.1% tried; color: 43.6% tried; $\chi^2(1) = 1.56$, $p = .22$). Thus, none of these variables were included for further analyses.

3.2. *Self-report*

For positive affect, there was no main effect of condition ($F(1, 109) = 0.01$, $p = .92$, $\eta_p^2 = 0.00$). The main effect of time was significant ($F(1, 109) = 9.28$, $p = .003$, $\eta_p^2 = 0.08$). The interaction effect between condition and time was not statistically significant ($F(1, 109) = 3.45$, $p = .07$, $\eta_p^2 = 0.03$). However, as seen in Table 2, while there was no

Table 2

Descriptive statistics for positive affect, negative affect and anxiety as a function of time and condition.

Condition	Variable	M (SD)		Simple effects
		Pre	Post	Mean difference [95% CI], p, Cohen's d
Plant (n = 56, 34 females)	Positive Affect	2.48 (0.72)	2.40 (0.78)	−0.08 [−0.25, 0.10], $p = .40$, $d = -0.11$
	Negative Affect	1.38 (0.38)	1.62 (0.75)	0.24 [0.08, 0.39], $p = .004$, $d = 0.41$
	Anxiety	1.84 (0.53)	2.35 (0.65)	0.51 [0.36, 0.66], $p < .001$, $d = 0.90$
Color (n = 55, 37 females)	Positive Affect	2.58 (0.70)	2.27 (0.76)	−0.31 [−0.49, −0.13], $p = .001$, $d = -0.46$
	Negative Affect	1.37 (0.40)	1.59 (0.69)	0.22 [0.03, 0.41], $p = .03$, $d = 0.31$
	Anxiety	1.83 (0.49)	2.45 (0.69)	0.62 [0.41, 0.82], $p < .001$, $d = 0.80$

Note. The simple effect of time is reported for each row.

significant change in positive affect in the plant condition (pre: M $=$ 2.48, SD $=$ 0.72; post: M $=$ 2.40, SD $=$ 0.78; $t(55) = -0.86$, $p = .40$, $d = -0.11$), positive affect significantly decreased in the color condition (pre: M $=$ 2.58, SD $=$ 0.70; post: M $=$ 2.27, SD $=$ 0.76; $t(54) = -3.41$, $p = .001$, $d = -0.46$).

For negative affect, there was no main effect of condition ($F(1, 109) = 0.04$, $p = .84$, $\eta_p^2 = 0.00$). A main effect of time emerged ($F(1, 109) = 13.67$, $p < .001$, $\eta_p^2 = 0.11$), while the condition-by-time interaction effect failed to reach significance ($F(1, 109) = 0.02$, $p = .90$, $\eta_p^2 = 0.00$). Negative affect significantly increased in both the plant condition (pre: M $=$ 1.38, SD $=$ 0.38; post: M $=$ 1.62, SD $=$ 0.75; $t(55) = 3.03$, $p = .004$, $d = 0.41$) and color condition (pre: M $=$ 1.37, SD $=$ 0.40; post: M $=$ 1.59, SD $=$ 0.69; $t(54) = 2.29$, $p = .03$, $d = 0.31$) (see Table 2).

For anxiety, there was no main effect of condition ($F(1, 109) = 0.29$, $p = .59$, $\eta_p^2 = 0.003$). A main effect of time emerged ($F(1, 109) = 77.27$, $p < .001$, $\eta_p^2 = 0.42$), while the condition-by-time interaction effect failed to reach significance ($F(1, 109) = 0.69$, $p = .41$, $\eta_p^2 = 0.01$). Anxiety significantly increased in both the plant condition (pre: M $=$ 1.84, SD $=$ 0.53; post: M $=$ 2.35, SD $=$ 0.65; $t(55) = 6.73$, $p < .001$, $d = 0.90$) and color condition (pre: M $=$ 1.83, SD $=$ 0.49; post: M $=$ 2.45, SD $=$ 0.69; $t(54) = 5.94$, $p < .001$, $d = 0.80$) (see Table 2).

3.3. Cardiovascular activity

Due to technical problems during data collection, nine participants' ECG data were not recorded, and eleven participants were excluded due to excessive noise in their ECG signals. Finally, data from 91 participants (plant condition n $=$ 45; color condition n $=$ 46) were included in analyses.

For SDRR, the main effect of condition was not significant ($F(1, 89) = 3.41$, $p = .07$, $\eta_p^2 = 0.04$). The main effect of period was significant ($F(1, 89) = 9.55$, $p = .003$, $\eta_p^2 = 0.10$) while the interaction effect between condition and period failed to reach statistical significance ($F(1, 89) = 3.25$, $p = .08$, $\eta_p^2 = 0.04$). However, while SDRR did not significantly change in the plant condition (baseline: M $=$ 0.026, SD $=$ 0.013; VR: M $=$ 0.025, SD $=$ 0.013; $t(44) = -1.51$, $p = .14$, $d = -0.23$), SDRR significantly decreased in the color condition (baseline: M $=$ 0.022, SD $=$ 0.014; VR: M $=$ 0.019, SD $=$ 0.010; $t(45) = -2.73$, $p = .01$, $d = -0.40$) (see Table 3). This suggests that there were no changes in the balance between parasympathetic and sympathetic activity – corresponding to no changes in stress – in the plant condition, whereas there was an increase in sympathetic dominance – corresponding to increase in stress – in the color condition.

For RMSSD, the main effect of condition ($F(1, 89) = 1.95$, $p = .17$, $\eta_p^2 = 0.02$), main effect of period ($F(1, 89) = 0.51$, $p = .48$, $\eta_p^2 = 0.01$) and interaction effect of condition and period ($F(1, 89) = 2.39$, $p = .13$, $\eta_p^2 = 0.03$) all failed to reach statistical significance. Although it did not reach conventional statistical significance, RMSSD increased slightly in the plant condition (baseline: M $=$ 0.024, SD $=$ 0.019; VR: M $=$ 0.025, SD $=$ 0.022; $t(44) = 1.22$, $p = .23$, $d = 0.18$), whereas RMSSD decreased slightly in the color condition (baseline: M $=$ 0.021, SD $=$ 0.017; VR: M $=$ 0.018, SD $=$ 0.013; $t(45) = -1.22$, $p = .23$, $d = -0.18$) (see Table 3). This suggests that parasympathetic activity increased slightly during the walk in the plant condition whereas it decreased slightly during the walk in the color control.

Table 3
Descriptive statistics for heart rate variability as a function of time and condition.

Condition	Variable	M (SD)		Simple effects
		Baseline	VR	Mean difference [95% CI], p, Cohen's d
Plant (n = 45, 28 females)	SDRR	0.026 (0.013)	0.025 (0.013)	−0.001 [−0.002, 0.000], $p = .14$, $d = -0.23$
	RMSSD	0.024 (0.019)	0.025 (0.022)	0.001 [−0.001, 0.002], $p = .23$, $d = 0.18$
Color (n = 46, 30 females)	SDRR	0.022 (0.014)	0.019 (0.010)	−0.003 [−0.006, −0.001], $p = .01$, $d = -0.40$
	RMSSD	0.021 (0.017)	0.018 (0.013)	−0.002 [−0.006, 0.002], $p = .23$, $d = -0.18$

Note. The simple effect of period is reported for each row.

4. Discussion

An ample amount of research has shown the restorative effects of various types of nature including roadside vegetation and indoor plants. In this research, we examined the buffering effects of vertical greenery, an increasingly popular form of urban nature in high-density cities, by using VR to simulate the experience of walking through a noisy downtown area where buildings' exteriors were covered with vertical greenery. Our results suggest that vertical greenery on city buildings can buffer against the negative psychophysiological consequences of stress. Walking through the street with vertical greenery did not result in any changes to positive affect, whereas walking through the same area with green color replacing vertical greenery led to a significant reduction in positive affect. In addition, participants in the plant condition did not exhibit any change in stress measured by SDRR, but those in the color condition exhibited a significant increase in stress indicated by a decrease in SDRR. While it did not reach statistical significance, this trend was also shown by RMSSD such that only the color condition showed lower RMSSD compared to baseline, corresponding to increased stress during the walk. This study contributes to the scant literature on nature's buffering effects. In addition, the use of VR enabled us to control for the effects of color, teasing out the unique effects of nature.

Our findings corroborate with previous research suggesting that nature can extenuate stress (Brown, Barton, & Gladwell, 2013; Kweon et al., 2007). However, our results differ from previous studies in two ways. First, in self-report measures, our results showed that the buffering effects of vertical greenery prevented a decrease in positive affect, but did not have extenuating effects on increases in negative affect and anxiety. This differs from the study by Kweon et al. (2007) where nature posters in an office led to lower anger and stress compared to no posters. In their study, positive affect was not measured. Moreover, stress was measured only after completing the anger-provoking tasks and was not compared with a baseline measure. Thus, it is difficult to directly compare our contrasting results. Nonetheless, it is possible that changes in positive affect, negative affect, and stress are sensitive to the type of stressor and type of nature exposure. Given the lack of research on nature's buffering effects, more studies are required to further understand the differential buffering effects that nature may exert on positively toned and negatively toned emotion. Second, in physiological measures, our study found that the plant condition prevented a decrease in SDRR and also prevented a decrease, albeit not statistically significant, in RMSSD. This differs from that of Brown et al. (2013) where SDRR increased similarly during the recovery period for both nature and urban views, whereas RMSSD increased only for nature views during the recovery period. It is important to note that nature was experienced before the stressor in that study, and these changes were observed during the recovery period that followed the stressor. In contrast, our study observed physiological changes while participants were exposed to nature and the stressor at the same time. Therefore, the findings of our study and theirs are not incompatible, and suggest that the effects of nature on physiological responses depend on the timing of nature and the stressor. It is possible that nature buffers stress by maintaining both parasympathetic and sympathetic activity (reflected by SDRR) during the stressor, while enhancing parasympathetic activity (reflected by RMSSD) after the stressor. This is supported by the fact that the sympathetic branch controls activation (Andreassi, 2010) which presumably occurs more during a stressor, while the parasympathetic branch controls relaxation (Andreassi, 2010) which presumably occurs more after a stressor is removed.

Traffic noise was used as an acute stressor in our study. Past cross-sectional studies have suggested that nearby nature can reduce the negative impacts of noise pollution on well-being in urban areas (Dzhambov, Markevych, Tilov, & Dimitrova, 2018; Gidlöf-Gunnarsson & Öhrström, 2007). However, various mechanisms may be at play, including sound absorption by vegetation (Van Renterghem et al., 2015; Wong et al., 2010) and availability of recreational space (Dzhambov et al., 2018). Our study extends past research by providing experimental evidence showing beneficial psychophysiological effects of vertical greenery on noise pollution. While our study induced stress using traffic noise, stressors may also arise from social processes (e.g., divorce, work and family demands) (Serido, Almeida, & Wethington, 2004) and other environmental factors such as air pollution (Lu, Lee, Gino, & Galinsky, 2018). Future research may examine if the buffering effects found in our study hold under other types of stressors.

The present study demonstrates how VR can be used to address methodological barriers in environmental research. While in real-life field studies it is difficult to create a control condition that matches the experimental condition in all aspects except the element of nature, VR allows researchers to manipulate nature in two identical scenes controlling for common confounding variables such as sound, traffic, and weather. Our study further replaced greenery with green color to control for the visual sensation of color, teasing out nature's unique effect beyond the color green.

Our findings have important practical implications for city planning and design, especially for high-density urban areas. It suggests that vertical greenery systems, and possibly even artificial plants, may provide buffering effects to minimize the detrimental consequences of stress. While our study focused on outdoor environments, it is possible that vertical greenery can be applied to indoor environments such as metro stations or shopping malls where spaces are limited. However, more research is needed to assess the effectiveness of such an idea. In addition, VR can be used to simulate design plans and landscape construction, and assess their potential psychological outcomes.

4.1. Limitations

There are a couple of limitations in this study. First, a glaring question is whether the effects found in VR will be replicated in real-world settings. Past research has shown that experiencing nature in VR produced comparable physiological responses to those in real life (Yin, Zhu, MacNaughton, Allen, & Spengler, 2018). Conducting a real-world study involving vertical greenery on a row of buildings' exteriors is also an arduous task that requires coordinated effort among a cluster of buildings. Therefore, we conducted our study in VR. Although we tried to model our VR scenes as realistic as possible, our scenes are still not completely the same as real-life scenes. For example, there is no shading, shadowing, and humans in our scenes. Nonetheless, the advantage of using VR is that it provides researchers with full control of the experimental setting, such that the control and experimental conditions can be set up exactly the same except for the aspect that is expected to cause the effect. This is key to establishing a causal relationship between vertical greenery and psycho-physiological change. To address the limitation due to the loss of realism in VR, future research should extend our study to examine the effects of vertical greenery in real-life settings and provide naturalistic evidence of vertical greenery's effects. Second, our study did not examine psychophysiological recovery after the stressor because our primary research objective was to investigate nature's buffering effect during a stressor. Future research may consider how nature's buffering effect influences downstream recovery. Third, our VR immersion was only five minutes long and therefore not able to determine if habituation may occur after a while. Future research should further examine how long the stress-buffering effect may last. Fourth, we only examined one design of vertical greenery which may not represent various types of vertical greenery in urban settings. Future research needs to examine vertical greenery in indoor settings or with different types of plants to provide a complete understanding of the effects of vertical greenery. Furthermore, our study only compared the presence and absence of vertical greenery. It did not measure how the parameters of the greenery (e.g., size, placement, and color) would influence its effects. Future study can vary the parameters and observe corresponding changes in psychological outcomes. Finally, our participants are undergraduate students and the majority of them are females. Despite the limitations of college students' generalizability to the wider population (Arnett, 2016; Henrich, Heine, & Norenzayan, 2010), student samples nonetheless serve as an important benchmark against other populations of interest (Gächter, 2010; Herrmann, Thöni, & Gächter, 2008; Rad, Martingano, & Ginges, 2018). It is important to examine the effects found in this research with a more diverse sample.

5. Conclusion

Urban living is characterized by increased environmental stressors like noise pollution, and reduced opportunities to visit natural environments. This research has shown that vertical greenery on city buildings can exert buffering effects against negative psychophysiological responses to stress, and reveals how nature can be integrated within urban contexts to improve resilience against stressors. Our findings contribute important insights for urban planning and design, and underscore the utility of VR in environmental research.

6. Data Accessibility Statement

The data analysed in this study has been uploaded as research data.

CRediT authorship contribution statement

Sarah Hian May Chan: Conceptualization, Methodology, Investigation. **Lin Qiu:** Conceptualization, Methodology, Investigation, Funding acquisition. **Gianluca Esposito:** Methodology, Investigation. **Ky Phong Mai:** Software.

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.

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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.2021.104127.

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