The Restorative Effects of Biophilic Design in Identical Physical and Virtual Environments

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1. ABSTRACT

Does architecture affect us similarly in virtual reality (VR) and physical spaces? Architects and researchers alike would benefit from the ability to systematically test how different designs feel in VR without needing to physicalize them. However, it has not been established that architectural design manipulations which affect people in real life will have the same effect when experienced in VR. This study investigates whether the presence of plants affects subjects' recovery from psychosocial stress the same way in identical virtual and physical environments. We used a mixed 2 × 2 factorial (split-plot) design with 20 total participants: environment modality (physical vs. VR) was manipulated between participants, while biophilic presence (plants vs. no plants) was manipulated within participants for each modality group. Heart rate (HR), heart rate variability (HRV), respiration rate, and electrodermal activity (EDA) were recorded to measure physiological recovery. A Sustained Attention to Response Task (SART) was used to measure attentional recovery. Finally, the Perceived Restorativeness Scale (PRS-11) was administered to assess subjective ratings of environmental restorativeness. While we were not able to identify significant differences between plant and no plant conditions or physical and virtual conditions, this study provides valuable methodological insights to contribute to the growing literature on Cognitive and Neuroscience for Architecture (CNfA).

2. INTRODUCTION

Recent developments in VR technology now allow us to have experiences entirely virtually, occasionally replacing the physical, embodied alternative. Many researchers conduct experiments entirely in VR due to the ability to quickly and inexpensively simulate various experimental conditions while providing enhanced control over potentially confounding variables (e.g., Yin et al., 2019; Mostajeran et al., 2023; Hmaiti et al., 2024; Kisker et al., 2021). Architects may also utilize VR to anticipate how it will feel to be in a building before it has been built, or try out variations of an architectural design. However, it has not been determined whether experimental results generated in a VR space can be generalized to behavior in a corresponding physical space. What are the behavioral and psychological implications of experiencing an architectural space through VR? To what extent will human experience, performance, and behavior in a physical space align with their counterparts in a VR replica of that same space? If architectural manipulations have the same effect on relevant aspects of human behavior and experience in virtual environments as in corresponding physical environments, then VR can be leveraged as a valid and useful tool to study how the principles of cognitive and neuroscience can be used to inform architectural design decisions.

In this study, we chose to focus on biophilic design for several reasons. First, there are limited architectural features which we have the ability to easily and quickly manipulate in both the physical environment and in VR. Beyond biophilic design, these manipulable features included elements such as lighting conditions, furniture layout, color of surfaces, size of room, temperature, and sound. Of those identified, we concluded that biophilia would be of interest to architects and designers. Secondly, the physiological and psychological restorative effects of biophilic design have already been robustly studied. This allows us to compare the expected effects of the presence versus absence of biophilic design elements and the scale of those effects in physical and virtual environments with the assumption that there would be some meaningful differences to examine based on our design changes. However, future research could investigate whether other manipulable architectural factors, such as acoustics or furniture layout, have any influence on human experience and cognition, and whether that influence is consistent between physical and virtual environments.

Thus, we propose two main research questions:

RQ 1: Will subjects recover from psychosocial stress faster and more completely in a physical room with plants than one without plants?

RQ 2: If plants do help subjects recover from stress in physical environments, will the same effect be observed in near-identical virtual environments?

Our first hypothesis is that, in line with previous research, the presence of biophilic design elements will incite faster stress recovery time in both physical and virtual environments. Our second hypothesis is that, because our virtual environment is similar in those aspects which are most relevant to the task but not perfectly realistic, the presence of plants will improve stress recovery more in physical settings than virtual ones.

3. PRIOR WORK

3.1 Virtual Reality as a Research Tool

VR has the potential to support experimental designs with high levels of both control and ecological validity (Loomis et al., 1999). However, this is dependent upon the effectiveness of the virtual environment at inciting cognitive, behavioral, and experiential outcomes similar to what would be observed in a physical environment. In prior work, VR has been used to study the human experience of the environment.

Multiple previous studies created virtual copies of physical spaces and compared the two using general definitions of experience, behavior, or cognition. Oftentimes, subjects were not given any specific task while in the environments, and only subjective measures such as survey responses were used to compare experiences. Immersive and interactive methods of viewing a space such as VR may enhance perceived realism by increasing the participants' sense of presence, potentially inciting psychological and physiological responses similar to what would be observed in a physical space (Higuera-Trujillo et al., 2017). One study comparing the experiential qualities of walking through real and virtual buildings found that there were no statistically significant differences between the environmental ratings of the real and virtual environments, and participants generally rated geometry, structure, sizes, and furniture similarly between the two conditions but experienced the virtual environment as excessively clean, artificial, and sterile (Kuliga et al., 2015). In another study, workers who experienced a virtual video tour of an office building that had not yet been built then walked through the completed building two years felt that the VR model provided a fairly good understanding of what the completed building would look like (Westerdahl et al., 2006).

If basic elements of the virtual stimuli are being systematically misinterpreted, the behavioral and experiential results generated from those stimuli will not accurately predict what would be seen in real life. Distance perception in virtual and physical environments has been extensively studied, demonstrating a pattern of underestimation of virtual distances. A review of the literature on egocentric distance estimation in virtual environments indicated that on average, egocentric distances in virtual environments are estimated by subjects to be 74% of the actual distances (Renner et al., 2013). Other researchers have compared distance perception in an outdoor setting between real and virtual environments and found underestimation across conditions with little difference between conditions (Plumert et al., 2005). Other studies which also compared verbal distance estimates from 8 to 13 meters between real and virtual outdoor environments similarly found no significant difference between the two, but some effect of the order of conditions (Feldstein et al., 2020). In an inquiry on visual complexity of environments, it was found that participants thought they were more accurate at judging distances in high visual complexity environments, even though there was no actual difference in estimation accuracy between complexity levels. (Hmaiti et al., 2024). To give subjects a sense of confidence in their perception of the environment, higher visual complexity and realism may be useful.

Fig. 1: Stimuli used in Hmaiti et al (2024).

Behavioral and psychophysiological responses to a real and virtual experience of going up in a fire truck basket were highly similar to each other with regards to biometric and EEG measures (Schöne et al., 2023). When asked to traverse a narrow path while exposed to extreme height in VR, subjects showed realistic responses when compared with the same task on the ground in VR (Kisker et al., 2021). This illustrates the capacity of virtual stimuli to induce significant physiological and psychological responses in users.

Other studies have investigated specific aspects of human experience and behavior and whether they differ between physical and virtual environments. In these studies, subjects were given a specific task, allowing researchers to control for the participants' engagement with the environment and draw specific conclusions relating to niche aspects of human cognition. In an investigation on the ecological validity of virtual environments for assessing human navigation ability, there were no significant performance differences between the conditions for landmark recognition, route position, and route distance estimation (Van de Ham et al., 2015).

Several studies have investigated spatial orientation in virtual settings (Pastel et al., 2021 & 2022; Kimura et al., 2017). In one, it was found that geometry in virtual environments was not used for spatial orientation in the same way that it was used in real environments (Kimura et al., 2017). In another, walking distance estimations and route recall were not significantly different between virtual and real environments (Pastel, 2020). Another study used virtual environments to study individual variations in cognitive maps and navigation performance (Weisberg et al 2014). Heydarian et al. (2015) compared performance on specific office-related tasks and sense of presence in an immersive VR environment with the same variables in a physical environment and found no significant difference between environments.

3.2 What Makes Virtual Experiences Seem Real?

Although users know for certain that VR experiences are not actually real, how can they be useful tools to predict responses to analogous real situations? There have been a range of theories as to what predicts the accuracy of human responses to simulated environments.

Slater & Wilbur (1997) describe immersion as a result of the technological capabilities of the system presenting the virtual environment, which determine the realism and extent of the illusion of the virtual environment being real. According to them, immersion can be predicted by four objective technological factors in how the environment is presented:

1. Inclusive: how much the technology prevents the user's perception of physical reality
2. Extensive: how much the technology involves all of the user's senses.
3. Surrounding: whether the technology supports a panoramic view.
4. Vivid: the quality of the visual stimuli with regard to resolution, color, and so on.

Several other factors are also highlighted. One such critical feature is matching, which is the coupling between the user's physical movements and what they see in the virtual world. Another is self-representation, or the incorporation of a virtual body. Finally, they emphasize the importance of plot: each virtual environment should provide a realistic and independent "story-line".

While immersion is a description of the capabilities of a technological system, presence is a state of consciousness. Slater & Wilbur (1997) defined presence as "the psychological sense of being in the virtual environment" which increases as immersion increases. They argue that at the most basic level, users should feel that the virtual environment overpowers the physical one, and that the sights they experience virtually are places they have visited, not just pictures they have seen. This is particularly relevant to the current study, as we are interested in whether our current technological systems can provide a sufficient sense of presence such that participant experience and behavior will be the same in an identical virtual and physical environment.

Lombard & Ditton (1997) claim that understanding the concept of presence is critical to the success and practicality of digital technologies and how they affect our daily lives. They also highlight how researchers would like to rely on "mediated stimuli", and often generalize to claim that the results they find with these stimuli accurately reflect what would have been found with the actual stimuli. They list similar requirements for enabling a sense presence as Slater & Wilbur: sensory inputs and outputs, visual display quality and size, visual field, interactivity, and dimensionality. Notably, Lombard & Ditton focus deeply on social realism as a key component of presence, including the sense of a virtual space being shared by others.

3.3 The Biophilia Effect

Biophilic design, an application of Edward O. Wilson's biophilia hypothesis (1984), integrates natural elements, patterns, and processes into built environments to foster psychological and physiological well-being, as extensively explored by (Kellert et al., 2008). We would like to test whether this proven restorative effect in the physical world will also be observed in an identical virtual world. Much research has been done to robustly establish the restorative effects of biophilic and natural elements in the past few decades.

A synthesis of environmental psychology studies found that several biophilic design strategies were overall effective at creating restorative environments (Gillis & Gatersleben 2015). They found that plants, water, and wood are all especially effective at fostering human wellbeing. Natural environments can have restorative effects for stress recovery and psychological well-being. Research into the effects of natural environments can measure physiological, behavioral, and self-reported factors to create a robust scientific foundation for planning urban settings in a human-centered way (Berto, 2014). Another review paper analyzed the social, environmental, and economic benefits of biophilic architecture (Söderlund & Newman, 2015). They found strong evidence that the incorporation of nature-based elements in design can have significant psychological and physiological benefits for people. Biophilic and nature-based architecture is an important intervention that can positively influence human psychological and physiological functioning (Joye, 2007).

Direct exposure to nature– either through a window or by walking through it– has been shown to have restorative effects. Hospital patients with a natural view required shorter stays (7.96 vs. 8.70 days) and required fewer strong painkillers than patients with a view of a brick wall (Ulrich, 1984). This paper sparked widespread interest in how nature can be incorporated into the built environment and have positive effects on the people occupying the spaces. Approximately 40-minute long exposure to natural environments after cognitive fatigue had restorative effects for subjects' cognitive performance, emotional well-being, and relaxation compared with urban environments and passive resting, though no physiological differences were observed between the conditions (Hartig et al., 1991). This restorative effect of walks in natural environments versus urban ones has been observed in individuals with depression, improving memory span and mood (Berman et al., 2012b).

While the above work focuses on direct exposure to nature or multiple types of biophilic design, what is the effect of bringing plants into the built environment? Prior work has shown that interior plants can improve productivity and attention capacity in office settings (Lohr et al., 1996; Raanaas et al., 2011). However, contradictory results indicated that more plants in an office setting corresponded with lower productivity on a repetitive task, despite subjects rating those office spaces with more plants as more attractive and comfortable (Larsen et al., 1998).

A review of the psychological benefits of passive interactions with indoor plants found mixed results (Bringslimark et al., 2009). They were particularly interested in changes in cognition, emotion, and physiology which improved subjects' experience or performance on tasks. They found that while pain tolerance and stress reduction were improved by the presence of plants, other cognitive effects such as performance, productivity and mood had mixed results depending on the context of the indoor plant encounter. One variable they highlighted was the importance of visual salience in determining the effect of the plants, which includes the amount of plants in the room, the position of the plants, the type of plant, and the size of each plant. They also mentioned how focusing on a task brought subjects' attention away from the plants, which they imply reduced their effect.

While the restorative effects of direct experiences of nature have been robustly studied, what about digital representations of natural elements? This is relevant to the current study because plants will be viewed either directly, in the physical environment, or indirectly, by viewing digital models in VR. What is known about the restorative effects of representations of nature?

Viewing images of natural scenes prior to exposure to a stressor improved the recovery process compared with viewing built scenes (Brown et al., 2013). Experiencing nature in VR was shown to have similar restorative effects as viewing images of nature (Valtchanov et al., 2010). In subjects suffering from stress and/or burnout syndrome, real natural environments were more effective at reducing stress than simulated natural environments, though both had a positive effect (Kjellgren & Buhrkall, 2010).

3.4 What Makes Nature Restorative?

It is clear that nature can have restorative effects. Several theories have been proposed to explain these effects. The most prominent theories are Stress Recovery Theory proposed by Ulrich (1983), and Attention Restoration Theory proposed by Kaplan (1995). Though distinct in some ways, the two are not inherently contradictory (Hartig & Evans, 1993).

Stress Recovery Theory (Ulrich, 1983) focuses on the improved emotional state and decreased stress hormones that natural environments can induce. SRT is primarily interested in physiological and emotional recovery from stress. It proposes that natural environments are subconsciously restorative because of the evolutionary benefit of attraction to settings conducive to survival and reproduction (Joye, 2007). Exposure to natural elements thus automatically reduces stress without the need to direct conscious effort to it. Ulrich's (1984) surgery recovery study offers empirical support of the theory that exposure to nature can have positive effects without our realizing.

Attention Restoration Theory focuses on how natural environments can support the recovery of the ability to focus one's attention (Kaplan & Kaplan, 1989). They argue that the stimuli provided by natural environments can gently capture attention without requiring intense focus, allowing attention capacity to recover. Supporting this theory, performance on tasks requiring directed attention was improved after time spent in natural settings (Kaplan, 1995).

3.5 Key Prior Work

It has been shown that biophilic design elements experienced in VR can have a restorative effect. However, is this on par with the effect those same biophilic design elements would have in a physical space? These studies provide a precedent for studying biophilic design within the built environment using VR.

Kort et al. (2003) tested the validity of virtual environments for predicting experimental results in real environments. They had subjects explore identical spaces through a virtual model on a computer screen or in real life, and also manipulated the presence of plants in the environments. Participants were asked to explore the space in VR while imagining what functions it could have for 3½ minutes. While size estimation and cognitive mapping was shown to be better in the real environment, the effect of manipulating the presence of plants was the same in both real and virtual environments.

Yin (2018) investigated whether the presence of biophilic design elements in indoor environments has a similar effect when experienced in a physical environment and a virtual one. 28 participants viewed each of the four conditions for 5 minutes each. In the physical condition, participants viewed a non-biophilic classroom or a biophilic common area. In the virtual condition, they were physically located in the same environments but viewed them via a 5 minute video on a VR headset. They found that participants experiencing the biophilic design elements had lower blood pressure and skin conductance, but no significant change in heart rate. Participants in the biophilic condition also performed better on the cognitive tests. Self-reported emotion data showed a decrease in stress and frustration and an increase in engagement and excitement for subjects in the biophilic condition. There was no significant difference in results between the physical and virtual conditions. However, one major limitation of this study was that it did not isolate any specific element in the design of the rooms to change. The two settings were completely different, and so it is hard to conclude that any differences are due to the presence or absence of biophilic elements and not any of the other changes between environments.

Yin (2019) studied the restorative effects of natural elements in indoor environments using VR. The researchers compared subjects' stress and anxiety recoveries in one virtual office with no biophilic design element to their recoveries in three virtual offices with different kinds of biophilic design elements. They did not isolate a single element, and instead varied many design features. They found that the environments with biophilic design elements induced better recovery responses after exposure to a stressor than environments without. However, it is again difficult to identify the salient features of the room which led to these observed differences. In our study, we will be isolating green plants as the single biophilic design element of interest.

Lighting conditions and all other aspects of the environment should remain consistent; in our case the only difference will be the presence or absence of green plants in the room.

While these studies provide a useful basis for the current work, there are several key differences that set us apart. One major difference is that we will be isolating the effect of a singular biophilic element (the presence vs. absence of indoor plants) rather than many different factors which change in several of the aforementioned studies. We also have the subjects performing a specific task designed to focus their attention on their surroundings, rather than environmentally unrelated cognitive tests.

4. METHOD

4.1 Study Population & Demographics

We recruited 29 healthy adults to participate in this study. Participants were recruited primarily through the UC San Diego Psychology Department SONA Subject Pool. Subjects signed up voluntarily and received compensation in the form of academic course credit. We did not accept participants who had a history of severe motion sickness, medical conditions that would be affected by visual effects viewed in virtual reality, any neurological/vestibular issues, or any uncorrected visual impairments. Ultimately, data from 9 subjects was excluded from analysis due to significant technical challenges which altered the subject's experience to such an extent that their data would not be reasonably comparable to that of a typical participant (e.g. VR headset not connecting to display the test rooms, repeated transcription errors, interface crashing, etc).

Of the remaining 20 total participants, 70% were female with an average age of 21.05 years. Subjects had slept an average of 6.84 hours the night before, with a minimum of 4 hours and a maximum of 8 hours. For the half assigned to the physical modality, 80% were female with an average age of 19.90 years. For the half which experienced VR, 60% were female with an average age of 22.33 years. All trials were started and completed between the hours of 8am and 5pm. Subjects were asked to abstain from caffeine for at least 4 hours prior to their appointment.

This study was approved by the University of California San Diego Institutional Review Board, and the researcher verbally explained any potential risks to all participants. All participants signed the consent form digitally on DocuSign prior to beginning the experiment.

4.2 Stimuli

Four conditions were tested:

1. Physical environment with plants (Physical-Plants)
2. Physical environment with no plants (Physical-No Plants)
3. Virtual environment with plants (Virtual-Plants)
4. Virtual environment with no plants (Virtual-No Plants)

	Physical	Virtual
Plants	Physical room with real plants	Virtual room with virtual plants
No Plants	Physical room with no plants	Virtual room with no plants

Subjects were each randomly assigned to a modality (Physical or Virtual) and experienced both Plant and No Plant versions within that modality. That is, we tested Plants/No Plants within subjects and Virtual/Physical between subjects. The order in which subjects experienced Plants or No Plants alternated.

Fig. 2: The four environments tested, from the subject's perspective.

For the purpose of this study, a "digital twin" is defined as a digitally reconstructed replica of the physical environment in which the dimensions of the space, the furniture, the colors and textures, and the lighting are all as close as possible to the physical version. The overall architecture and textures of the stimulus rooms were modeled after the physical space in SketchUp (Trimble Inc., n.d.) and rendered in Enscape (Enscape GmbH, n.d.). Plant models were obtained via a combination of assets from Poliigon, a high-quality photorealistic asset library (Poliigon, n.d.), and scanned models collected using the Reality Composer application (Apple Inc., n.d.). The VR environments were viewed through a MetaQuest Pro headset (Meta Platforms, Inc., 2020). The researcher helped the subject put on and adjust the headset while they were standing, then asked them to close their eyes as they activated the test environment to avoid motion sickness. Next, the subject found the chair depicted in the VR stimulus and moved a real chair to match the position of the one they saw. Finally, the subject sat in the chair so they were viewing the room from the same perspective as the physical subjects. Participants had the ability to physically look around the virtual space just as they would in the physical space. Participants were also physically located in the same space, helping to keep factors such as temperature, humidity, and acoustics constant between physical and virtual conditions.

The exact strategy for including plants in the indoor space was systematic and quantifiable, based on guidance from Bringslimark et al. (2009). We placed plants with green foliage around the space where they are readily observable from the participant's perspective. Subjects always sat in an identical chair in the same corner of the room, and completed the tasks verbally from that position.

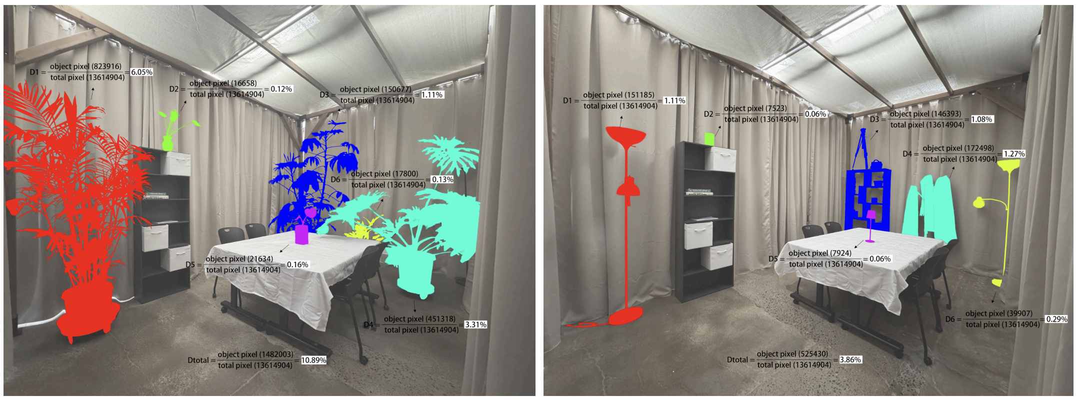

Fig. 3: Pixel-count analysis of the size of objects meant to balance visual weight.

The Plants and No-Plants conditions were identical with regards to visual weight. We included furniture in the No-Plant condition which was intended to control for the visual weight introduced by the addition of plants. If we had not done so, the Plants room would also have many more features and interesting objects than the No Plants room, which would have introduced a potential confound- we would not have been able to determine whether any effect of the plants was due to the plants themselves or just the additional visual complexity they create.

In order to induce stress in participants, we used an adapted version of the Mental Arithmetic Task (MAT) from the original Trier Social Stress Test (TSST) (Kirschbaum et al., 1993). Our MAT was administered using a custom-built digital platform. Subjects were instructed to subtract a two-digit number (e.g. 13) from a four-digit number (e.g. 1009) sequentially for five minutes. The subjects had 10 seconds to speak each answer aloud, which was visualized via a countdown on screen. After they spoke their answer, they pressed "Submit" and were shown a transcription of their answer to confirm whether the transcription was correct. If they got an answer incorrect, or if they did not answer within the 10 allotted seconds, they heard a buzzer and were instructed by the program to start over from the original four-digit number (e.g. 1009). During the entire task, they heard a ticking noise through the AirPods that got louder as the timer neared 0. At minute 2 and minute 4, they heard pre-recorded social evaluative feedback criticizing either their speed or their accuracy (e.g., for accuracy: "Your accuracy is below the average so far. Please double check your calculations" and for speed: "We notice that you are taking longer than average to answer. Please respond more quickly"). These social-evaluative elements and uncontrollable factors were incorporated in order to maximize the task's effectiveness at causing a stress response in the subjects (Dickerson & Kemeny, 2004).

4.3 Measures & Devices

Participants' physiological responses to stress were measured using heart rate (HR), heart rate variability (HRV), electrodermal activity (EDA), and respiratory rate. We used an Emotibit device on the subjects' thumb to measure a suite of indicators (Montgomery et al., 2024). Green, red, and infrared photoplethysmography (PPG), electrodermal activity, and heart rate were all recorded using the Emotibit sensor. Respiratory rate was recorded using the Vernier Go Direct® Respiration Belt worn around the torso at the height of the sternum (Vernier Software & Technology, n.d.).

We used a wireless lavalier microphone to record subjects' speech. Speech was transcribed using *Whisper* speech recognition software (OpenAI, 2022). Subjects wore wireless earbuds to receive audio instructions and feedback throughout the experiment.

The Sustained Attention to Response Task (SART) was used as a non-biometric, indirect measure of stress. SART is a go/no-go task designed to measure an individual's capacity to sustain attention (Jha et al., 2017). Subjects have to accurately respond (press spacebar) or withhold their response (no press) based on the number shown on screen. They are instructed to press the spacebar as fast as possible for every number except the number 3. Periodically, probes appear asking the subject to rate where their attention was focused before the probe and how aware they were of where their attention was focused. This task is sensitive to changes in cognitive performance caused by stress, and thus ideal for detecting subtle recovery effects. Subjects completed the SART multiple times throughout each trial, allowing us to quantify how their performance, which was calculated by taking both their speed and their accuracy into account, changes as a function of their current stress level.

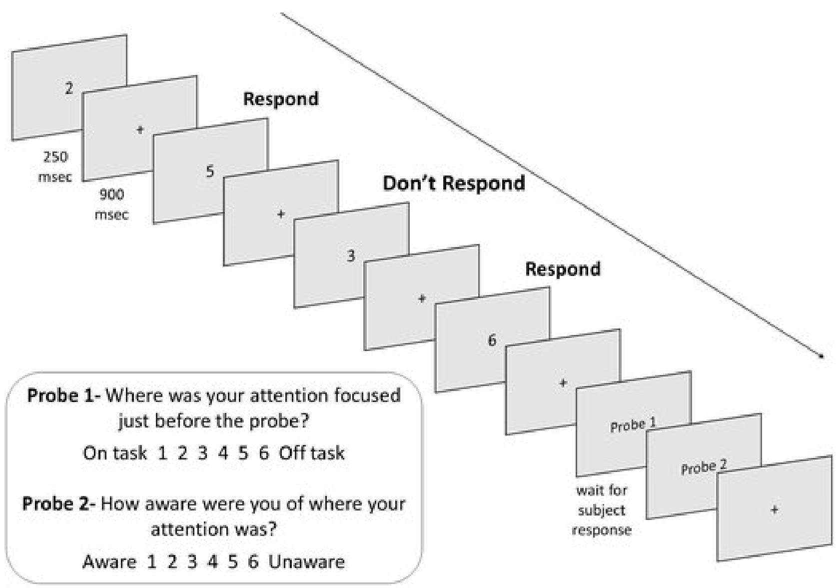

Fig. 4: Diagram of the structure of SART (Jha et al., 2017).

Lastly, the 11-item version of the Perceived Restorativeness Scale (PRS-11) was used to assess subjects' subjective perception of how restorative each environment felt. We used the 11-item version instead of the original 26-item version because it has been shown to have a comparable level of validity, and we required a task that did not last too long since it was repeated twice (Pasini et al., 2014). Subjects were asked to rate their level of agreement with each statement about their surroundings from 0-6, and provide a justification for each rating. This ensured that subjects were focused on their surroundings and also speaking aloud, to facilitate SER analysis during their time in the test environment.

4.4 Procedure

1. Subject entered the lab, signed the informed consent document, and completed two pre-test surveys. The first survey asked about their age, gender, hours of sleep the night before, and prior experience with VR. The second survey was the 10-item Perceived Stress Scale (PSS-10) which is designed to measure individual perceptions of stress and asks respondents to respond to ten questions on a Likert scale from 0 - "never" to 4 - "very often" (i.e. "In the last month, how often have you been able to control irritations in your life?") (Cohen, 1988).
2. We fitted the biometric sensors on the subject and began to collect data. These sensors then recorded data continuously throughout the entire procedure.
3. For two minutes, the subject was asked to sit and do nothing to establish a baseline level for their biometric stress levels.
4. Subjects verbally answered a series of questions about their day to provide a baseline for Speech-Emotion Recognition (SER) analysis. SER is capable of inferring the emotional state of the subject based on their tone of voice using machine learning techniques. While we did not perform Speech-Emotion Recognition analysis for this project, the audio recordings and transcriptions from our trials are available for future investigation.
5. If the subjects were assigned to the Virtual modality, we completed headset training to ensure they knew how to put on the headset, could look around, and see their surroundings in focus. This also helped to minimize any novelty effects, ensuring their first experience in VR was non-experimental.
6. Next, the subjects completed the SART for the first time. The purpose of this SART was to get a baseline of their performance before exposure to the stressful task.
7. Before beginning the first MAT, subjects completed a practice version to familiarize themselves with the interface. They subtracted 5 from 20 until they reached 0. Besides for the values themselves, the total length, and the lack of auditory social evaluative feedback, the practice test was identical to the actual test.
8. The subject engaged with the MAT for five minutes to induce stress as described in Section 4.2, without stopping or breaks.
9. After completing the stressor task, subjects did another SART to benchmark the degree to which the stress task initially affected their performance.

10. The researcher transitioned the subject to the test environment. While in the environment, the subjects did two tasks:
    a. Freeform observational task which prompted subjects to spend one minute in silence observing the room around them, then answer two questions to encourage them to engage with each aspect of the details and design of the room.
        i. Prompt 1: "Describe the room in detail to someone who cannot see it."
        ii. Prompt 2: "How would you rearrange the furniture in the room for alternative use cases?"
    b. After answering the observational prompts for a total of about 5 minutes, subjects rated all items on the PRS-11 scale from 0-6 with justifications. The order of the 11 statements was randomized for each subject.

    The tasks were designed to ensure that the subjects' attention was focused completely on their surroundings. Furthermore, both tasks required substantial verbal responses to enable later SER analysis.
11. The researcher transitioned the subject back into the waiting area, where they completed another SART. This allowed us to compare how much the specific recovery room affected their performance.
12. The subject watched a 5 minute neutral break video to ensure they returned completely to their prior baseline and were prepared for the second round.
13. The procedure was repeated exactly the same besides for the training and practice tasks with the other condition (Plants or No-Plants) within the modality they had been assigned (Virtual or Physical).
14. After experiencing both the Plants and No-Plants versions of the Physical or Virtual rooms, the subject completed a post-test questionnaire which asked about prior experience with first-person perspective video games, how much they felt the plants had helped them recover, frequency of participation in outdoor activities, preferences towards spaces with live plants, and an opportunity to report any dizziness or nausea from the VR.
15. Subjects were debriefed, the purpose of the study was explained to them, and it was disclosed that any negative feedback received during the MAT was not reflective of their performance and was identical for all subjects. The researchers answered any questions from the participants, and they were dismissed.

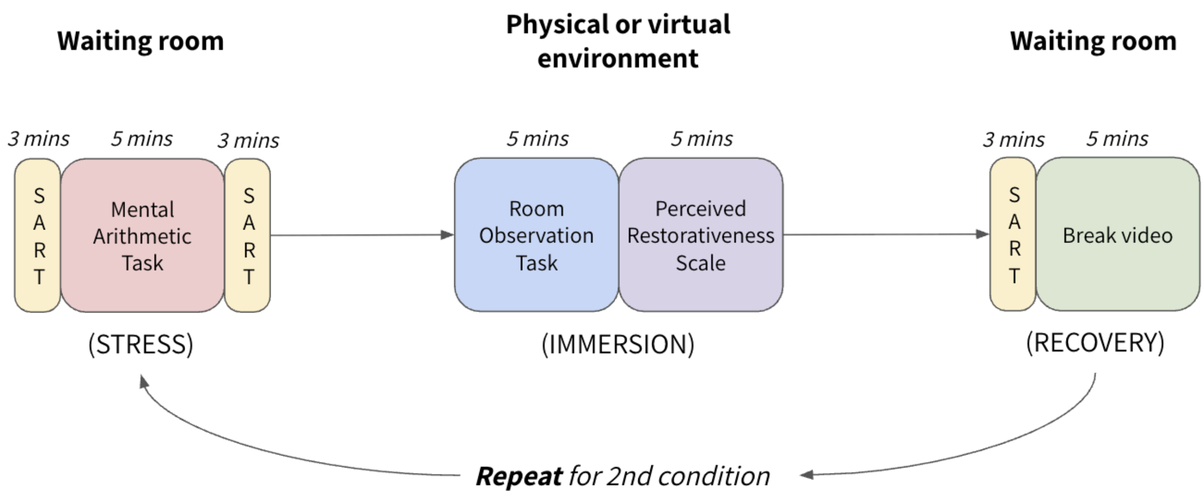

Fig. 5: Graphic depiction of the procedure followed for each trial.

5. RESULTS

Across all measures, our sample size of only 20 subjects limited the power of our analysis. This represents pilot data to inform the design of future studies in this area.

5.1 PSS-10

On the PSS-10, our pre-test survey to assess incoming stress state, a higher score would indicate more perceived stress. On average, the 10 subjects assigned to the physical condition had a score of 16.4 out of a maximum possible of 40. The 10 subjects assigned to the virtual condition had an average score of 14.4. This indicates that the physical group potentially had a slightly higher incoming stress state than the virtual group.

5.2 Heart Rate

For the heart rate data, we took the average heart rate of each subject over the two minute baseline collection period. Then, for every 30 second window from the first SART to the end of the recovery in the test environment, we found the distance of the subject's heart rate from their baseline during that period. For each condition, this difference between heart rate in that 30 second window from the subject's individual baseline was averaged across the 10 subjects who experienced that condition, producing a single line for each condition.

While we expected to see heart rate increase throughout the SARTs and the stress task as stress level rose and decrease in the test environment as stress level fell, we did not observe this trend. It appears that that stress test did not significantly affect subjects' heart rates compared to their baseline in any condition.

The only place where we do see a trend of heart rate increase is during the transition period between the second SART and the test environment, and from the test environment back to the waiting room. This spike is likely due to the physical movement of going from a sitting position to standing, as well as movement artifacts as the accuracy of the Emotibit sensor is affected by hand motion.

If the stress task had increased heart rate, we would have then expected to see a decrease in heart rate over the period of time spent in the test environment, with this decrease occurring faster in the Plants conditions than the No-Plants conditions. We did not observe this trend. Instead, there seems to be an indication that subjects had a higher heart rate in virtual environments than physical ones. However, the group assigned to the virtual environment seems to have had higher heart rates compared to their baselines even before entering the test environment, indicating that that group may have just had higher heart rates compared to their baseline overall and that this effect was not due to the environment.

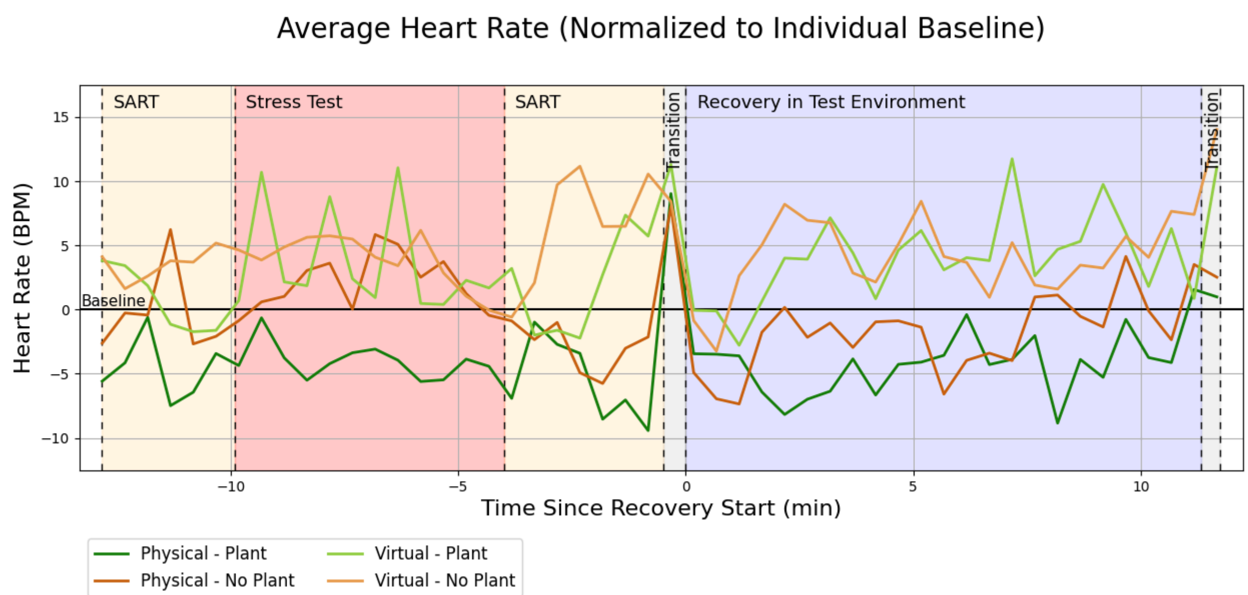

Fig. 6: Average heart rate (represented as beats per minute) over time since recovery start, normalized to individual baseline.

5.3 Heart Rate Variability

For heart rate variability (HRV), we took an identical approach as we did for heart rate. For each subject, average heart rate variability over the two minute baseline collection period was calculated. For every 30 second window from the first SART to the end of the recovery in the test environment, we found the distance of the subject's HRV during that time from their baseline value. This difference between heart rate variability in that 30 second window from the subject's individual baseline was averaged across the 10 subjects who experienced that condition.

While we expected to see HRV decrease throughout the SARTs and stress task as stress level went up and increase in the test environment as stress level went down, we did not observe this trend. It appears that that stress test did not significantly affect subjects' HRV compared to their baseline in any condition.

If the stress task had decreased HRV, we would have then expected to see an increase in HRV over the period of time spent in the test environment, with this decrease occurring faster in the Plants conditions than the No-Plants conditions. We did not observe this trend. Overall, HRV did not vary significantly from subjects' baseline at any point during the trial, with no differences between the four conditions.

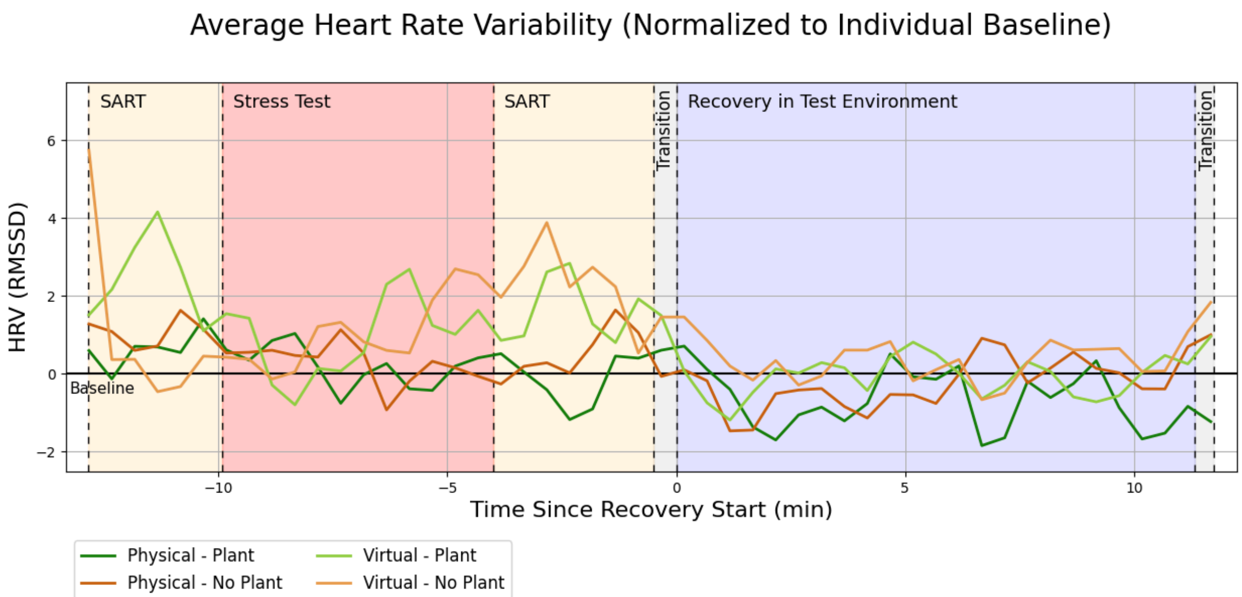

Fig. 7: Average heart rate variability (calculated as Root Mean Square of Successive Differences) over time since recovery start, normalized to individual baseline.

5.4 Electrodermal Activity

For electrodermal activity, we again used the same approach. For each subject, an average electrodermal activity value was calculated over the two minute baseline collection period. For every 30 second window from the first SART to the end of the recovery in the test environment, we found the distance of the subject's EDA level during that time from their baseline value. This difference between EDA in that 30 second window from the subject's individual baseline was averaged across the 10 subjects who experienced that condition.

While we expected to see EDA increase throughout the SARTs and stress task as their stress level went up and decrease in the test environment as their stress level returned to baseline, we did not observe this trend. It appears that that stress test did not significantly affect subjects' EDA compared to their baseline in any condition.

If the stress task had increased EDA, we would have then expected to see an increase in EDA over the period of time spent in the test environment, with this decrease occurring faster in the Plants conditions than the No-Plants conditions. We did not observe this trend. Overall, EDA did not vary significantly from subjects' baseline at any point during the trial, with no differences between the four conditions.

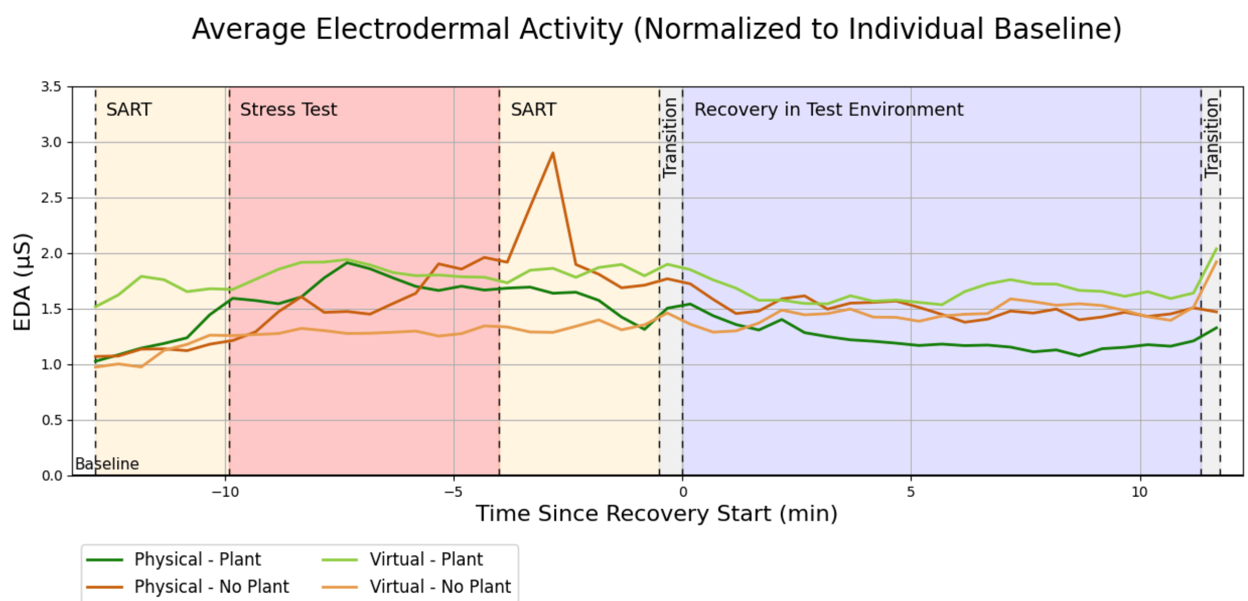

Fig. 8: Average electrodermal activity (represented as microsiemens) over time since recovery start, normalized to individual baseline.

5.5 Sustained Attention to Response Task

SART performance was analyzed by comparing subjects' performance on the SART before and after recovery in the test environment. Speed-Accuracy was calculated by:

$$\frac{mean\ reaction\ time}{mean\ accuracy\ \ (i.e.\ average\ of\ go\ \&\ no{-}go)}$$

Thus, a higher Speed-Accuracy means the subject was less accurate and slower to respond, so they had a worse performance. A lower Speed-Accuracy indicates that the subject was more accurate and faster to respond, so they had a better performance. Δ Speed-Accuracy, or change in speed accuracy, was calculated by finding the difference between Speed-Accuracy for the SART before recovery in the test environment and Speed-Accuracy for the SART after recovery in the test environment. A negative Δ Speed-Accuracy means that the subject improved from the SART before recovery to the SART after recovery, indicating that the environment helped them restore their attention capacity.

Based on our hypothesis, we expected to find that the Plants conditions had a lower Δ Speed-Accuracy than the No-Plants conditions. As is evident from Figure , the median Δ Speed-Accuracy for all four conditions is very close to zero, meaning that the environments did not change their performance on the SART at all.

Future analysis should also compare SART performance before and after the stressor task, to determine whether the stressor task had an effect on the subjects' attention capacity.

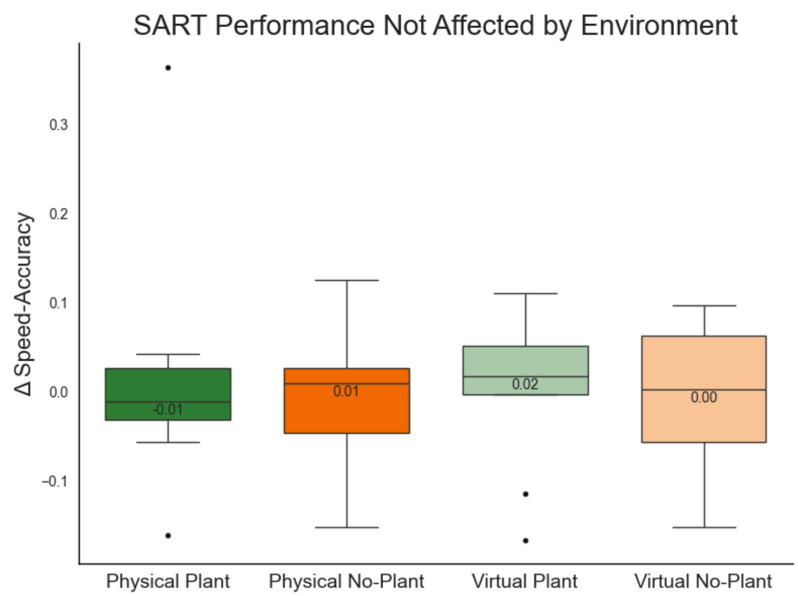

Fig. 11: Barplot of change in speed-accuracy between the SART before and the SART after recovery in test environment.

5.6 Perceived Restorativeness Scale

The results for the Perceived Restorativeness Scale (PRS-11) were compared by totalling the ratings provided by each subject for all 11 items, and identifying the median. The PRS-11 also had no significant differences between any conditions, though they did indicate a potential trend. Virtual environments overall were rated less restorative than physical ones, though this difference was not statistically significant. Since the subject groups for physical and virtual environments were separate, it is highly possible that the physical group just gave higher ratings overall than the virtual group and this difference is not due to the effect of the environment.

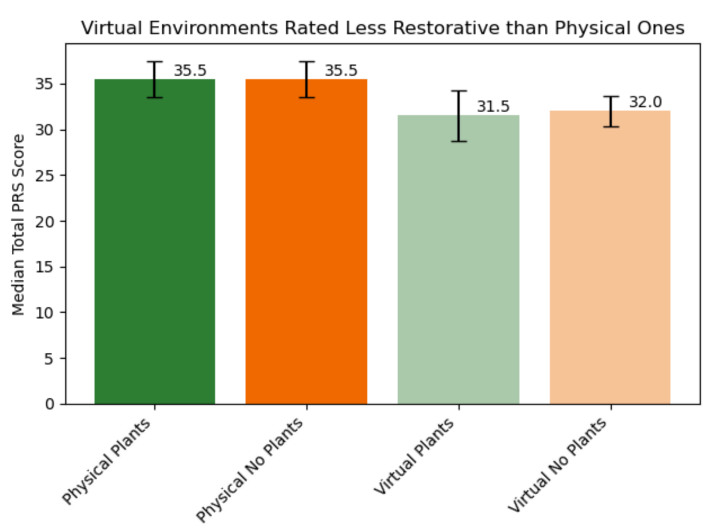

Fig. 9: Median total Perceived Restorativeness Scale (PRS-11) scores between conditions.

Paired t-test:	Independent t-test:
Physical plants vs. physical no plants: p = 0.922	Physical plants vs. virtual plants: p = 0.816
Virtual plants vs. virtual no plants: p = 0.432	Physical no plants vs. virtual no plants: p = 0.707

Fig. 10: Significance levels of PRS-11 results.

6. DISCUSSION

Our first hypothesis predicted that biophilic design elements would reduce stress recovery times. Our second hypothesis was that the stress recovery curve would not be significantly different between identical physical and virtual environments, under both plant and no plant conditions. The biometric, psychological, and subjective results did not support either hypothesis, as we did not find any significant differences between conditions.

There does seem to be a slight trend of the virtual environments inducing slightly higher stress responses– especially in heart rate and PRS– than the physical environments, though this difference was not statistically significant for any of our measures. More subjects should be tested to address each of our inquiries and increase the likelihood of detecting small effects.

Ultimately, a major limitation of this study is that the stressor task did not affect participants to a degree sufficient to appear in the measures we were observing. Without successfully inducing stress in the subjects, it was very difficult to observe any differences in recovery, since with regards to their physiological and psychological measures they never really left their baseline.

To address these limitations, we recommend modifying the stress task to more effectively induce a physiological response. This could be accomplished by adding more components from the original TSST, such as the public speaking task. Prior research has found that either the mental arithmetic task or the public speaking task in isolation are less effective at consistently inducing stress in subjects, but the combination of the two has a more reliably pronounced effect (Kirschbaum et al., 1993). It is critical that the stressor task be successful in inducing a response in subjects to ensure that they have something to recover from at the time when they enter the different environments.

Additionally, we did not observe any significant difference between the Plants and No-Plants conditions. This could be due to the overall similarity of the Plants and No-Plants rooms: in their design, they feel the same in many regards as both are designed to feel realistic and comfortable, which makes it less likely that subjects will respond dramatically differently to each. The specific plants we used were also larger and more sprawling than typical indoor plants, which may have reduced their efficacy as restorative elements. In future work, it is important to be highly intentional about the way in which biophilic design is incorporated so that the two conditions are different enough to induce the restorative effect that is expected.

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