EFFECTS OF BIOPHILIC RESTORATIVE EXPERIENCES ON DESIGNERS' BODIES, BRAINS, AND MINDS

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ABSTRACT

The research presented in this paper explores a novel method for assessing the effects of biophilic restorative experiences on designers' cognition by combining the use of physiological, neurocognitive and semantic measures. A total of 12 engineering graduate students participated in a three-step pilot experiment that consisted of (1) a stressor (the Trier Social Stress Test), (2) a destressing intervention (biophilic sound experience), and (3) a design task. Heart rate variability (HRV) was used to track subjects' autonomic nervous system (ANS) activity. Functional near-infrared spectroscopy (fNIRS) was used to track patterns of brain activation in subjects' prefrontal cortex (PFC). Changes in design quality were assessed by the semantic space they explored, measured through a natural language processing (NLP) technique. Preliminary findings suggest that an auditory biophilic restorative experience can change designers' bodies, brains, and minds. Results from this pilot study encourage further exploration of the use of exposure to nature-based stimuli as a method to help enhance engineering design cognition.

Keywords: Bio-inspired design / biomimetics, Design cognition, Semantic data processing, neurocognition, biophilia

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1 INTRODUCTION

Engineering design is a highly complex process that demands significant cognitive effort. It involves highly interdependent steps, such as problem identification, conceptualization, analysis, synthesis, and evaluation. When designing, engineers must consider a wide range of factors, such as material selection, environmental impact, cost-effectiveness, and user needs, among many others. Design cognition is critical to the success of engineering design because it encompasses the cognitive processes involved in each of these steps.

There are many methods to help enhance engineering design cognition, for example, the use of tools like Morphological analysis and TRIZ, applying predefined design heuristics, or the use of technology-based design aids. Whether using TRIZ, design heuristics, or computer aids, these tools are useful because they help to reduce the mental effort required when designing. TRIZ chunks the design into smaller phases, design heuristics provide common patterns or rules of thumb to follow, and computer-based design aids replace some mental calculations. However, the effectiveness of these approaches depends on how well they are integrated into the design process and how efficiently they are utilized by engineers. Improving design cognition is not simply a matter of adopting new tools or methodologies but changing the designer's mindset.

Changes in the physical environment can help to shift the designer's mindset. For example, architects designing buildings recognize that different workspaces, such as collaborative areas, quiet zones, and standing desks, can accommodate different work styles and preferences. Creating an environment that supports the designer's physical and mental well-being can help to reduce stress, increase engagement, and enhance cognitive performance (Gray and Birrell, 2014; Yin et al., 2020, 2019). The physical environment can shape design. For example, students designing within a certified sustainable building produced significantly more ideas with sustainability principles represented in their designs (Shealy, 2016). Interventions to the physical environment have the potential to not only change designers' mindsets but help restore depleted cognitive processes.

The Attention Restoration Theory (Kaplan, 1995) postulates that positive experiences in nature can promote the restoration of depleted cognitive, physiological, and psychological resources. Biophilic restorative experiences involve positive interactions with nature-based stimuli, either through direct (Song, Ikei and Miyazaki, 2016), indirect, or symbolic (Aristizabal et al., 2021) contact with nature. Biophilic restorative experiences help people switch from fight-or-flight (i.e., stressful state) to rest-and-digest mode. This switch from a heightened sense of alertness to a state of relaxation can be visualized by changes in autonomic nervous system activity (Rajendra Acharya et al., 2006). Achieving a state of relaxation, which enables creative ideas to arise, is also observable by the rest of executive network functions in the brain (Song, Ikei and Miyazaki, 2021).

While the positive effects of biophilic restorative experiences on cognition have been previously observed in different tests like the Remote Associates Task (Atchley, Strayer and Atchley, 2012), the Digit Span Backwards test (Yin et al., 2018), and the Operation Span test (Aristizabal et al., 2021), more investigation is needed into how these effects can be translated into better design. The pilot study presented in this paper introduces a novel combination of methods for assessing the effects of biophilic restorative experiences on designers' cognition when designing. The Background section provides an overview of the physiological and neurocognitive processes that work in response to environmental stimuli. The Methods section presents the experiment design and a thorough description of the data collection, processing, and analysis methods used for this pilot study. The Results section shows some of the preliminary findings, while the Discussion section offers insights into what the early findings could mean. The conclusion describes intentions for the continuation of this research.

2 BACKGROUND

To objectively quantify the effects of biophilic restorative experiences, researchers have explored the use of several methods to track physiological and neurophysiological responses to environmental conditions. Saliva cortisol, blood pressure, heart rate variability (HRV), electrodermal activity (EDA), and brain activity are some of the most common biological markers (Aristizabal et al., 2021; Igarashi et al., 2014; Park et al., 2007; Song et al., 2021; Yin et al., 2019). These markers are used to depict a clear picture of how a person's body reacts to environmental stimuli. The main driver behind some of these reactions is the automatic nervous system. The automatic nervous system controls the body's involuntary responses

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to outside stimuli and can be divided into two parts: the sympathetic nervous system and the parasympathetic nervous system (Ernst, 2017). The sympathetic nervous system and the parasympathetic nervous system play a balancing act in which the sympathetic nervous system overrules when a stressful event triggers the body's fight-or-flight mode (Rajendra Acharya et al., 2006). With the sympathetic nervous system in control, heart rate increases, HRV decreases, and skin conductance levels rise (Aristizabal et al., 2021; Parsons et al., 1998; Schubert et al., 2009). Ulrich et al. (1991) explained how nature exposure could help regulate the balance in the automatic nervous system in the Stress Reduction Theory. The theory suggests that exposure to nature has a role in increasing parasympathetic nervous system activity, promoting the restoration of physical and psychological resources, and switching the body to a rest-and-digest mode (Parsons et al., 1998; Ulrich et al., 1991).

When it comes to the restoration of cognitive resources, the Attention Restoration Theory, introduced by Kaplan & Kaplan (1989), links nature exposure to changes in brain activity. The Attention Restoration Theory splits human attention into involuntary and voluntary/directed. While involuntary attention requires little to no cognitive effort, directed attention can cause a significant increase in cognitive load (Kaplan, 1995). According to Kaplan and Kaplan, the benefits to cognition from being immersed in nature stem from the opportunity created for directed attention to rest when no distracting stimulations or need for decision-making are present (Berman et al., 2008). Some unnatural environments, like urban spaces, demand an overwhelming amount of cognitive resources, which leads to a state of mental tiredness (Plambech and Konijnendijk van den Bosch, 2015).

While many studies have used simple cognitive tests of attention and memory to validate the Attention Restoration Theory (Berman et al., 2008; Bratman et al., 2012; Sharam et al., 2023), it has received more support in recent years with the development of new brain imaging technologies. Tools like electroencephalogram (EEG) and functional near-infrared spectroscopy (fNIRS) have been used to objectively quantify changes to the brain behavior caused by exposure to nature (Igarashi et al., 2014; Kim et al., 2018; Lee et al., 2012; Park et al., 2007; Song et al., 2021). Exposure to forest-derived stimuli can lead to a decrease in oxygenated hemoglobin (oxy-Hb) recruitment in the prefrontal cortex (PFC) (Lee et al., 2012; Park et al., 2007; Song et al., 2021). Calculating the average change in oxy-Hb concentration in the PFC is the approach that has been mostly used by researchers to assess the effects of biophilic restorative experiences on neurocognition (Lee et al., 2012; Park et al., 2007; Song et al., 2021). fNIRS is also commonly used in engineering studies to measure designers' neurocognition (Hu and Shealy, 2019; Milovanovic et al., 2021).

The departure from this previous work measuring brain response to biophilic restorative experiences is its effect on engineering design. Designing is more than just a simple cognitive task, and while measuring the brain's response to biophilic environments is important, it is not enough to fully understand its impact on the design process. Combing neurocognitive and cognitive measures can offer new insight into the influence of biophilic restorative experiences on what and how engineers design.

There are many ways to measure engineering design, one increasingly popular method is semantic analysis. Semantic analysis is a technique that involves analyzing the meaning of text by identifying and categorizing the words used and their relationships. Examining the language used to describe a design provides insight into the design space that the design engineer explored. For example, Beaty and Johnson (2021) used the semantic similarity between concepts to quantify design space and measure the originality of design ideas. The associative theory of creativity suggests that novel connections between distant concepts in the semantic memory structure are key to creativity (Kenett, 2018). By calculating the average semantic similarity between the words used to describe a design product, researchers can assess the divergence from ordinary ideas.

Researchers can gain a more complete understanding of the impact of biophilic restorative experiences on design cognition by analyzing changes in the semantic similarity between design concepts, brain activity, and physiological response. This multi-dimensional approach provides a more robust and comprehensive view of how nature-based design interventions affect design thinking and creativity. Combining these various measures can help identify the specific cognitive and physiological mechanisms underlying the restorative effects of nature on designers, which can, in turn, inform the development of more effective design interventions that promote cognitive restoration and enhance design thinking.

3 RESEARCH QUESTION

The study presented in this paper attempts to answer the question: what are the effects of biophilic restorative experiences on designers' bodies, brains, and minds? A combination of measures on the effects of a nature-based stimulus on physiological, neurocognitive, and cognitive states can help design researchers understand how environmental interventions can change design cognition.

4 METHODS

Graduate civil engineering students (n=12) were randomly assigned to the control or intervention groups. First, participants underwent the Trier Social Stress Test (TSST) (Wang et al., 2019). The TSST induces stress by subjecting participants to two tasks: a job interview and a math test (Goodman et al., 2017). This study followed the TSST guidelines established by Labuschagne et al. (2019). Following the TSST, participants were given an 8-minute restoration break. The length of the intervention was based on the average time of prior similar studies (Leung et al., 2022; Song et al., 2021; Thoma et al., 2018; van den Berg et al., 2015; Yin et al., 2019). During the break, the intervention group received an auditory biophilic restorative experience. The intervention included immersive 3D sounds from the MindBreaks application (Delos Living LLC, 2020). This application was chosen because it provides crafted biophilic auditory experiences that are readily available to the public. The auditory experience used was the Castaway soundtrack from the Rest category, which is the most popular among the application's users. The soundtrack includes birdsong and water sounds. Birdsong and water sounds are rated as key nature qualities for a restorative experience (Deng et al., 2020; Krzywicka and Byrka, 2017; Ratcliffe et al., 2013). The auditory stimulus was provided through headphones. Consistent with studies on noise and comfort, participants that received the auditory experience were allowed to adjust the headphones' volume to their preference (Rashid and Zimring, 2008). The control group completed the break in silence. Participants from both groups were asked to close their eyes during the restoration break.

Given the study's goal to investigate the possible effects of biophilic restorative experiences on design cognition, after the restoration break, subjects were given the following design task: *"Imagine the Town of Blacksburg has hired you as a consultant to design a new playground for young children inside an existing park. You have as much time as you need to come up with your design. Use the paper provided if needed."*

Participants were allowed to use their preferred method for developing the design concept. Upon completion, participants were asked to verbally explain their design concept in as much detail as possible and describe the process for getting to it. Design explanations were recorded by a microphone and later transcribed. The phases of this process are illustrated in Figure 1.

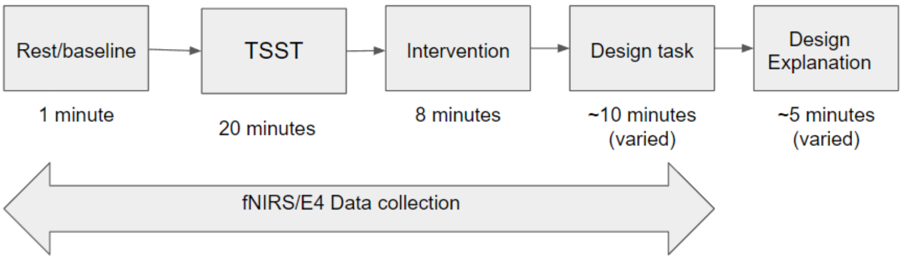

Figure 1: Experiment phases

Physiological responses to stress were measured by the Empatica E4 wristband, a medical-grade device that allows for real-time physiological data streaming and visualization. The wristband collects heart rate variability (HRV) data through a Photoplethysmography (PPG) sensor (sampled at 64 Hz). The ratio of the low-frequency to the high-frequency (LF/HF) components of HRV was extracted from the E4 data for each participant in each step of the experiment. The natural logarithmic values were utilized to normalize the data, replicating previous studies (Jo et al., 2019). The (LF/HF) ratio reflects changes in the sympathovagal balance and is used to measure sympathetic nervous system activity (Ernst, 2017; Jo et al., 2019; Task Force of the European Society of Cardiology the North American Society of Pacing Electrophysiology, 1996).

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Changes in the concentration of Oxy-Hb in the prefrontal cortex (PFC) were measured by the OBELAB NIRSIT functional near-infrared spectroscopy (fNIRS) device. fNIRS measures increases in blood oxygenation level-dependent (BOLD) responses through an array of near-infrared light-emitting probes and near-infrared light-detecting sensors positioned on the subjects' forehead (Hu and Shealy, 2019b). The NIRSIT device emits light at wavelengths between 780 and 850 nm. Light emitted from 24 sources (dual wavelength VCSEL laser) scatter in the brain before reflecting back to the 32 active detection sensors. Oxy-Hb and deoxygenated (deoxy-Hb) blood absorbs a different amount of the near-infrared light in the brain. The difference between the emitted and reflected light is used to calculate the concentration of oxy-Hb in the PFC, using the Modified Beer–Lambert Law. Motion artifacts were removed using the Temporal Derivative Distribution Repair (TDDR) method (Fishburn et al., 2019). To understand the effects of the biophilic restorative experiences on designers' neurocognition when designing, the mean oxy-Hb across the PFC was calculated and illustrated using a heat map.

To measure possible effects on design cognition, specifically, the exploration of the design space, a semantic analysis of the design descriptions was utilized. First, mp3 files for the recorded design descriptions were transcribed. Next, punctuation, stop words, and repeated words were removed. Repeated words were removed because a second instance of a word would not represent an attempt to expand the semantic space utilized by the design engineer. This approach intends to assess participants' ability to connect seemingly remote concepts and develop novel design ideas, a key element of divergent thinking (Kenett, 2018). Semantic similarity scores were calculated for each pair of words utilized in the design description. The Mean Semantic Similarity score was then calculated for each participant.

Semantic analysis was conducted in python. Scores were calculated utilizing spaCY's "en_core_web_lg" pipeline package, with vectors generated by the word2vec algorithm (Honnibal et al., 2020). The model scores the similarity between two words giving them a score on a scale of 0 to 1, in which 1 represents the maximum similarity (i.e., the same word). To further assess the cognitive effect of the biophilic restorative experience on the intervention group, the semantic similarity between each word used in the design descriptions and the word "nature" was also calculated. Table 1 shows an example of semantic similarity scores for different pairs of words.

Table 1: Examples of pairwise comparison between words extracted from design explanations in the pilot study.

Word 1	Word 2	Semantic Similarity Score
"kids"	"playground"	0.548
"kids"	"gravel"	0.142
"nature"	"park"	0.410
"nature"	"cars"	0.162

5 RESULTS

Due to the sample size (n = 12), the findings of this study should be carefully interpreted as preliminary and exploratory. The intent is to demonstrate the use of multiple measures to triangulate physiological response, neurocognition, and cognition during design and the effect of a nature-related stimulus. The results from the statistical tests are reported, but more emphasis should be placed on the mean and trends across the three measures than on the statistical test results. Differences between groups were observed in the physiological response of participants. The intervention group had a lower mean natural log (ln) (LF/HF) ratio during the design task compared to the control group, though not below a confidence interval of 0.05 (Kruskal-Wallis H-test p = 0.07). The ln(LF/HF) for each group is reported in Table 2.

Table 2. Overall mean ln(LF/HF) ratio during each step of the experiment.

Group	TSST	Restoration Break	Design Task
Intervention	0.719 ± 0.398	0.279 ± 0.151	0.180 ± 0.349
Control	0.728 ± 0.254	0.564 ± 0.391	0.831 ± 0.341

Similar differences observed in their physiological responses were also observed in patterns of brain activation between tasks. The mean concentration of oxy-Hb in the PFC for each step in the

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experiment is illustrated in Figures 3 and 4. Differences between the two groups are most prominent in the design phase of the experiment. When designing, the control group recruited more oxy-Hb than the intervention group. The rest phase also appears different. The intervention group recruited less oxy-Hb when resting and designing than the control.

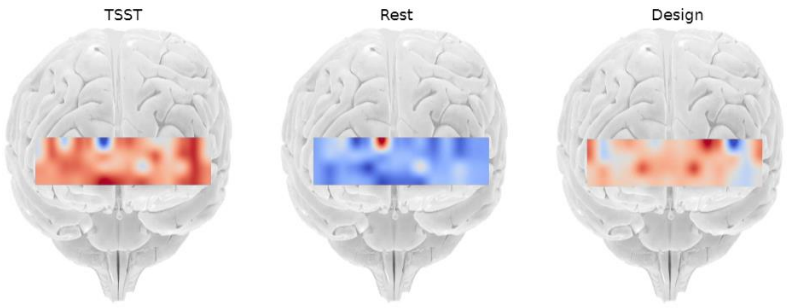

Figure 2: Brain activation during each experiment phase for the control group. Red indicates greater oxy-Hb recruitment, while blue indicates a decrease in oxy-Hb.

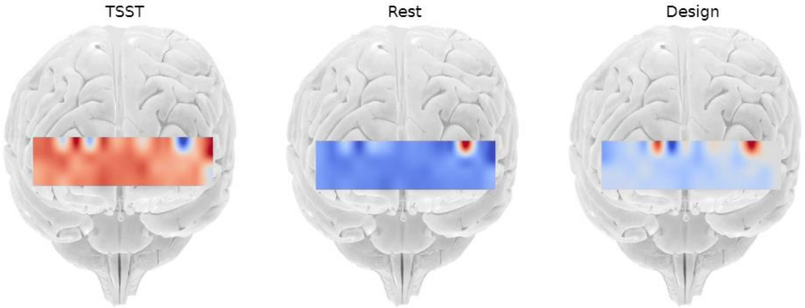

Figure 3: Brain activation during each experiment phase for the Intervention group. Red indicates greater oxy-Hb recruitment, while blue indicates a decrease in oxy-Hb.

Differences in physiological response and brain activation were not only observed between groups but also the mean semantic similarity between the words used by each participant to describe their design products. The semantic similarity of words were higher for the intervention group. The mean semantic similarity scores for the control and intervention groups were 0.290 ± 0.030 and 0.317 ± 0.014, respectively (see Figure 2 below). A Kruskal-Wallis H-test returned a p-value of 0.123, with a Cohen's d of 1.01 (large effect size). A large effect size with a non-significant p-value could be due to the small sample size. If the observed trend remained consistent with a larger sample, statistical results fall below a stated confidence interval of 0.05. For instance, duplicating the semantic similarity scores for each group so that the sample size is double produces a Kruskal-Wallis H-test p-value of 0.026.

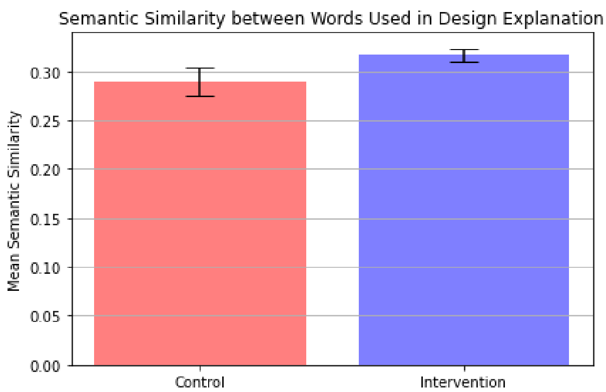

Figure 4: The control group used words that were overall less semantically similar when compared to the intervention group.

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When computing the semantic similarity between the words used to describe the design products and the word "nature," the mean semantic similarity score was higher for the intervention group (see Figure 3 below). The mean semantic similarity scores for the control and intervention groups were 0.307 ± 0.012 and 0.319 ± 0.009, respectively. These differences are illustrated in Figure 5. The results were normally distributed, so a two-tailed independent t-test returned a p-value of 0.108, with a Cohen's d of 1.03 (large effect size). Again, the sample is too small to draw statistical conclusions. Duplicating the results to increase the sample indicates what this trend means if it continues, returning a p-value < 0.05.

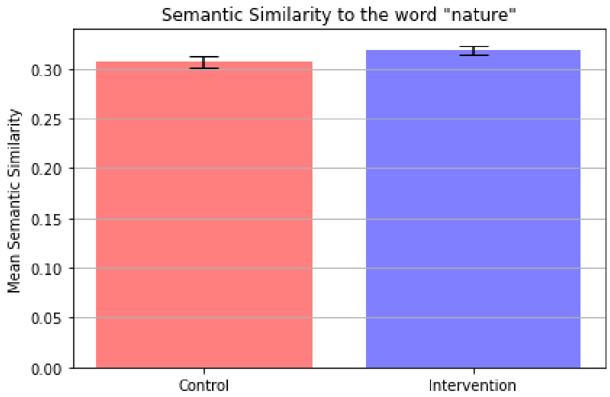

Figure 5: The intervention groups used words that were more semantically similar to the word "nature" when compared to the control group.

6 DISCUSSION

The observed effects of the auditory biophilic restorative experience on subjects' bodies, brains, and minds aligned with the findings of previous studies. Participants that listened to nature sounds had a lower LF/HF ratio during the restorative break and the design task. A lower LF/HF ratio indicates decreased sympathetic nervous system activity (Ernst, 2017; Jo et al., 2019). The intervention also influenced neurocognitive changes that correspond with the changes observed in the body. During the design task, participants that received the biophilic restorative experience recruited, on average, less oxy-Hb in their PFC to complete their design. Different studies have shown a relative improvement in performance on cognitive tests administered after exposure to biophilic restorative experiences (Atchley et al., 2012; Yin et al., 2018). While researchers have observed decreased oxy-Hb concentration in the PFC during biophilic restorative experiences (Jo et al., 2019; Song et al., 2016), observing the decreased concentration during a subsequent task brings a new perspective on the lasting effects of the restorative benefits. Coupled with the observed changes in design cognition, this finding sheds new light on the effect of biophilic restorative experiences on design.

Findings from the semantic analysis open room for discussion about how biophilic auditory experience's potentially influence design. Participants in the control group explored a wider semantic space when describing their design products, as indicated by lower mean semantic similarity scores. Scores for the semantic similarity between the design products and the word "nature" suggest that the biophilic restorative experience could have primed participants in the intervention group to integrate nature into their design products. Words used by the intervention group to explain the design products were more semantically similar to the word "nature" when compared to words used by the control group. By priming subjects to think about nature, the biophilic auditory experience might have narrowed the design space explored by the intervention group. Biophilic restorative experiences have been observed to increase feelings of connectedness with nature (Leung et al., 2022; Richardson and Butler, 2022). Changes in behavior and emotion can be a source of priming in the design process (She and MacDonald, 2013).

7 CONCLUSION

A biophilic auditory experience was observed to affect engineering students' bodies, brains, and minds. Analysis of the design descriptions showed that the intervention group explored a smaller

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design space, which contradicted expectations, but also used words semantically closer to "nature," which suggests a possible influence of the intervention on the adoption of biointegrative design practices. The restoration of cognitive resources promoted by the biophilic auditory experience could reduce the cognitive load associated with designing. A reduction in oxy-Hb was observed in the intervention group. This decrease could allow participants to sustain cognitive effort for longer, which could affect the quality of the design products (Shealy et al., 2022).

The observed changes in the dynamics between parasympathetic and sympathetic nervous systems could also be reflected in the engagement of different brain networks. Future research could apply different analysis methods of the neurocognitive data to allow for deeper insights into the neurocognitive responses to biophilic restorative experiences. Sophisticated analysis methods like functional connectivity (or brain network) analysis could help identify brain activation patterns of interest. Emerging literature suggests a coupling of the default and executive networks of the brain during creative thought, in which the default mode network (bottom-up) plays the early role of idea generation and the executive control network (top-down) plays an evaluative role in later stages (Lloyd-Cox et al., 2022). More research on the correlations between autonomic nervous system activity, brain functional connectivity, and creative cognition can help the development of new applications for biophilic restorative experiences.

The pilot study presented here is part of an ongoing research study that plans to collect data with 150 engineering students. Future plans include exploring the effects of biophilic restorative experiences that involve multisensory exposure (e.g. auditory and visual), as well as analyzing the design products for the incorporation of biophilia through the Biophilic Design Matrix (McGee and Marshall-Baker, 2015).

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