QUANTIFYING THE BENEFITS OF MULTISENSORY BIOPHILIC RESTORATIVE EXPERIENCES: AN EMPIRICAL STUDY MEASURING EFFECTS ON HOW ENGINEERS FEEL, THINK, AND DESIGN

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ABSTRACT

This dissertation investigates the effects of multisensory biophilic restorative experiences on how engineers feel, think, and design. While previous research on the restorative effects of biophilic experiences have mostly focused on the benefits of visual exposure, less is known about the potential of exposure to auditory and multisensory stimuli. Moreover, a knowledge gap exists in regards to how the cognitive benefits of biophilic restorative experiences influence performance in real-world cognitive tasks, like design. To address the identified knowledge gaps, a randomized controlled trial with 154 participants was conducted, exploring the restorative effects of biophilic auditory, visual, and multisensory (auditory + visual) experiences after induced psychosocial stress. To assess the potential influence on the performance of a real-world cognitive tasks, an open-ended design task was given to participants following the exposure period. Dependent variables tracked covered three key domains of the research question: (1) psychological and physiological responses (feel), (2) neurocognitive responses (think), and (3) design originality and incorporation of biophilia (design). Results showed that the biophilic auditory experience induced higher physiological arousal during and after exposure, while the visual and multisensory conditions presented evidence of increased neural efficiency. The biophilic conditions assisted in restoring cognitive resources and improved prefrontal cortical functional connectivity, specifically within main hubs of the Default Mode Network (DMN). However, better engagement of the DMN did not result in more original design products. No significant differences were found for exploration of the design space across conditions. Interestingly, the visual group incorporated significantly more biophilic design patterns, such as “Visual Connection with Nature” and “Presence of Water”, in their design concepts. This finding suggests a potential priming effect, where exposure to biophilic stimuli influenced designers’ choices towards more nature-connected ideas. The study here presented contributes to the understanding of biophilic restorative experiences’ nuanced effects on physiology, neurocognition, and design cognition. Accessibility and availability of the interventions tested affords readily replication of the experiment design and application of findings to the general public.

Quantifying the Benefits of Multisensory Biophilic Restorative Experiences:

An Empirical Study Measuring Effects on How Engineers Feel, Think, and Design

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GENERAL AUDIENCE ABSTRACT

This dissertation explores how exposure to simulated nature experiences through different senses affects how engineers feel, think, and design. Two main environmental psychology theories propose that nature experiences can aid in the recovery from stressful states and mental fatigue. The Kaplans' Attention Restoration Theory suggests that looking at nature can help the brain recover from overuse by allowing it to restore attentional resources. Roger Ulrich's Stress Reduction Theory proposes that nature experiences can reduce stress by calming the body and the mind. While previous studies have mainly explored the effects of exposure to nature through visual experiences, the study presented here examines the effects of exposure to nature-based sounds (birdsong and water sounds), as well as exposure to the combination of sounds and visuals (indoor plants, nature-inspired art, and daylight). Additionally, it investigates how the potential benefits to the brain and mind influence performance in real-world tasks like designing. To explore these effects, 154 engineering students were randomly assigned to different groups and exposed to nature sounds, nature visuals, or a combination of both, after being induced to a stressful state. After the exposure period, participants were given an open-ended design task. Throughout the experiment, participants' bodily responses were tracked by a wrist-worn device and participants' brain activity was tracked by a brain-imaging headset. Design concepts produced in the design task were assessed for originality and for the incorporation of nature-inspired ideas. Results showed that listening to nature sounds increased arousal of the body both during and after the exposure period. Visual, as well as combined auditory and visual exposure improved brain efficiency. All nature experiences helped restore mental resources and improved brain connectivity, particularly in areas associated with mind wandering. Although better brain connectivity did not result in more original design concepts, interestingly, participants in the visual exposure group incorporated more nature-related features, like bodies of water and natural views, into their designs. This finding suggests that seeing nature might inspire more nature-connected design ideas. This study enhances our understanding of how nature experiences affect the body, brain, and mind. The interventions tested can be easily replicated and applied in everyday settings so that anyone can benefit off of their outcomes.

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ABBREVIATIONS

DSB – Digit Span Backwards

RAT – Remote Associates Task

EPA – Environmental Protection Agency

ART – Attention Restoration Theory

HRV – Heart Rate Variability

EDA – Electrodermal Activity

SRT – Stress Reduction Theory

ANS – Autonomic Nervous System

PNS – Parasympathetic Nervous System

SNS – Sympathetic Nervous System

EEG – Electroencephalogram

fNIRS – Functional Near-Infrared Spectroscopy

Oxy-Hb – Oxygenated Hemoglobin

Deoxy-Hb – Deoxygenated Hemoglobin

PFC – Prefrontal Cortex

PEB – Pro-Environmental Behavior

ECN – Executive Control Network

DMN – Default Mode Network

TSST – Trier Social Stress Test

NR-6 – Short-form Nature Relatedness Scale

VR – Virtual Reality

SCL – Skin Conductance Level

IEQ – Indoor Environmental Quality

IRB – Institutional Review Board

GSR – Galvanic Skin Response

SCR – Skin Conductance Response

PPG – Photoplethysmography

BOLD – Blood Oxygenation Level-Dependent

VCSEL – Vertical-Cavity Surface-Emitting Laser

MBLL – Modified Beer–Lambert Law

DOT – Diffuse Optical Tomography

PANAS – Positive Affect Negative Affect Scale

NDIR – Non-Dispersive Infrared

ppm – parts per million

CDA – Continuous Decomposition Analysis

NN – Normal to Normal

HF – High Frequency

LF – Low Frequency

VLF – Very-Low Frequency

HF.nu – Normalized values for HF

LF.nu – Normalized values for LF

LF/HF – Low Frequency to High Frequency ratio

HR – Heart Rate

SDNN – Standard Deviation of all NN intervals

RMSSD – Root Mean Square of Successive Differences between normal heartbeats

IQR – Interquartile Range

ANOVA – Analysis of Variance

TDDR – Temporal Derivative Distribution Repair

FIR – Finite Impulse Response

ROI – Region of Interest

DMPFC – Dorsomedial Prefrontal Cortex

DLPFC – Dorsolateral Prefrontal Cortex

VLPFC – Ventrolateral Prefrontal Cortex

OFC – Orbitofrontal Cortex

M – Mean

SD – Standard Deviation

NEH – Neural Efficiency Hypothesis

DSI – Divergent Semantic Integration

BDM – Biophilic Design Matrix

HPA - Hypothalamus-pituitary-adrenal

Chapter 1 – Introduction:

The American population spends about 87% of their days indoors (Klepeis et al., 2001). During the Covid-19 pandemic, quarantining and social distancing measures further increased the time spent in indoor spaces (Leon et al., 2020), which negatively affected people's mental health (Xiao et al., 2022). Having evolved in a sensory rich world, the human body is sensitive to and constantly responds to environmental stimuli. Overexposure to non-natural visual and sound stimuli, which are common in the built environment, creates stress on the bodies and minds of urban dwellers (Söderlund et al., 2015). Stress induced by sensory overload in the built environment affects building occupants' capacity to perform their best at work, given that stressful states disrupt human cognitive abilities, especially the capacity to focus (Berto, 2014; Yin et al., 2019).

One solution for this problem is reconnection with nature. Exposure to "natural environments protect people against the impact of environmental stressors and offer physiological, emotional, and attention restoration" (Berto, 2014). Also, nature exposure correlates with psychological well-being and improvements in mental health (Bratman et al., 2019). The benefits of nature immersion can be linked to the concept of biophilia: "the inherent human affinity to affiliate with natural systems and processes" (Kellert & Wilson, 1993). People who spend most of their days in the office, school, or even at home cannot regularly enjoy the benefits of immersing themselves in nature. Some believe that if not nurtured, the human biophilic tendency can become dormant (Kellert et al., 2011). Bringing nature indoors could be one way to recreate this connection.

Replicating such a complex and rich experience as nature in the built environment is a challenge. *Biophilic design* focuses on "the necessity of maintaining, enhancing, and restoring the beneficial experience of nature in the built environment" (Kellert et al., 2011). Two frameworks help operationalize biophilic design. Stephen Kellert, a leader in the biophilic design movement, has built a framework splitting biophilic design into two basic dimensions: organic and place-based, followed by six different elements: environmental features, natural shapes and forms, natural patterns and processes, light and space, place-based relationship, and evolved human-nature relationships (Kellert et al., 2011). These six elements are then broken down into more than 70 different attributes. Another framework is Browning et al.'s (2014) "14 Patterns of Biophilic Design". In this framework, biophilic design was broken down into three categories and 14 different patterns. The 14 different patterns include nature in the space (visual connection with nature, non-visual connection with nature, non-rhythmic sensory stimuli, thermal & airflow variability, presence of water, dynamic & diffuse light, connection with natural systems), natural analogues (biomorphic forms & patterns, material connection with nature, complexity & order) and nature of the space (prospect, refuge, mystery, risk/peril). While plenty of empirical evidence confirms how beneficial it is for humans to spend time outdoors connecting with nature, less "is known about possible health and wellbeing benefits of encountering nature indoors" (Yin et al., 2019). Many of the possible effects of biophilic design have not yet been adequately explored or even found.

I performed a systematic literature review, which revealed 1053 publications on biophilic interventions, yet only 90 explored the effects of said interventions on cognition. Less than one percent of those papers mentioned creativity, divergent thinking, or design cognition. Many studies have oversimplified cognitive performance by reducing it to attentional or focusing capacities (Berman et al., 2008; Bratman et al., 2012). For example, testing the effects of symbolic exposure to nature, Yin et al. (2018) observed that after 5-min period of exposure to a biophilic indoor environment, participants scored 14% higher in the Digit Span Backwards (DSB) test (Ramsay & Reynolds, 1995). The DSB test has been used to assess cognitive performance in other similar studies (Berman et al., 2008, 2012), nonetheless it is limited to the assessment of short-term working memory, neglecting other, more complex cognitive capacities. Atchley et al. (2012) used the Remote Associates Task (RAT) to test the effects of exposure to nature on convergent creative cognition. Results showed that performance on the RAT increased by 50% after a hike. While Atchley et al.'s (2012) study explored a different type of cognitive capacity, by utilizing a standardized cognitive test it still neglects to consider how the cognitive benefits derived from nature exposure can be translated to real-world scenarios.

The aim of the proposed research was to understand the applicability of the possible gains in cognitive performance to specific job tasks. Biophilic design can be used to improve human cognitive performance (C. Song et al., 2021; Yin et al., 2018a, 2019). However, further exploration is needed to understand how biophilic interventions can enhance performance in particular job types.

1.1 The Biophilia Hypothesis

1.1.1 The human need for nature

Urbanization is a relatively recent phenomenon in the timeline of the human species (Osaki et al., 2011; C. Song et al., 2016). The rural exodus has accelerated the disconnection between humans and nature. For example, a 2001 survey sponsored by the Environmental Protection Agency (EPA) found that Americans spend around 93% of their lives indoors (87% in buildings and 6% in vehicles) (Klepeis et al., 2001). More recently, a 2012 study about the app Mappiness, which randomly, twice a day, asks users to report how happy they are, and links their responses to their GPS location, also found users spent approximately 93% of their time indoors (MacKerron & Mourato, 2013). Even when controlling for factors such as relationships, physical activities, and financial situation, MacKerron & Mourato (2013) found that people report being significantly happier outdoors. An explanation for this finding could be biophilia. In the book *The Biophilia Hypothesis*, Edward O. Wilson and Stephen R. Kellert introduce the idea that humans have an innate connection with and love for nature (Kellert & Wilson, 1993). Many cultures and people recognize this connection and the need for it. For example, in the Japanese culture, biophilia is enjoyed through *shinrin-yoku*, or “forest bathing.” Forest bathing is found to help people recover from stressful states (Osaki et al., 2011; Song et al., 2016; Ulrich et al., 1991), increase cognitive performance (Atchley et al., 2012b; Berman et al., 2008), and even enhance the immune system (Lee et al., 2012; Li et al., 2009; Li, 2010). Given the array of benefits that can be reaped from being outdoors and the human “biophilic” tendencies, why are humans becoming more and more distant from nature?

1.1.2 Human disconnection from nature

Some researchers believe that the human species has adapted, and continues to evolve to cities being their “natural” habitat, becoming what Jason Vargo (2014) coined as *“Metro sapiens.”* Others are worried about the possible physical and psychological costs of the human disentanglement with nature (Kahn et al., 2009). Increasing urbanization correlates with a decrease in outings for immersive experiences with nature (Bratman et al., 2015; Maller et al., 2006). Anxiety, depression, and mood disorders are more prevalent among urban dwellers (Lederbogen et al., 2011; Marques & Lima, 2011). Looking at the possible physiological effects, stroke, respiratory, circulatory, and cardiovascular-related mortality is higher in communities without access to green spaces (Africa et al., 2014). Accessibility to green spaces is an essential factor, and the numbers for the U.S. are alarming. According to the Trust for Public Land, the national nonprofit behind the ParkScore® index, more than 100 million Americans do not have access to a park within a 10-minute walk from their homes.

The lack of access to positive experiences with nature can eliminate the opportunity for urban dwellers to restore depleted cognitive, physiological, and psychological resources (Kellert et al., 2011; Saegert & Winkel, 1990). The theoretical premise behind the need for restoration concerns the consumption of resources by the need to adapt to environmental demands. The demands of daily life, whether it be working, studying, or even maintaining social interactions, consume “physiological, psychological, material, and social resources” (Kellert et al., 2011). While cities grow and access to nearby nature become scarcer, designers are trying to bring nature indoors.

1.1.3 Biophilic design

Stephen Kellert presents a new approach to the design of the built environment tailored to combine low environmental impact with the facilitation of human-nature connection (Kellert, 2005). This approach is called *restorative environmental design*, which “focuses on avoiding excessively consuming energy, resources, and materials; generating massive amounts of waste and pollutants; and separating and alienating people from the natural world” (Kellert, 2005). Kellert argues that the sustainable, or “green,” design movement had focused for too long on mitigating the negative impacts of human activity on the natural environment and neglected the opportunities for fostering positive human-nature interaction within the built environment. The process of crafting these positive interactions, which rely on humans’ tendency to value nature and non-human life (biophilia), is biophilic design. The Attention Restoration Theory (ART) (S. Kaplan, 1995) posits that positive experiences of nature in the built environment can promote the restoration of depleted cognitive, physiological, and psychological resources (Kellert et al., 2011; Saegert & Winkel, 1990). Thus, “biophilic restorative experiences” enhance opportunities for restoration through exposure to nature-based stimuli. Researchers have explored the use of direct (Q. Li, 2010; Shin et al., 2011; C. Song et al., 2016), indirect (Soga et al., 2017; Van Den Berg &

Custers, 2011), and symbolic (Annerstedt et al., 2013; Aristizabal et al., 2021; Deng et al., 2020; C. Song et al., 2021) contact with nature in buildings as interventions for restorative purposes.

When evaluating the potential effects of exposure to controlled environmental conditions on humans, a definition of which of the five senses are being engaged is needed. Given sight's direct influence on how humans experience the world, due to the connection between the brain and the eyes, most studies exploring the benefits of biophilic restorative experiences have focused primarily on visual exposure (Aristizabal et al., 2021; Ayuso Sanchez et al., 2018; Yin et al., 2018a, 2019). While visual exposure to nature, whether it be through a window (Ulrich, 1984) or a virtual representation on a screen (Ulrich et al., 1991; Yin et al., 2019), can lead to some benefits, crafting multisensory biophilic experiences within the built environment should be a more reliable way to replicate the benefits derived from "forest bathing", when all the five senses are engaged in direct contact with nature.

The power of olfactory stimuli (smell) has been well documented by studies on the influence of environmental factors on humans (Ikei et al., 2015, 2016; Joung et al., 2014; Q. Li et al., 2009). The human olfactory system is believed to be able to recognize more than one trillion different stimuli, outperforming all of the other senses (Bushdid et al., 2014). Given the olfactory system's role in regulating physiological and emotional responses and social behaviors, smells can directly affect humans (Lledo et al., 2005). For example, in a study assessing the effects of exposure to lavender and rosemary scents, subjects' salivary cortisol levels significantly dropped, a proxy for stress reduction (Atsumi & Tonosaki, 2007). Another study highlighted the potential of aromatherapy in helping people with anxiety symptoms (Lee et al., 2011). In laboratory studies exploring the effects of exposure to the scent of essential oils extracted from cypress trees, Ikei et al. (2015) observed significant physiological and neurocognitive responses on participants. When exploring a combination of olfactory and visual stimuli, Song et al. (2019) found that activity in the brain was significantly lowered after participants looked at images of cypress trees and smelled cypress leaf essential oils.

The benefits of biophilic auditory experiences have been less explored than olfactory or visual experiences (C. Song et al., 2019). Studies on urban noise pollution indicate it is harmful to human health, increasing risks of cardiovascular issues (Evans et al., 1998; Griefahn et al., 2008; Kaltenbach et al., 2008), hearing impairments, sleep deprivation, and even productivity and social behavior changes (Berglund & Lindvall, 1995). Less is known about the possible benefits of natural "noises". However, the few studies on the restorative effects of biophilic auditory experiences have found promising results. In a study that compared the effects of four different 90-second interventions (no stimulation, visual stimulation, auditory stimulation, and combined stimulation) on participants' brains and autonomic nervous system, Song et al. (2021) found that the auditory stimulus led to a significant decrease in activity in participants' prefrontal cortex. Furthermore, participants that received the combined stimulation intervention had an even more significant decrease when compared to the control group. In the only other known study that investigated the effect of a combined auditory and visual biophilic experience, results were consistent with what Song et al. found. Aristizabal et al. (2021) found that a multisensory intervention could reduce participants' stress levels and improve participants' cognitive performance. Nonetheless, while stress levels were assessed both objectively and subjectively, cognitive performance was still only assessed by standardized cognitive tests (working memory, response inhibition, and task switching), leaving room for further exploration.

1.2 Quantifying cognitive performance and wellness

Much of what is known about the positive effects of nature exposure on human performance and well-being comes from studies that rely on subjective measures like perceived happiness and perceived stress levels (MacKerron & Mourato, 2013). More and more studies have been tracking human physiological and neurophysiological changes to objectively quantify the restorative effects of nature exposure. Salivary cortisol, blood pressure, heart rate variability (HRV), electrodermal activity (EDA), and brain activity are some of the most common biological markers used in the literature (Aristizabal et al., 2021; Igarashi et al., 2014; Park et al., 2007; C. Song et al., 2021; Yin et al., 2019). These markers depict a more complete picture of how one's body reacts to environmental stimuli. The main driver behind many of these physiological reactions is the autonomic nervous system (ANS). The ANS controls the body's involuntary responses to outside stimulus, and is divided into two parts: the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS) (Ernst, 2017). The SNS and the PNS play a balancing act in which the SNS overrules when a stressful event triggers the body's fight-or-flight mode (Rajendra Acharya et al., 2006). With the SNS in control, heart rate increases, HRV decreases, and EDA is present (Aristizabal et al., 2021; Parsons et al., 1998; Schubert et al., 2009). Nature exposure can help regulate the balance in the ANS (Ulrich et al., 1991). According to the Stress Reduction Theory (SRT), exposure to nature has a role in increasing PNS activity, promoting the restoration of physical and psychological resources, and switching the body to rest-and-digest mode (Parsons et al., 1998; Ulrich et al., 1991).

Regarding the restoration of cognitive resources, the ART, introduced by Kaplan and Kaplan (1989), links nature exposure to changes in brain activity. The ART splits human attention into two types: involuntary and directed. Involuntary attention requires little to no cognitive effort. Directed attention can cause a significant cognitive load (S. Kaplan, 1995). The benefits to cognition due to immersion 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 for processing different stimuli, leading to a state of mental tiredness (Plambech & Konijnendijk van den Bosch, 2015). Many studies have used simple cognitive tests of attention and memory to validate the ART (Berman et al., 2008; Bratman et al., 2012). More recently, this theory has received new support with the development of brain imaging technologies. Techniques like electroencephalogram (EEG) and functional near-infrared spectroscopy (fNIRS) are used to objectively quantify the changes to the brain 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 blood (Oxy-Hb) recruitment in the prefrontal cortex (PFC) (Lee et al., 2012; Park et al., 2007; Song et al., 2021). Biophilic restorative experiences can affect human cognition. What remains unanswered is how this improvement in cognitive performance eventually translates into workers' or students' performance in their daily tasks.

1.3 The connection between cognitive performance and divergent thinking

Co-founder of the *Biomimicry Institute*, Janine Benyus, believes that immersion in different environments can alter how designers think and what ideas they come up with (Kellert et al., 2011). Some evidence can back up this belief. In a research study, a class of senior civil engineering students was separated into two groups and asked to work on a request for a proposal to design a new academic building. Students from each group gathered to work on their projects in different buildings. Students in the group working within a newer, more sustainable building (LEED Gold) were significantly more prone to include sustainability goals in their design than those working within a much older, non-LEED-certified building (Shealy, 2016). A meta-analysis by Whitburn et al. (2020) confirmed that greater feelings of connectedness with nature are positively associated with pro-environmental behavior (PEB), independent of age, gender, or location. Connectedness with nature has also been positively correlated with motivation for future nature engagement (Leung et al., 2022; Nisbet et al., 2009). Testing interventions that push engineers towards pro-environmental design can lay the ground for a more sustainable built environment.

To increase the applicability of biophilic design benefits, researchers should not limit the assessment of cognitive performance to attention or memory tests. New studies should not assess how the intervention affects what subjects can remember, but what they can create. I proposed to add more complexity to biophilic design research by using a more realistic task to assess cognitive performance. In two studies exploring the effects of short-term auditory and multisensory (auditory + visual) biophilic restorative experiences, an open-ended design task was used to evaluate the impact of the interventions on participants' cognitive performance. By giving participants a chance to work on a real-world scenario problem, the task created an opportunity for the assessment of changes in how participants think and what ideas they come up with. The contribution to knowledge sought here is the exploration of the benefits of biophilic restorative experiences to specific job types that demand a more abstract type of cognitive performance.

1.4 Gaps in Knowledge

A systematic literature review conducted in the Academic Search Complete database from EBSCOhost about studies on the effects of biophilic interventions showed that few publications touch on potential cognitive effects. Only nine percent of all peer-reviewed publications that mention "biophilic design" or biophilia in their abstract also mention effects on cognition throughout the paper. From this nine percent (90 papers), only eight touch on the possible effects of exposure to biophilic restorative experiences on creativity and the ability to think divergently. Another gap was found when looking for studies investigating the effects of multisensory biophilic interventions. Only 10 out of 1053 publications on biophilic interventions made any mention of “multisensory” or “combined stimuli” experiences. Filling this gap is essential given that multisensory interventions are a better representation of nature immersion and have the potential for the most impact (Aristizabal et al., 2021; C. Song et al., 2021).

When sharing recommendations for future work, some prior researchers have highlighted the significance of more studies investigating the effects of biophilic restorative experiences on particular sample groups selected by occupation (Aristizabal et al., 2021; Hartig, 2021). While Cordoza et al. (2018) have conducted studies on nurses and Gulwadi (2006) on elementary school teachers, none have used engineers as their target sample. Engineering students should be an appropriate sample population for a couple of reasons. Deng et al. (2020) reported that academic majors play a significant role in personal restorative experiences. By sampling a somewhat homogenous group (i.e., engineering students), the confounding potential of subjects’ educational background is reduced, and an opportunity for new insights on the correlations between the benefits of biophilic restorative experiences and specific job types is created.

1.5 Research Question and Hypotheses

To address the gaps in knowledge identified in the literature, this dissertation aims to answer the question: *what are the effects of biophilic restorative experiences on how engineers **feel**, **think**, and **design**?* This research question aims at three different levels of influence by which environmental conditions can affect humans.

At the first level, questioning the effects on how engineers ***feel*** involves the exploration of physiological and psychological changes due to external stimuli.

Hypothesis 1 (*H1)*: Biophilic restorative experiences will help participants feel less stressed. According to the Ulrich et al.'s (1991) SRT, positive interactions with nature-based stimuli should lead to an increase in PNS activity, helping switch the subjects’ bodies from a fight-or-flight mode to a restful state. Changes in subjects’ “in the moment” feelings of stress should be correlated with changes in ANS activity.

To capture the effects on how engineers ***think***, the second level involves the investigation of cognitive and neurocognitive responses to the intervention.

Hypothesis 2 (*H2)*: Biophilic restorative experiences will decrease the mental demand associated with designing. As the ART proposes, positive direct, indirect, or symbolic contact with nature should restore cognitive resources (S. Kaplan, 1995). By allowing subjects to rest their directed attention, and restoring resources in the executive control network (ECN) of the brain, the intervention could help participants sustain cognitive effort for longer (Beaty et al., 2015; Chen et al., 2010; L. N. Vieira, 2016; Williams et al., 2018). Furthermore, a decrease in ECN activity could be coupled with increased activity in the brain's default mode network (DMN).

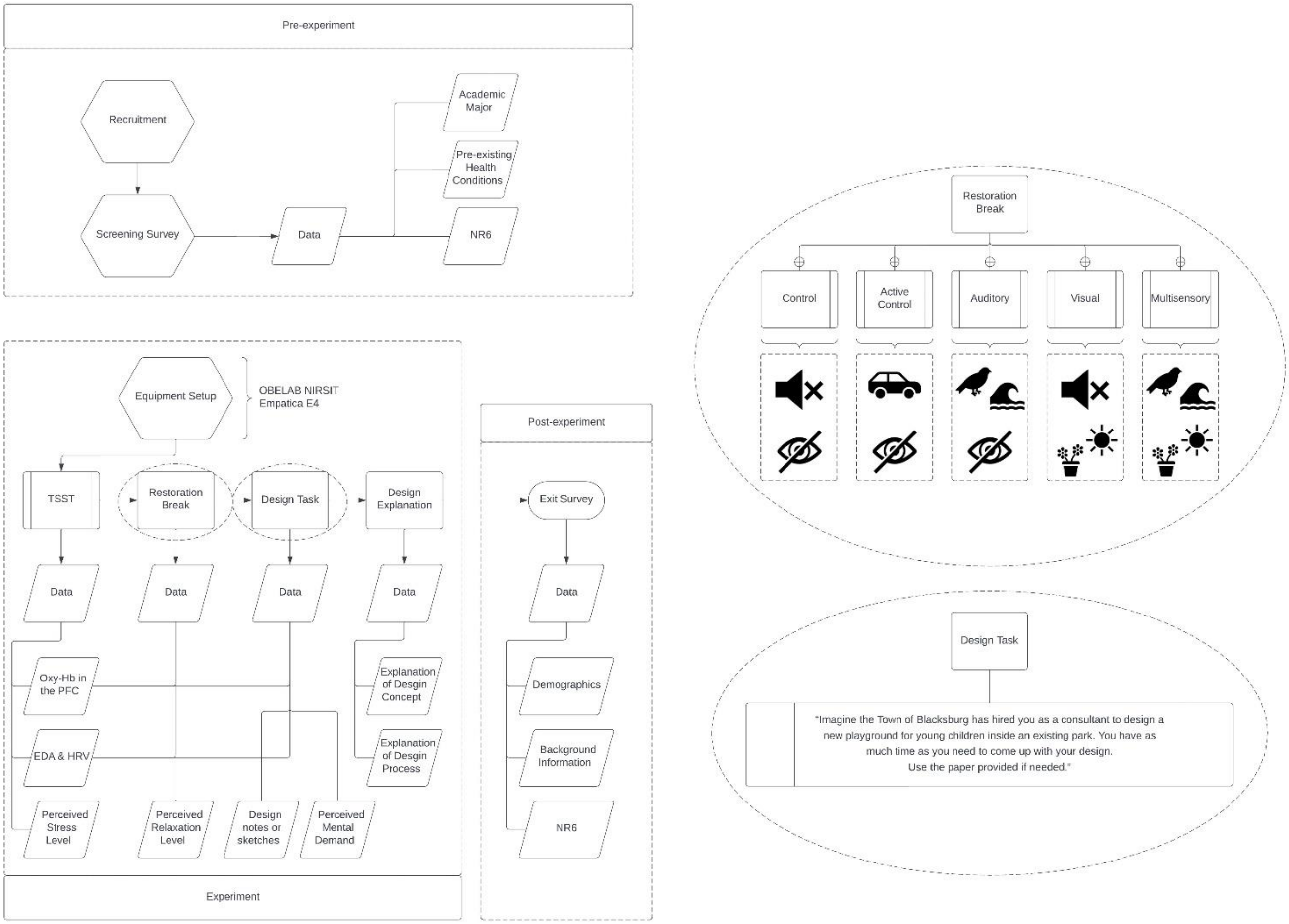
Lastly, when asking how the intervention can affect how engineers ***design***, the third level of influence concerns changes in design cognition and decision-making.

Hypothesis 3 (*H3*): Biophilic restorative experiences will lead to the production of more original design concepts. According to the associative theory of creativity, activation of the DMN of the brain should facilitate the ability to think laterally and visualize connections between seemingly remote concepts, which is essential for the generation of original, unique ideas (Beaty et al., 2014; Lloyd-Cox et al., 2022; Williams et al., 2018). Also, a positive correlation exists between time spent on idea generation and originality (Baas et al., 2008; Barr et al., 2015; Christensen et al., 1957; Getzels & Csikszentmihalyi, 1976; Studente et al., 2016). The restoration of cognitive resources promoted by the positive experiences of nature should allow subjects to sustain cognitive effort for longer periods of time, which could be associated with an increase in creative performance.

Hypothesis 4 (*H4*): Biophilic restorative experiences will prime engineers to incorporate biophilia into design concepts. Biophilic restorative experiences, both through direct and indirect contact with nature, have been observed to increase feelings of connectedness with nature (Leung et al., 2022; Richardson & Butler, 2022; Whitburn et al., 2020). Connection to nature has been observed to increase even after short-term exposure to nature-based stimuli (Mayer et al., 2009). Acting as a priming intervention, biophilic restorative experiences could also affect designers' behavior (Bargh et al., 1996a; Hu & Shealy, 2022). Changes in behavior could be reflected in design choices. The "incorporation of newly acquired information and new experiences can be a source of priming in the design process" (She & MacDonald, 2013). Previous knowledge about biophilic design is not necessary since this approach to design, which "occurred as a natural extension of the neurological processes that make us alive and human," has existed long before it was coined as biophilic design and operationalized by a list of attributes, elements or patterns (Salingaros & Masden, 2011).

1.6 Addressing the Research Question

To address the research question "*what are the effects of biophilic restorative experiences on how engineers **feel**, **think**, and **design**?"*, I designed a randomized controlled trial composed of three main steps: (1) a stress induction test, (2) a restoration break, and (3) an open-ended design task. An overview of the experiment design is shown below in Figure 1.1. More details on the different conditions tested during the restoration break, as well as on data analysis methods are introduced in the following chapters.



"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."

Figure 1.1. Overview of the experiment design.

The main body of this dissertation is divided into three chapters (chapters 2, 3, and 4), which each present a proposed journal paper and attempts to answer part of the main research question. Chapter 2 is formatted for submission to the Journal of Environmental Psychology. Chapters 3 and 4 are formatted for submission to the Nature Human Behavior journal. A breakdown of the dissertation framework is given on Table 1.1.

Table 1.1 Dissertation framework

Proposed Journal Papers	Aims	Research Questions
Exploring the effects of a biophilic auditory experience on the restoration of neurocognitive and physiological resources post induced psychological stress	Explore the restorative effects of a biophilic auditory experience on the body and the brain	What are the effects of a biophilic auditory experience on the ANS and the PFC post induced psychological stress?
Effects of nature-based auditory stimuli on the mind and brain when designing	Explore the effects of biophilic auditory experience on design	What are the effects of a biophilic auditory experience on design cognition and neurocognition post induced psychological stress?
Effects of multisensory biophilic restorative experiences on how engineers feel, think, and design	Compare the effects of auditory, visual and multisensory biophilic experiences	

Chapter 2 - Exploring the effects of a biophilic auditory experience on the restoration of neurocognitive and physiological resources post induced psychological stress

Key words: Biophilia, Biophilic Design, Indoor environment, Stress Recovery, Neurocognition, Cognitive Resources, Physiological Resources, Attention Restoration Theory, Neuroimaging

Abstract

Modern urban life generates stress, but the therapeutic potential of biophilic experiences—particularly auditory stimuli—holds promise in facilitating stress recovery and cognitive restoration. This study investigates the effects of biophilic auditory experiences on the restoration of two critical physiological and cognitive domains post induced psychological stress: the autonomic nervous system (ANS) and the prefrontal cortex (PFC). We hypothesize that listening to birdsong and water sounds leads to greater restoration of neurocognitive and physiological resources spent in a stressful event. To test this hypothesis, a sample of 96 graduate and undergraduate students was randomly split into three cohorts. After going through the Trier Social Stress Test (TSST), each cohort was given one out of three different auditory experiences: urban noises, silence, or nature sounds. After the restoration period, participants were given a design task. Electrodermal activity (EDA), heart rate variability (HRV), and changes in oxygenated blood flow in the prefrontal cortex (PFC) were measured throughout the whole experiment by wearable biomonitoring and neuroimaging devices. Participants' baseline connectedness to nature (CN) was measured by the short version of the Nature Relatedness Scale (NR-6). Our results show that participants in the nature condition had higher physiological arousal during the restoration period, contrary to expectations. Nonetheless, participants who received the biophilic auditory experience reported feeling significantly more relaxed than participants in the urban condition. Furthermore, during the restoration, the biophilic group recruited significantly less resources to a region of the PFC responsible for inhibitory control and cognitive flexibility. This study provides evidence that biophilic auditory experience significantly affect the consumption and restoration of neurocognitive and physiological resources, expanding the relatively small body of knowledge on the topic.

2.1 Introduction

2.1.1 The depletion of neurocognitive, physiological, and psychological resources throughout the work day.

Modern life imposes many demands upon human beings, which end up living in an almost constant stressful state (Luo & Jiang, 2022). From the moment one wakes up to the time they fall asleep, modern humans are being exposed to, and consequently reacting and adapting to, a plethora of environmental stimuli. Whether it be working, studying, or even just maintaining social interactions, humans spend their limited cognitive, physiological, and psychological resources when responding to the various stimuli (Gaekwad et al., 2023; Goldstein, 2013; Kellert et al., 2011; McSweeney et al., 2021; Schnell et al., 2013).

Physiological responses to external stimuli impact the human body's homeostasis, the balancing act between the two components of the autonomic nervous system (ANS): sympathetic and parasympathetic nervous systems (SNS and PNS). Environmental factors that are perceived as a threat trigger a 'fight-or-flight' response, which indicates an override by the SNS and is characterized by, among other factors, the release of the neurotransmitter epinephrine (also known as adrenaline), a modulator of behavioral and physiological changes (Wong et al., 2012). As the body is prepared to flee or confront the perceived threat, physiological resources are spent in increasing alertness and preparedness (Calvo & Gutiérrez-García, 2016). For instance, increases in heart beat frequency and respiration rate help increase the availability of oxygen for muscles and brain (Ernst, 2017; Gaekwad et al., 2023; McCarty, 2016; Thayer et al., 2012). In order to avoid the engagement of the expensive physiological changes associated with the "fight or flight" response when exposed to common modern life stressors, the human brain is able to develop mechanisms to cognitively and emotionally appraise situations before responding to them (Dantzer, 2016). Nevertheless, this process still depletes one from precious resources.

Under stress, cognitive abilities regulated by the prefrontal cortex (PFC), such as working memory and attention regulation, are impaired (Arnsten, 2009). Furthermore, when performing its role in evaluating environmental cues and inhibiting "fear" responses, the PFC inevitably consumes limited cognitive resources (Thayer et al., 2012). The idea that cognitive resources are limited and can be depleted is first introduced by Kahneman (1973), and then further elaborated by Wickens' (1980) Multiple Resource Theory. While Kahneman's theory draws a parallel between attention and mental effort, arguing that attention is limited, the Multiple Resource Theory asserts that only a finite set of cognitive resources is available to be spent in different mental processes, and that cognitive performance may be impaired when too many resources are disbursed (Basil, 2012; Shealy et al., 2023). During the work day, knowledge workers are required to perform tasks that at times demand the simultaneous engagement of different cognitive capacities. Designers, for example, when tackling ill-defined design problems, need not only to come up with creative ideas, but also frame and reframe the design problem as the context changes and the problem-solution space evolves (Gero, 1990; Gero & Milovanovic, 2023; Simon, 1969), increasing the cognitive demand associated with the task (Alexiou et al., 2009). The combination of effort exerted on a demanding task and the inhibition of triggering external stimuli ultimately leads to a depletion of cognitive resources. Fortunately, in the right circumstances, the human body and brain are able to enjoy the restoration of depleted resources.

2.1.2 The restorative effects of biophilic experiences.

Positive experiences of nature, or biophilic experiences, can assist with the restoration of depleted cognitive and physiological resources. The restorative effects of biophilic experiences are explained by two leading theories in the environmental psychology literature. Roger Ulrich's seminal work on the restorative potential of natural environments led to the development of the Stress Reduction Theory (SRT). The SRT argues that due to evolutionary biological adaptations, exposure to natural environments following a stressor can promote psychophysiological restoration. A combination of bodily responses derived from an initial positive affective response to the natural stimuli should lead to a reduction in psychological stress, by suppressing negative emotions, and a reduction in the mobilization of physiological resources, by engaging the PNS (Ulrich, 1981; Ulrich et al., 1991). While the SRT focuses mainly on psychophysiological effects, another leading theory explores the restorative potential of biophilic experiences to cognition. The Kaplans' Attention Restoration Theory (ART) defends that one's ability to sustain directed attention - a cognitive capacity that requires effort (Kahneman, 1973) and is susceptible to fatigue - can be restored by immersion in natural settings (Kaplan & Kaplan, 1989; Kaplan, 1995). According to the ART, four different characteristics of natural settings qualify them as restorative environments: eliciting *soft fascination*, affording the feeling of *being away*, having enough *extent* to create an immersive experience, and presenting *compatibility* to one's search for restoration (Kaplan, 1995; Stevenson et al., 2018).

Numerous studies have tested the ART and the SRT. For instance, in a series of studies in Japan, researchers assessed volunteers' physiological responses to *shinrin-yoku*, the practice of nature therapy also known as forest bathing (Miyazaki et al., 2011). When compared to a group that walked in an urban area, volunteers in the forest setting had significantly lower salivary cortisol levels, heart rate, and systolic blood pressure (Park et al., 2011). In addition, HRV analysis showed that the forest group presented greater PNS activity, and lower SNS activity when compared to the city group (Park et al., 2011). Effects to cognition have also been explored. Berman et al. (2008) explored how nature walks could differentially affect cognitive performance when compared to walks in an urban setting. Participants performed the backwards digit-span task, a task that relies heavily on directed-attention, before and after a walk through a park or through a downtown area. Participants that walked in nature performed significantly better on their second time taking the backwards digit-span task, unlike participants who ventured in the city. In an attempt to quantify the restorative effects of nature exposure in an objective fashion, Song et al. (2020) measured changes in oxy-hemoglobin (Oxy-Hb) concentration in the PFC, a proxy for the recruitment of resources, in subjects that sat either in a forest or a city area. When compared to participants that watched the urban area, participants that had a view of the forest had lower concentrations of Oxy-Hb in the left PFC and significantly lower concentrations of Oxy-Hb in the right PFC. Still, knowing of the restorative potential of immersion in nature does not guarantee that one can enjoy it. With access to nature becoming more and more scarce, how can modern humans restore the cognitive and physiological resources that are depleted on a daily basis?

2.1.3 Accessibility to biophilic experiences.

The rapid urbanization of the world has accelerated the disconnection between humans and nature by limiting access to biophilic experiences. The share of the world's population living in urban areas surpassed 50% in 2007 and is expected to reach 68% by 2050 (United Nations, Department of Economic and Social Affairs, 2019). Increasing urbanization correlates with a decrease in outings for immersive experiences with nature (Bratman et al., 2015; Maller et al., 2006), whereas anxiety, depression, and mood disorders are more prevalent among urban dwellers (Lederbogen et al., 2011; Marques & Lima, 2011). Humans have no "biologically prepared readiness" to enjoy restoration within the built environment (Ulrich et al., 1991). As cognitive and psychophysiological resources are mobilized and spent in an attempt to adapt to the excessive sensory stimulation present in the city, urban dwellers end up living in a constant state of mental fatigue and stress (Hedblom et al., 2019; Stevenson et al., 2018; Thayer et al., 2012). With this issue in mind, researchers have put an emphasis in exploring the restorative potential of symbolic contact with nature.

Looking at pictures, watching videos, and, more recently, wearing virtual reality (VR) headsets are the common methods used by researchers to simulate nature experience. In 1981, Roger Ulrich observed that when shown pictures of natural landscapes, especially those that contained water, study participants enjoyed greater psychophysiological effects, as well as increased attention and interest, when compared to when shown pictures of urban environments (Ulrich, 1981). While seeing nature through a screen can replicate some of the restorative potential, it cannot replicate the immersion of a full-sensory experience. In a series of three experiments, Mayer et al. (2009) compared the psychological effects of a walk through an arboretum versus a video replicating the same path and duration of the walk. Although watching the video led to some positive effects, the group that experienced real nature reaped greater psychological benefits. Immersion matters, and VR presents itself as the solution for simulated immersion. Studies investigating the effects of biophilic experiences in VR have observed decreases in blood pressure, greater physiological arousal recovery, improvements to short-term memory, and higher creativity scores when comparing exposure to biophilic versus non-biophilic virtual environments (Yin et al., 2018, 2019, 2020). However, the emphasis on visual exposure has neglected the potential of other sensory experiences.

2.1.4 Knowledge gaps in the literature and the current study.

Few studies have investigated the use of biophilic auditory experiences, albeit their underlying restorative potential. When Ratcliffe et al. (2013) interviewed 20 adults in South East England and prompted them to think about places where they could enjoy restoration in a scenario of mental fatigue or stress, interviewees mentioned natural sounds 186 times, with birdsong accounting for 35% of the mentions, followed by water with 24%. Within the few randomized controlled trials that have investigated the restorative potential of biophilic auditory experiences, only a handful of studies (Alvarsson et al., 2010; Thoma et al., 2013, 2018) have utilized a stressor to simulate a need for restoration in participants. Using skin conductance level (SCL) as a measure of ANS activity, Alvarsson et al. (2010) observed that subjects that listened to nature sounds after a stressor enjoyed faster physiological stress recovery than subjects in the high traffic noise condition. Similarly, Thoma et al. (2013) found that, after going through a social stress test, participants that listened to sounds of rippling water had the lowest salivary cortisol levels when compared to groups that either listened to relaxing music or rested in silence. As called for in Gaekwad et al.'s (2023) meta-analysis of physiological stress responses to natural environments, "there is a conspicuous lack of studies… that use a stressor as part of their experimental method." Another gap in knowledge found in the literature is the lack of studies that investigate the neurocognitive effects of biophilic auditory experiences. Only two studies have used neuroimaging techniques to observe changes in brain activity. In both of these studies, the concentration of Oxy-Hb in the PFC was significantly lower when participants listened to natural sounds, compared to an urban sounds condition (Jo et al., 2019; I. Song et al., 2023).

The research presented in this paper is intended to build upon the current literature by addressing the knowledge gaps presented above and answering the research question: What are the effects of a biophilic auditory experience on the ANS and the PFC post induced psychological stress?

The research hypotheses are:

Hypothesis 1. Following a stressor, a short restoration break with a biophilic auditory experience (intervention) will lead to greater restoration of physiological resources when compared to a short restoration break in silence (control) or with an urban auditory experience (active control), both in terms of ANS activity and perceived stress/relaxation.

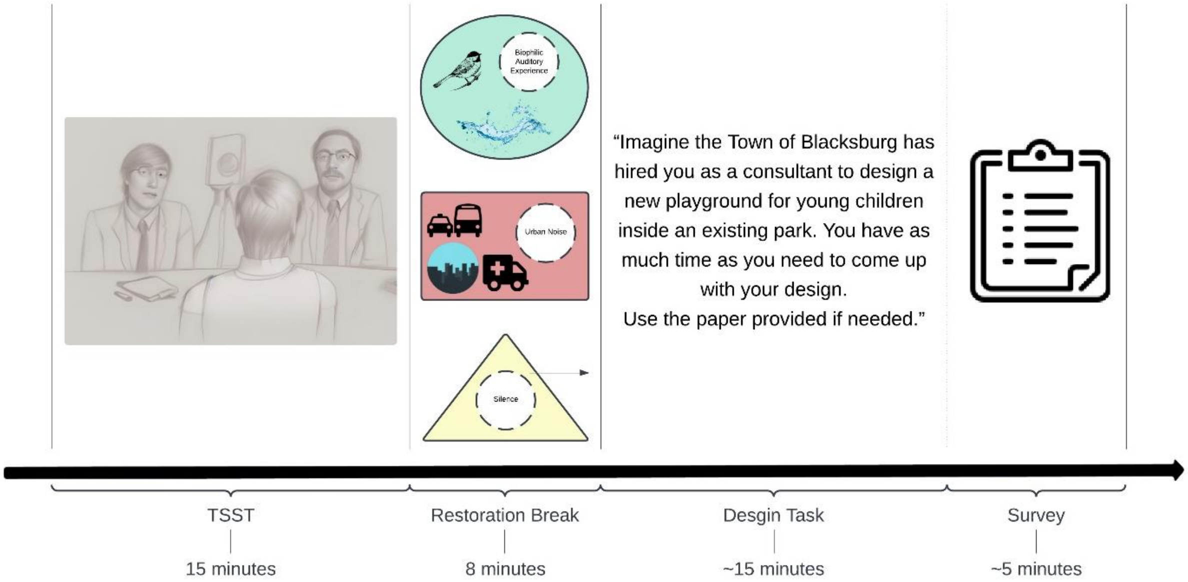
Hypothesis 2. Following a stressor, a short restoration break with a biophilic auditory experience (intervention) will lead to greater restoration of cognitive resources when compared to a short restoration break in silence (control) or with an urban auditory experience (active control), both in terms of Oxy-Hb recruitment to the PFC and perceived mental demand.

2.2 Methods

2.2.1 Overview of the experiment design

This study aimed to investigate the effect of a biophilic auditory experience on the restoration of physiological and neurocognitive resources of distressed college students. Data collection took place between February and May 2023 at the Virginia Tech campus in Blacksburg, VA. Subjects were randomly assigned to one of three different groups: *active control*, *control*, and *intervention*. The experiment consisted of three different phases, starting with a stress-induction phase, going into a restoration phase and then finishing with a complex, open-ended cognitive task (see Fig. 2.1). Stress was induced in subjects through a social stress test. The restoration phase consisted of an 8-minute break, during which each of the groups was exposed to different auditory experiences. While the *intervention* group got exposed to biophilic sounds, the a*ctive control* group got exposed to urban noise, and the *control* group was not exposed to any auditory stimulus. All subjects were asked to close their eyes during the restoration phase to null any visual stimulus. During the design task, subjects were given as much time as needed to complete their designs.

Subjects' physiological responses were tracked throughout the experiment by a medical-grade wrist-worn device. Subjects' neurocognitive responses were measured by a wireless brain-imaging device, also worn throughout all experiment phases. Perceived levels of stress pre- and post-stressor, relaxation post restoration phase, and mental demand associated with the cognitive task were collected at the conclusion of each experiment phase through Likert scales. Post-experiment survey questions were used to collect demographic data. Potential confounding variables accounted for include indoor environmental quality (IEQ) factors and connectedness to nature.



"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."

Figure 2.1 Timeline of events.

2.2.2 Participants

Virginia Tech students were recruited to participate in a "study about design" through department listservs, class visits, and flyers distributed around campus. All recruitment efforts and experimental procedures were approved by the Institutional Review Board (IRB #22-448). Potential participants were asked to fill out an eligibility survey (see Appendix A). The survey's purpose was to limit participation to volunteers who did not present any pre-existing conditions that could affect the study results. The questions covered cardiovascular, neurological, and psychiatric conditions, hearing impairments, use of controlled substances, past episodes of anxiety and/or depression, and alcohol/illicit drug dependency. A power analysis conducted with data from a pilot study (Ignacio Junior & Shealy, 2023) suggested that a minimum of 21 subjects was needed in each group in order to achieve an acceptable power of 80%, with the significance level set at 5%. A conservative approach was applied and the target was set at 30 subjects per group. Participants that passed the screening process (n = 96, 18-39 years old, 21 females, 74 males and one transman, 6 left-handed and 90 right-handed) were randomly assigned to one of three different cohorts: *active control*, *control*, and i*ntervention*.

Demographic information was collected through a survey given to participants at the end of the experiment. Information collected included age, gender, handedness, and first language. Participants were also asked about background information that could affect their response to the treatment and/or performance in proposed tasks. Most participants (81%) did not consume any caffeine within 2 hours before the experiment. The average self-reported stress level before the beginning of the experiment was low, with an average of 1.66 on a scale of 0 to 5. See Table 2.1 for a complete compilation of participants' background and demographic information.

Table 2.1 Characteristics of the sample (n = 96).

Demographics and Environmental Factors	Mean ± SD or n (%)			
	Overall	Active Control	Control	Intervention
N	96	32	32	32
Age	22 ± 4	23 ± 4	23 ± 4	22 ± 3
Gender	-	-	-	-
Female	21 (22)	8 (25)	7 (22)	6 (19)
Male	74 (77)	24 (75)	25 (78)	25 (78)
Trans	1 (1)	-	-	1 (3)
Handedness	-	-	-	-
Right	90 (94)	29 (91)	29 (91)	32 (100)
Left	6 (6)	3 (9)	3 (9)	-
English is first language	-	-	-	-
Yes	67 (70)	22 (69)	20 (63)	25 (78)
No	29 (30)	10 (31)	12 (37)	7 (22)
Caffeine intake (up to 2 hours before experiment)	-	-	-	-
Yes	18 (19)	3 (9)	8 (25)	7 (22)
No	78 (81)	29 (91)	24 (75)	25 (78)
Time of the day	-	-	-	-
Morning (8am-12pm)	40 (42)	15 (47)	12 (37)	13 (41)
Afternoon (12-5pm)	56 (58)	17 (53)	20 (63)	19 (59)
Self-reported baseline stress level (0-lowest to 5-highest)	1.66 ± 1.15	1.94 ± 1.39	1.50 ± 0.72	1.53 ± 1.22

2.2.3 Treatment

2.2.3.1 Trier Social Stress Test

The experiment began with the researcher reading the instructions for the first task, the Trier Social Stress Test (TSST). The TSST is a well-established method for inducing physiological and psychological stress (Annerstedt et al., 2013; Labuschagne et al., 2019; Liszio et al., 2018; Thoma et al., 2018; Wang et al., 2019). The intent was to deplete participants from their cognitive, physiological, and psychological resources. The three parts of the test – anticipatory stress, public speaking, and mental arithmetic – aim to replicate the demands of daily life faced when working, studying, or even just maintaining social interactions (Goodman et al., 2017; Labuschagne et al., 2019). In the first part of the TSST, participants are asked to prepare for a mock job interview in which they will deliver a 5-minute speech describing why they are the best candidate for their ideal job, having 5 minutes to take notes. Next, participants are asked to stand up in front of a camera and the panel of judges, turn in their notes and deliver their speech, being reminded to continue speaking after each 20-second silence period. Finally, during the last 5 minutes, participants are asked to sequentially subtract 13 from 1022 and report answers aloud, having to start over from the 1022 whenever a mistake is made. The TSST guidelines established by Labuschagne et al. (2019) were applied, with the only modification being the presence of one judge, instead of two. By the end of the TSST protocol, the judge exited the room and the participant was asked to sit down.

2.2.3.2 Restoration break

During the 8-minute restoration break, each of the cohorts received a different auditory experience. While participants in the *control* group sat in silence for the duration of the break and participants in the *active control* group listened to urban noises (Alvarsson et al., 2010; Jo et al., 2019; Krzywicka & Byrka, 2017; I. Song et al., 2023), participants in the *intervention* group listened to nature sounds, more specifically birdsong and water sounds. This sounds are labeled as biophilic for its potential to elicit some form of positive experience of nature (Kellert, 2005). Assessments of the restorativeness of soundscapes have rated birdsong and water sounds as the most restorative auditory stimuli (Deng et al., 2020; Krzywicka & Byrka, 2017; Ratcliffe et al., 2013). The length of the restoration break is based on the average time of prior similar studies (Barton & Pretty, 2010; Leung et al., 2022; Ojala et al., 2022; C. Song et al., 2021; Thoma et al., 2018; van den Berg et al., 2015; Yin et al., 2019). Short (5-10 min) biophilic restorative experiences, whether it be through direct, indirect, or symbolic contact with nature, have yielded a myriad of beneficial outcomes, including recovery from stressful states (Thoma et al., 2018; van den Berg et al., 2015; Yin et al., 2019), restoration of cognitive resources (C. Song et al., 2021), and enhanced feelings of connectedness with nature (Leung et al., 2022). In order to rule out the influence of any visual stimulus, all participants were asked to close their eyes for the duration of the restoration break. All auditory experiences were distributed through headphones. All participants wore headphones throughout the experiment. Consistent with studies on noise and comfort, participants were allowed to adjust the headphones' sound volume to their preference (Rashid & Zimring, 2008). Both auditory experiences are binaural recordings that are available to the general public. The urban sounds are available as virtual traffic 3D audio on YouTube (Vadlamudi, 2018), while the nature sounds come from the Castaway soundtrack in the MindBreaks mobile app (Delos Living LLC, 2020).

2.2.4 Outcome measures

To assess the potential effects of the independent variable, the biophilic auditory experience, on participants' bodies and brains after the stressor, three dependent variables were tracked. Objective data collection included the tracking of physiological and neurocognitive responses. Subjective data was collected through surveys. The combination of objective and subjective data helps to depict a clear picture of how participants were affected, on physiological and psychological levels, by the intervention tested.

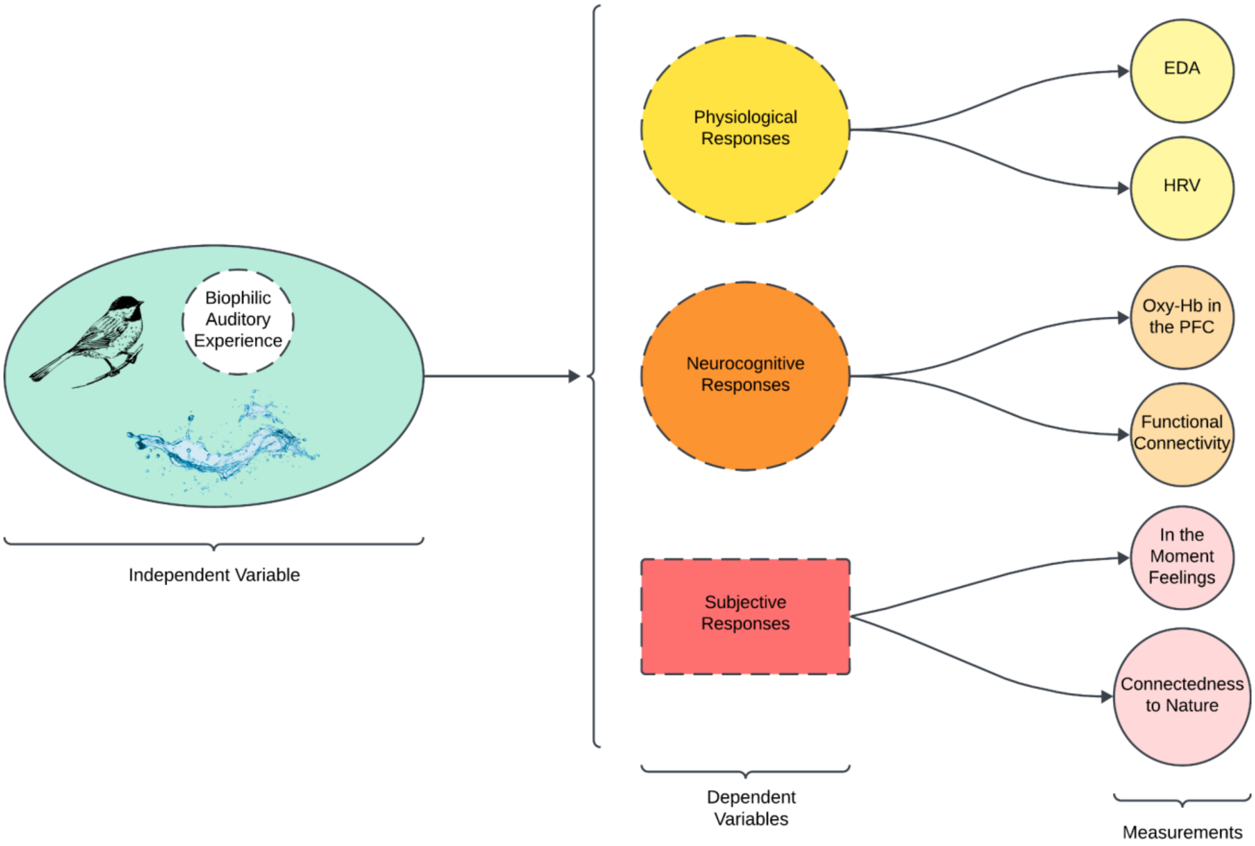


Figure 2.2 Operationalization of the variables

2.2.4.1 Physiological effects

The autonomic nervous system (ANS) governs the body's involuntary reactions to external stimuli and can be partitioned into two components: the SNS and the PNS (Ernst, 2017). The

SNS and PNS engage in a delicate equilibrium, a homeostatic process, in which the SNS partially assumes dominance when a stressful event elicits the body's fight-or-flight response (Gaekwad et al., 2023; Rajendra Acharya et al., 2006). Two indexes are commonly used to track changes in SNS and PNS activity - Electrodermal Activity (EDA) and Heart Rate Variability (HRV) (Aristizabal et al., 2021; Ojala et al., 2023).

EDA, or galvanic skin response (GSR), is a widely adopted biomarker used to objectively assess physiological responses to stress (Aristizabal et al., 2021; Ergan et al., 2019; Li & Sullivan, 2016; Yin et al., 2019). EDA varies due to sweat gland activity, which is partly controlled by the SNS (Benedek & Kaernbach, 2010). EDA can also be split into two different components: phasic and tonic skin conductance. The phasic component, normally referred to as skin conductance response (SCR), indicates arousal by short-term environmental conditions. On the other hand, the tonic component, or skin conductance level (SCL), is used as a better indicator of arousal caused by continuous exposure to an environmental condition (Aristizabal et al., 2021; Boucsein et al., 2012).

The variability found in the intervals between successive heart beats, or HRV, indicates the heart's capacity to adapt and react to constantly changing environments (H.-G. Kim et al., 2018). The interbeat interval is modulated by the ANS. A relative increase in sympathetic activity tends to shorten the interbeat interval, whereas a relative increase in parasympathetic activity leads to a longer interbeat interval (Thayer et al., 2012). Therefore, HRV is commonly used to objectively assess physiological responses to stressors (Annerstedt et al., 2013; Ergan et al., 2019; Igarashi et al., 2014; Yin et al., 2020).

To assess how participants' bodies responded to the induced stress and quantify the potential restorative effects of the intervention, both HRV and EDA were measured by an Empatica E4 wristband *(Empatica Inc., Cambridge, MA)*, a medical-grade device with real-time physiological data streaming and visualization capabilities. The wristband collects HRV data through a Photoplethysmography (PPG) sensor (sampled at 64 Hz) and skin conductance data through an EDA sensor (sampled at 4 Hz).

2.2.4.2 Neurocognitive effects

Psychosocial stress caused by the demands of daily life can negatively impact a range of prefrontal cortical cognitive functions, including creativity (Beversdorf et al., 1999), decision-making and overall working-memory (Arnsten, 1998, 2009). Therefore, the TSST, a social stress test by definition, was here utilized to purposefully affect subjects' cognitive and neurocognitive resources in a negative fashion. With all subjects being brought up to a state of mental fatigue, one of the most prominent theories that emerged from the "Biophilia Hypothesis" (Kellert & Wilson, 1993), the Kaplans' ART (R. Kaplan & Kaplan, 1989; S. Kaplan, 1995), could be tested. The ART argues that exposure to natural environments promotes an opportunity for directed attention - a mechanism that is susceptible to fatigue - to rest. Given the PFC's involvement in a wide range of top-down, executive cognitive processes such as attention, inhibition, and working-memory (Laird et al., 2011; Mezzacappa, 2017), in order to measure the potential restorative effects of the biophilic auditory experience on subjects' cognitive and neurocognitive resources, changes in recruitment of oxygenated hemoglobin (Oxy-Hb) to the PFC were measured.

The changes in Oxy-Hb recruitment were measured by an OBELAB NIRSIT wireless 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 that are positioned on subjects' forehead (Hu & Shealy, 2019). 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 to the 32 active detection sensors, compounding in a total of 48 channels. Oxygenated (Oxy-Hb) and deoxygenated (Deoxy-Hb) blood absorb more of the near-infrared light than water and other tissue in the brain. The difference between the emitted light and reflected light is used to calculate the concentration of Oxy-Hb in the PFC, using either the Modified Beer–Lambert Law (MBLL) or the Diffuse Optical Tomography (DOT) methods.

2.2.4.3 Subjective data

Surveys on comfort levels were used to correlate participants' physiological and neurophysiological responses (objective data) with what participants perceptions (subjective data) throughout the experiment. The survey questions aimed to extract participants' "in the moment" feelings in response to the stimuli given (i.e., TSST, restoration break, design task). Surveys measuring "in the moment" feelings are widely used as a form of comparison between objective and subjective data (Aristizabal et al., 2021; Yin et al., 2018b, 2019). Participants were asked to report "in the moment" feelings utilizing a Likert scale. Likert scales are one the most used, reliable, and validated tools for psychometrics research (Joshi et al., 2015). Data collected for "in the moment" feelings of stress and relaxation can be compared to EDA and HRV data, while subjects reported feelings of mental demand associated with the design task can be compared to brain activity data. This approach for recording participants "in the moment" feelings is inspired by the Positive Affect Negative Affect Scale (PANAS) (Watson et al., 1988), which has been used in previous, similar studies (Aristizabal et al., 2021; Yin et al., 2019). Below are the prompts used to extract participants "in the moment" feelings:

How stressed did you feel during the previous task?

0 (Not stressed at all) – 5 (Extremely stressed)

How relaxed do you feel after this 8-minute break?

0 (Not relaxed at all) – 5 (Extremely relaxed)

How mentally demanding was the design task?

0 (Not mentally demanding at all) – 5 (Extremely mentally demanding)

Why asking participants how mentally demanding was the design task? Designing is a complex task that requires the engagement and simultaneous use of multiple cognitive resources. Some of the cognitive capacities utilized during design include reasoning, creativity, analysis, and evaluation (Gero & Milovanovic, 2020). Utilizing all of these resources creates a high cognitive load, in turn increasing the perception of cognitive demand (Stevenson et al., 2018). Subjects that received different auditory experiences during the restoration break could come into the design task at different levels of mental fatigue. In accordance with the ART, exposure to the biophilic auditory experience should lead to a restoration of cognitive resources (Kaplan, 1995; Williams et al., 2018). The availability of more or less cognitive resources could ultimately affect subjects' perception of mental demand.

Exposure to biophilic experiences, whether they be in real or simulated settings, can also increase one's positive emotions (affect) towards nature (Coughlan et al., 2022; Leung et al., 2022; Mayer et al., 2009). In order to record feelings of connectedness to nature, as well as potential changes in those feelings fostered by the different auditory experiences during the restoration break, participants completed the simplified version of the Nature Relatedness Scale (NR-6) (Nisbet & Zelenski, 2013) before and after participation in the study.

2.2.4.4 Environmental conditions

Since this experiment tested a treatment distributed through a sensory stimulus (sound), other stimuli present in the environment needed to be accounted for. To curb exposure to any visual stimulus, participants were asked to keep their eyes closed during the restoration break.

The room's indoor environmental quality (IEQ) was monitored by an Aranet4 non-dispersive infrared sensor (NDIR) for a quarter (24 out 96) of the data collection sessions. Overall mean CO2 level, temperature, and relative humidity were 756 ppm ± 112, 21.8°C ± 1.8, and 41.1% ± 11.5, respectively.

2.2.5 Data processing and analysis

2.2.5.1 Physiological responses

EDA data collected by the Empatica E4 wristbands was downloaded from the E4 connect web portal, where data was automatically uploaded to after each experiment session. Phasic and tonic components of the EDA data were extracted through a continuous decomposition analysis (CDA) over the length of each step in the experiment (TSST, restoration break, design task) utilizing the Matlab-based software Ledalab® (Benedek & Kaernbach, 2010). A threshold of 0.01 µS was applied to the skin conductance response amplitude (Aristizabal et al., 2021; Boucsein et al., 2012). Ledalab's default settings for data filtering and smoothing were utilized. Outputs from the CDA presented in this study include the number of significant SCRs (nSCR), the mean phasic driver (SCR), and the mean tonic activity (SCL), all within the response window for each of the three steps in the experiment.

HRV-related data was processed utilizing the hrvanalysis Python module. The data processing procedure started with the removal of outliers and ectopic (i.e. irregular) heartbeats from the RR-intervals, transforming them into Normal to Normal (NN) intervals. RR-intervals below 300 and above 2000 milliseconds were removed. Linear interpolation was utilized to replace outliers (Peltola, 2012). After the transformation, frequency and time domain features were extracted. Frequency domain features included power at high (HF, 0.15 to 0.40 Hz), low (LF, 0.04 to 0.15 Hz), and very low (VLF, 0.003 to 0.04 Hz) frequencies, as well as the normalized values for high (HF.nu) and low (LF.nu) frequencies and the LF/HF ratio, which have been used by Ojala et al. (2022) and others (Aristizabal et al., 2021; Ergan et al., 2019; Yin et al., 2020). Time domain features extracted from the periods for each experiment phase included the mean heart rate (HR), the standard deviation of all NN intervals (SDNN), and the square root of the squares of the successive differences between NN intervals (RMSSD), summing up to a total of nine different HRV metrics.

Statistical analysis was performed using Python packages. Outliers within groups were identified and removed utilizing the interquartile range (IQR) method. For normally distributed datasets, a parametric ANOVA test (i.e. F-test) was utilized. If the dataset presented a skewed distribution, a non-parametric ANOVA test (i.e. Kruskal-Wallis) was performed. A p-value of 0.05 was set as threshold for significance. If the ANOVA results pointed out any statistically significant difference between the three groups, a post-hoc T-test with a Holm-Bonferroni *p*-value adjustment was performed to identify where the significant difference exists. The Cohen’s *d* was computed and utilized to measure the effect size.

2.2.5.2 Neurocognitive responses

Raw fNIRS data for each participant had outliers removed utilizing z-scores (threshold = 2 standard deviations). Next, the data was pre-processed utilizing the Matlab-based NIRS Brain AnalyzIR Toolbox (Santosa et al., 2018). First, the data sampling rate was reduced from 8 Hz to 5 Hz. Light intensity was then converted to optical density. Motion artifacts were then removed using the Temporal Derivative Distribution Repair (TDDR) method (Fishburn et al., 2019). Following the motion correction, bandpass filtering was performed. An 1000th order finite impulse response (FIR) bandpass filter was applied. The applied cutoff range - 0.01–0.25Hz - corresponds to the range in which hemodynamic responses happen (Pinti et al., 2019). Next, changes in optical density were converted to hemoglobin (Hb) concentration utilizing the MBLL method (Kocsis et al., 2006). The last step in the data preparation process was removing other physiological noise. The Mayer wave noise (from blood pressure) was removed by regressing out the median time series (Yücel et al., 2016).

Statistical analysis was conducted using Python. The mean Oxy-Hb across the whole PFC and across each ROI was calculated for all groups during each of the experiment phases. The right and left dorsomedial prefrontal cortex (DMPFC), frontopolar cortex, dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex (VLPFC), and orbitofrontal cortex (OFC) were the ROIs utilized (see Fig. 2.3). Outliers within groups (outside IQR) were removed from statistical analysis. All datasets were tested for normality utilizing the Shapiro-Wilk test. A parametric or a non-parametric ANOVA was used depending on normality. For normally distributed datasets, a parametric ANOVA test (i.e. F-test) was utilized. If the dataset presented a skewed distribution, a non-parametric ANOVA test (i.e. Kruskal-Wallis) was performed. A p-value of 0.05 was set as threshold for significance. If the ANOVA results pointed out any statistically significant difference between the three groups, a post-hoc test with a Holm-Bonferroni *p*-value adjustment was performed to identify where the significant difference exists. The Cohen's *d* was computed and utilized to measure the effect size.

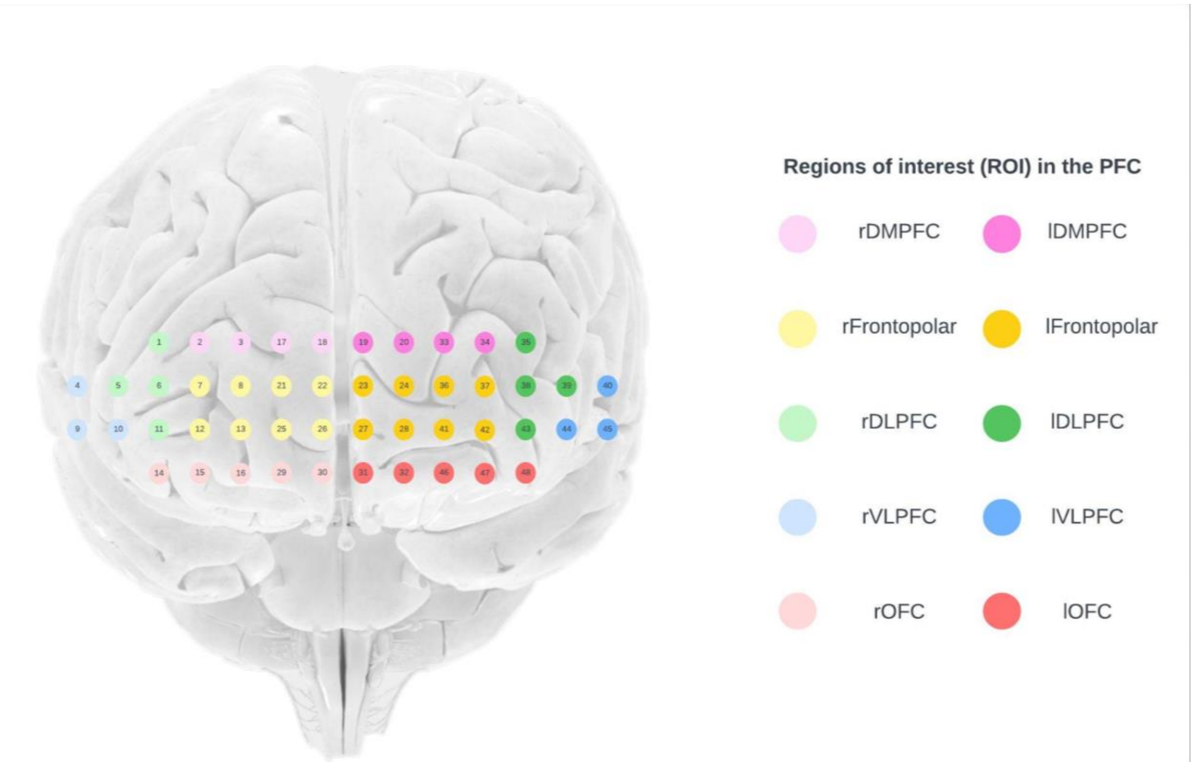


Figure 2.3 Spatial distribution of ROIs with the OBELAB NIRSIT channel configuration.

2.2.5.3 Subjective data

Subjects' self-reported in the moment feelings (stress, relaxation, and mental demand) and results for the pre- and post-experiment NR-6 survey were compared between groups utilizing the same statistical methods applied to the objective data, with the exception of no outliers being removed.

2.3 Results

2.3.1 Summary of significant findings:

- During the Restoration Break, the mean frequency of SCRs for the Intervention group was significantly higher than the Control group ($p = 0.032$), with a medium effect size (Cohen's $d = 0.691$). However, the difference between the Intervention and Active Control groups was not significant ($p = 0.108$).
- During the Restoration Break, the mean SCL for the Intervention group was significantly higher than both the Control ($p = 0.008$, Cohen's $d = 0.850$) and the Active Control ($p = 0.012$, Cohen's $d = 0.757$) groups, with large and medium to large effect sizes, respectively.
- During the Design Task, the mean SCL for the Intervention group was significantly higher than both the Control ($p = 0.005$, Cohen's $d = 0.839$) and the Active Control ($p = 0.001$, Cohen's $d = 0.984$) groups, with large effect sizes.
- During the Restoration Break, the mean LF/HF ratio for the Intervention group was significantly higher than the Control group ($p = 0.010$), with a medium to large effect size (Cohen's $d = 0.77$). However, the Active Control group did not significantly differ from the Intervention and Control groups.
- During the Restoration Break, the mean RMSSD for the Intervention group was significantly lower than both the Control ($p = 0.003$, Cohen's $d = 0.910$) and the Active Control ($p = 0.005$, Cohen's $d = 0.841$) groups, with a large effect size.
- During the Restoration Break, the mean VLF for the Control group was significantly higher than the Active Control group ($p = 0.035$), with a medium to large effect size (Cohen's $d = 0.707$). However, the Intervention group did not significantly differ from the Active Control and Control groups.
- During the Design Task, the mean Oxy-Hb concentration across the PFC for the Active Control group was significantly lower than the Control group ($p < 0.005$), with a large effect size (Cohen's $d = 0.838$). However, the Intervention group did not significantly differ from the Active Control and Control groups.
- During the Design Task, the mean Oxy-Hb in the rDLPFC for the Active Control group was significantly lower than both the Control ($p = 0.003$, Cohen's $d = 0.939$) and the Intervention ($p = 0.016$, Cohen's $d = 0.757$) groups, with large and medium to large effect sizes.
- After the Restoration Break, participants in both the Intervention and Control groups reported feeling significantly more relaxed than participants in the Active Control group.

2.3.2 Physiological responses

2.3.2.1 Electrodermal activity

Analysis of three EDA metrics (nSCR, SCR, and SCL) showed that participants who received the biophilic auditory experience had higher physiological arousal during the Restoration Break and the Design Task. Results for each of these metrics are provided in the following subsections.

2.3.2.1.1 Mean frequency of skin conductance responses (nSCR)

The Intervention group had a significantly ($p < 0.05$) larger frequency of skin conductance responses (SCRs) during the Restoration Break (see Table 2.2).

Table 2.2 Mean frequency of SCRs for all groups during each phase of the experiment. Outliers within groups were removed from analysis using the IQR method.

Phase	Group	n	Mean	SD	Shapiro-Wilk *p*-value	t	*p*-value
TSST	Active Control	31	489.452	164.194	0.919	0.183	0.833
	Control	29	467.172	146.481	0.990		
	Intervention	32	491.969	203.787	0.073		
Restoration Break	Active Control	29	160.621	91.972	0.104	4.336	0.016^{*}
	Control	27	137.593	96.888	0.197		
	Intervention	32	218.000	130.474	0.615		
Design Task	Active Control	31	217.806	181.873	0.015	0.299	0.861
	Control	30	213.233	160.311	0.066		
	Intervention	32	185.438	135.625	0.012		

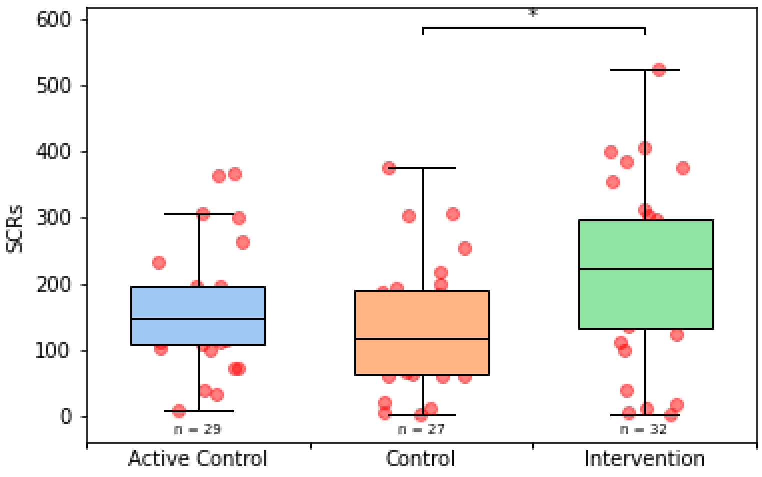


Figure 2.4 Mean frequency of SCRs for all groups during the Restoration Break.

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the Restoration Break, the mean frequency of SCRs for the Intervention group was significantly higher than the Control group (*p* = 0.032), with a medium effect size (Cohen's *d* = 0.691). However, the differences between the Intervention and Active Control (*p* = 0.108), as well as between the Active Control and Control (*p* = 0.366) groups were not significant.

2.3.2.1.2 Mean Phasic Driver (SCR) within response window

Participants' mean phasic driver (SCR) during each experiment phase were averaged for each group. No significant differences were found between groups in any of the phases (see Table 2.3).

Table 2.3 Mean phasic driver (SCR) for all groups during each phase of the experiment. Outliers within groups were removed from analysis using the IQR method.

Phase	Group	n	Mean	SD	Shapiro-Wilk *p*-value	t	*p*-value
TSST	Active Control	30	0.082	0.073	0.001	2.369	0.306
	Control	30	0.126	0.109	0.006		
	Intervention	31	0.112	0.088	0.012		
Restoration Break	Active Control	27	0.018	0.019	< 0.001	2.153	0.341
	Control	28	0.028	0.028	< 0.001		
	Intervention	28	0.027	0.025	0.002		
Design Task	Active Control	30	0.029	0.030	< 0.001	0.180	0.914
	Control	28	0.040	0.050	< 0.001		
	Intervention	29	0.030	0.038	< 0.001		

2.3.2.1.3 Mean Tonic Activity (SCL) within response window

The Intervention group had a significantly ($p < 0.05$) larger mean tonic activity during the Restoration Break and the Design Task (see Table 2.4).

Table 2.4 Mean SCL for all groups during each phase of the experiment. Outliers within groups were removed from analysis using the IQR method.

Phase	Group	n	Mean	SD	Shapiro-Wilk *p*-value	t	*p*-value
TSST	Active Control	28	2.125	2.070	0.003	2.807	0.246
	Control	27	1.469	1.405	0.002		
	Intervention	29	2.700	2.696	< 0.001		
Restoration Break	Active Control	27	1.264	1.103	0.002	6.659	0.036*
	Control	25	1.116	0.821	0.034		
	Intervention	30	2.737	2.469	0.008		
Design Task	Active Control	27	0.372	0.405	0.001	14.338	< 0.001*
	Control	26	0.456	0.521	< 0.001		
	Intervention	31	1.150	1.012	0.003		

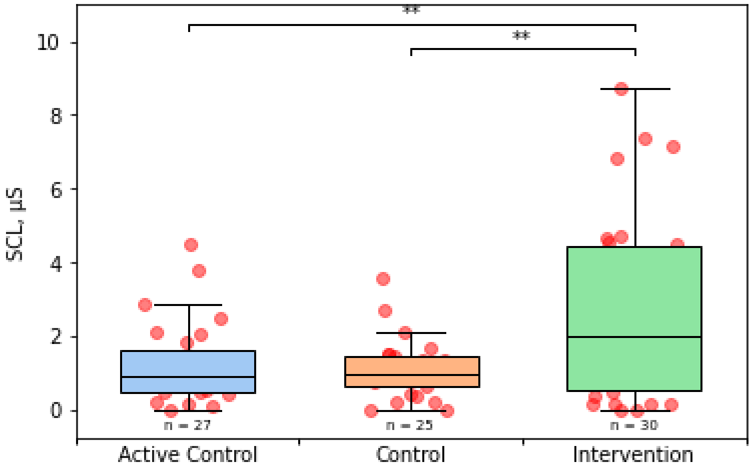


Figure 2.5 Mean SCL for all groups during the Restoration Break.

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the Restoration Break, the mean SCL for the Intervention group was significantly higher than both the Control (p = 0.008, Cohen's d = 0.850) and the Active Control (p = 0.012, Cohen's d = 0.757) groups, with large and medium to large effect sizes, respectively.

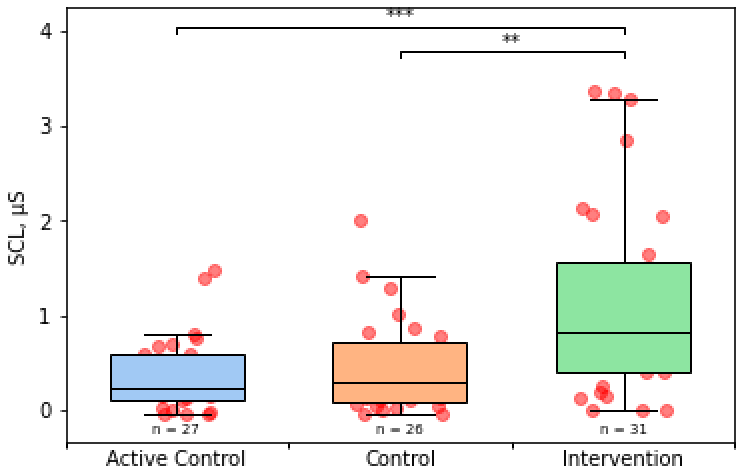


Figure 2.6 Mean SCL for all groups during the Design Task.

A post hoc T-test with a Holm-Bonferroni p-value adjustment indicated that during the Design Task, the mean SCL for the Intervention group was significantly higher than both the Control (p = 0.005, Cohen's d = 0.839) and the Active Control (p = 0.001, Cohen's d = 0.984) groups, with large effect sizes.

2.3.2.2 Heart rate variability

Analysis of nine HRV metrics (Mean HR, LF/HF, RMSSD, SDNN, VLF, LF, HF, LF.nu, and HF.nu) showed that participants who received the biophilic auditory experience had higher SNS activity and lower PNS activity during the Restoration Break. Results for each of these metrics are provided in the following subsections.

2.3.2.2.1 Mean heart rate

Participants' mean HR during each experiment phase were averaged for each group. No significant differences were found between groups in any of the phases (see Table 2.5).

Table 2.5 Mean HR results for all groups during each phase of the experiment. Outliers within groups were removed from analysis using the IQR method.

Phase	Group	n	Mean	SD	Shapiro-Wilk *p*-value	t	*p*-value
TSST	Active Control	31	93.373	16.000	0.935	0.809	0.449
	Control	29	90.911	20.870	0.670		
	Intervention	31	96.373	12.697	0.077		
Restoration Break	Active Control	31	77.607	9.226	0.339	1.563	0.215
	Control	30	76.405	14.248	0.715		
	Intervention	32	81.245	9.838	0.282		
Design Task	Active Control	31	77.198	10.523	0.320	1.070	0.347
	Control	30	79.166	10.911	0.274		
	Intervention	32	80.981	9.351	0.420		

2.3.2.2.2 LF/HF

The Intervention group had a significantly ($p < 0.05$) higher low-frequency to high-frequency ratio in the Restoration Break, when compared to the Control group (see Table 2.6).

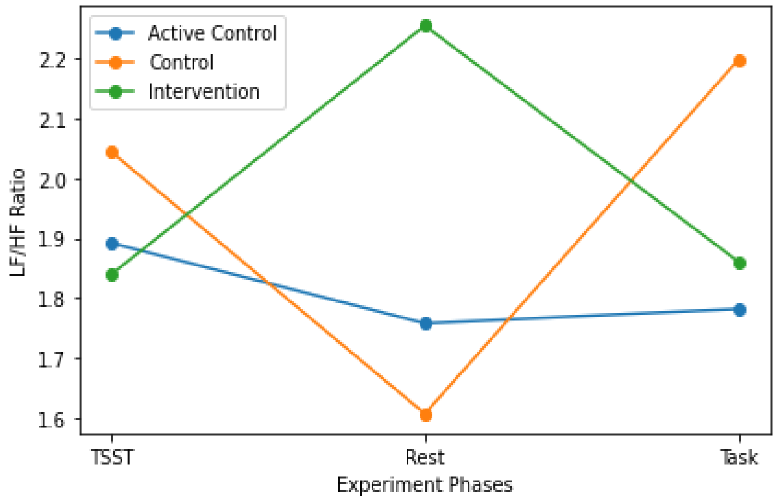


Figure 2.7 Changes in the mean LF/HF ratio throughout each experiment phase, for each group.

Table 2.6 LF/HF results for all groups during each phase of the experiment. Outliers within groups were removed from analysis using the IQR method.

Phase	Group	n	Mean	SD	Shapiro-Wilk *p*-value	t	*p*-value
TSST	Active Control	30	1.892	0.673	0.879	0.821	0.443
	Control	30	2.044	0.654	0.315		
	Intervention	28	1.840	0.567	0.684		
Restoration Break	Active Control	30	1.758	0.967	0.098	4.610	0.012*
	Control	30	1.607	0.660	0.471		
	Intervention	32	2.255	0.974	0.435		
Design Task	Active Control	30	1.782	0.852	0.616	2.607	0.272
	Control	30	1.055	1.055	0.565		
	Intervention	31	0.826	0.826	0.016		

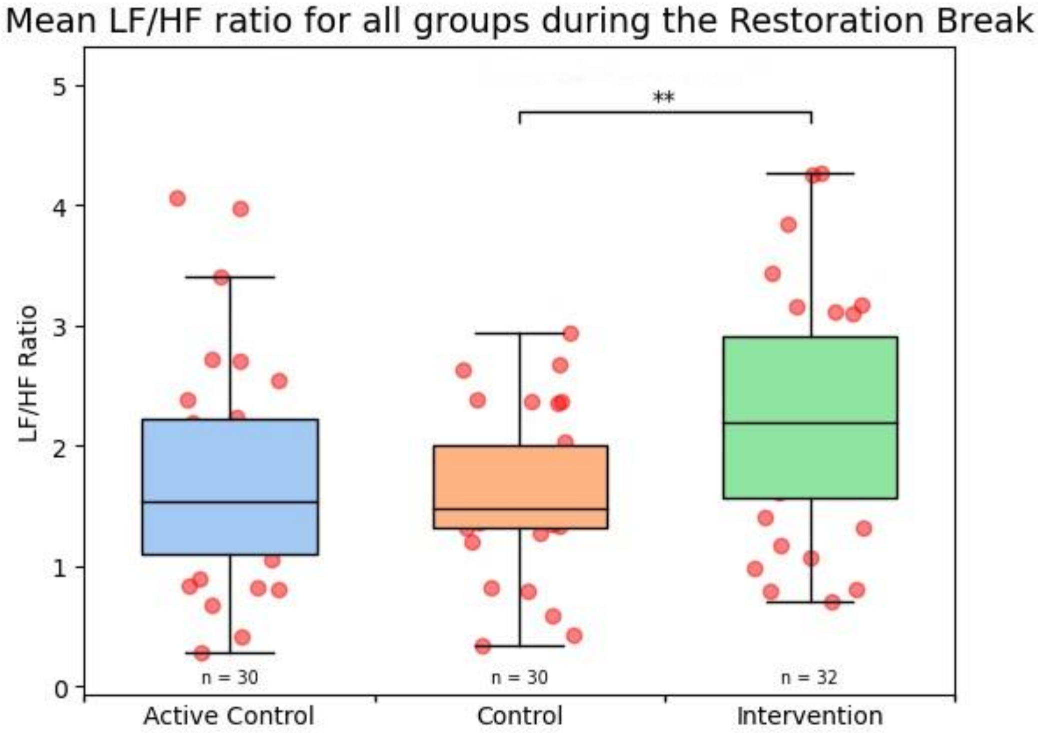


Figure 2.8 Mean LF/HF ration for all groups during the Restoration Break.

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the Restoration Break, the mean LF/HF ratio for the Intervention group was significantly higher than the Control group (*p* = 0.010), with a medium to large effect size (Cohen's *d* = 0.77). A comparison between the Active Control and the Intervention groups yielded a *p*-value of 0.097, while the *p*-value for the comparison between the Active Control and the Control groups was 0.483.

2.3.2.2.3 RMSSD

Statistical analysis for the RMSSD showed that significant differences existed between the Intervention group and the other two groups during the Restoration Break (see Table 2.7).

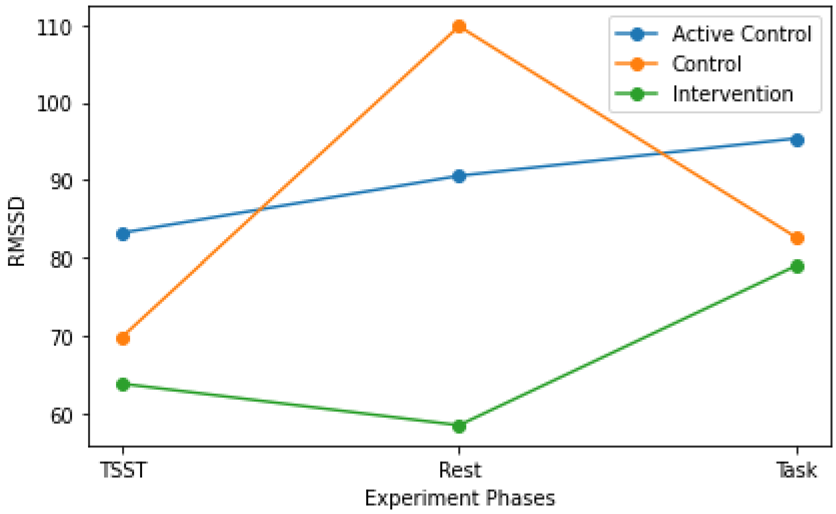


Figure 2.9 RMSSD throughout each experiment phase, for each group.

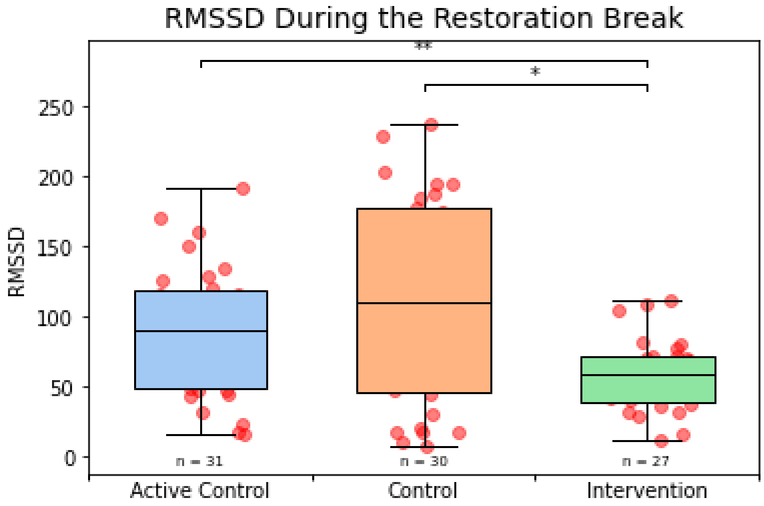


Figure 2.10 RMSSD during the Restoration Break

Table 2.7 Mean RMSSD for all groups during each phase of the experiment. Outliers within groups were removed from analysis using the IQR method.

Phase	Group	n	Mean	SD	Shapiro-Wilk *p*-value	t	*p*-value
TSST	Active Control	31	83.194	39.549	0.275	2.122	0.126
	Control	29	69.828	39.051	0.199		
	Intervention	30	63.800	34.154	0.212		
Restoration Break	Active Control	31	90.548	46.116	0.601	9.353	0.009^{**}
	Control	30	109.833	73.680	0.034		
	Intervention	27	58.444	26.232	0.551		
Design Task	Active Control	30	95.367	62.691	0.379	1.595	0.450
	Control	27	82.630	63.766	0.029		
	Intervention	30	79.000	63.058	0.004		

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the Restoration Break, the mean RMSSD for the Intervention group was significantly lower than both the Control ($p = 0.003$, Cohen's $d = 0.910$) and the Active Control ($p = 0.005$, Cohen's $d = 0.841$) groups, with a large effect size.

2.3.2.2.4 SDNN

Statistical analysis for the SDNN showed that no significant differences existed between groups in any of the experiment phases (see Table 2.8).

Table 2.8 Mean SDNN for all groups during each phase of the experiment. Outliers within groups were removed from analysis using the IQR method.

Phase	Group	n	Mean	SD	Shapiro-Wilk *p*-value	t	*p*-value
TSST	Active Control	28	54.211	17.555	0.076	0.508	0.776
	Control	29	55.111	29.944	0.002		
	Intervention	31	51.647	18.497	0.250		
Restoration Break	Active Control	29	49.720	13.230	0.969	2.700	0.073
	Control	30	57.215	20.867	0.568		
	Intervention	30	47.911	13.976	0.370		
Design Task	Active Control	29	26.181	9.931	0.986	0.787	0.458
	Control	27	25.471	12.008	0.669		
	Intervention	32	29.002	12.543	0.287		

2.3.2.2.5 VLF

Statistical analysis for the power at very low frequency (VLF, 0.003 to 0.04 Hz) showed that significant differences existed between groups during the Restoration Break (see Table 2.9).

Table 2.9 Mean VLF (power) for all groups during each phase of the experiment. Outliers within groups were removed from analysis using the IQR method.

Phase	Group	n	Mean	SD	Shapiro-Wilk *p*-value	t	*p*-value
TSST	Active Control	30	324.815	160.287	0.357	0.073	0.964
	Control	30	401.075	338.554	0.0009		
	Intervention	30	330.941	199.815	0.173		
Restoration Break	Active Control	25	310.395	151.681	0.581	3.691	0.029*
	Control	30	468.218	268.328	0.097		
	Intervention	30	361.191	219.780	0.057		
Design Task	Active Control	30	83.737	62.337	0.012	1.436	0.488
	Control	28	115.276	110.729	0.002		
	Intervention	26	67.964	54.920	0.001		

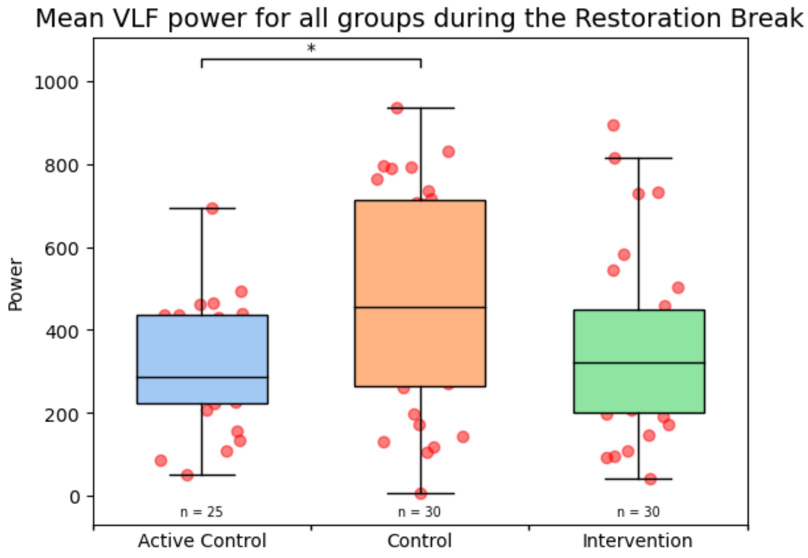


Figure 2.11 Mean power at VLF for all groups during the Restoration Break.

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the Restoration Break, the mean VLF for the Control group was significantly higher than the Active

Control group ($p = 0.035$), with a medium to large effect size (Cohen's $d = 0.707$). However, the Intervention group did not significantly differ from the Active Control and Control groups.

2.3.2.2.6 LF

Statistical analysis for the power at low frequency (LF, 0.04 –0.15 Hz) showed that no significant differences existed between groups in any of the experiment phases (see Table 2.10).

Table 2.10 Mean LF (power) for all groups during each phase of the experiment. Outliers within groups were removed from analysis using the IQR method.

Phase	Group	n	Mean	SD	Shapiro-Wilk *p*-value	t	*p*-value
TSST	Active Control	29	421.746	210.785	0.597	3.305	0.192
	Control	29	349.641	234.594	0.027		
	Intervention	28	341.047	220.702	0.006		
Restoration Break	Active Control	29	609.938	392.575	0.023	1.579	0.454
	Control	29	687.826	382.646	0.799		
	Intervention	30	704.169	371.822	0.765		
Design Task	Active Control	29	163.267	117.212	0.065	1.061	0.588
	Control	29	242.835	220.329	0.007		
	Intervention	29	176.712	143.505	0.003		

2.3.2.2.7 HF

Statistical analysis for the power at high frequency (HF, 0.15 –0.4 Hz) showed that no significant differences existed between groups in any of the experiment phases (see Table 2.11).

Table 2.11 Mean HF (power) for all groups during each phase of the experiment. Outliers within groups were removed from analysis using the IQR method.

Phase	Group	n	Mean	SD	Shapiro-Wilk *p*-value	t	*p*-value
TSST	Active Control	30	229.626	113.189	0.117	2.832	0.243
	Control	30	195.233	144.121	0.002		
	Intervention	31	196.657	106.539	0.485		
Restoration Break	Active Control	31	425.246	241.895	0.185	2.789	0.067
	Control	28	478.217	310.175	0.414		
	Intervention	29	325.425	179.487	0.105		
Design Task	Active Control	29	95.123	53.880	0.700	0.076	0.963
	Control	27	98.492	79.741	0.059		
	Intervention	29	97.014	68.902	0.033		

2.3.2.2.8 Normalized power at low frequency (LF.nu)

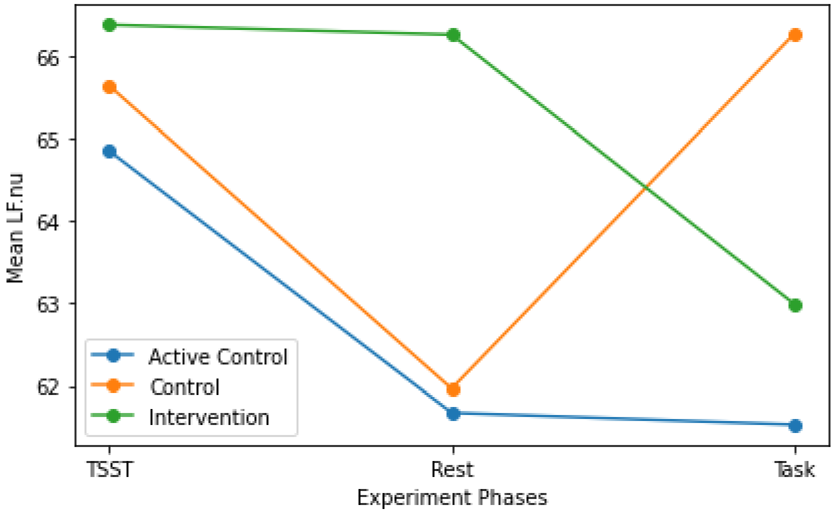


Figure 2.12 Normalized power at LF (0.04-0.15 Hz) throughout each experiment phase, for each group.

Statistical analysis for the normalized power at low frequency (LF.nu) showed that no significant differences existed between groups in any of the experiment phases.

Table 2.12 Mean LF.nu for all groups during each phase of the experiment. Outliers within groups were removed from analysis using the IQR method.

Phase	Group	n	Mean	SD	Shapiro-Wilk *p*-value	t	*p*-value
TSST	Active Control	30	64.850	9.143	0.201	0.254	0.776
	Control	30	65.640	7.457	0.221		
	Intervention	31	66.380	8.470	0.381		
Restoration Break	Active Control	30	61.674	13.625	0.968	4.477	0.107
	Control	27	61.966	7.700	0.182		
	Intervention	32	66.260	10.989	0.017		
Design Task	Active Control	31	61.531	13.975	0.313	1.267	0.287
	Control	29	66.267	10.717	0.209		
	Intervention	32	62.994	10.215	0.575		

2.3.2.2.9 Normalized power at high frequency (HF.nu)

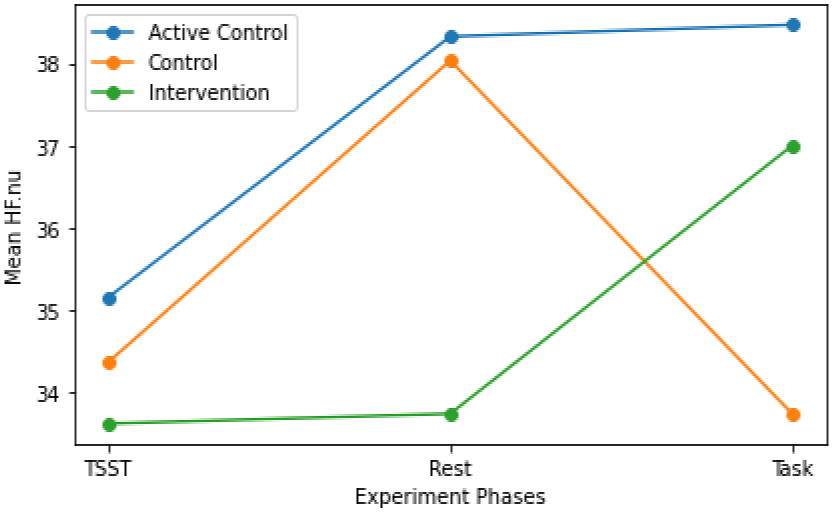


Figure 2.13 Normalized power at HF (0.15-0.4 Hz) throughout each experiment phase, for each group.

Statistical analysis for the normalized power at high frequency (HF.nu) showed that no significant differences existed between groups in any of the experiment phases (see Table 2.13).

Table 2.13 Mean HF.nu for all groups during each phase of the experiment. Outliers within groups were removed from analysis using the IQR method.

Phase	Group	n	Mean	SD	Shapiro-Wilk *p*-value	t	*p*-value
TSST	Active Control	30	35.150	9.143	0.201	0.254	0.776
	Control	30	34.360	7.457	0.221		
	Intervention	31	33.620	8.470	0.381		
Restoration Break	Active Control	30	38.326	13.625	0.968	4.477	0.107
	Control	27	38.034	7.700	0.182		
	Intervention	32	33.740	10.989	0.017		
Design Task	Active Control	31	38.469	13.975	0.313	1.267	0.287
	Control	29	33.733	10.717	0.209		
	Intervention	32	37.006	10.215	0.575		

2.3.3 Neurocognitive responses

Analysis of the patterns of brain activation throughout the experiment phases showed that participants who received the biophilic auditory experience had significantly lower recruitment of Oxy-Hb in one specific ROI during the Restoration Break. On the other hand, the Active Control group had significantly lower overall activation during the Design Task and significantly higher activation in a right-lateralized fronto-parietal region during the Restoration Break. Results for each of these metrics are provided in the following subsections.

2.3.3.1 Mean Oxy-Hb across the PFC

The Active Control group had significantly ($p < 0.05$) lower recruitment of Oxy-Hb to the PFC during the Design Task when compared to the Control group (see Table 2.14).

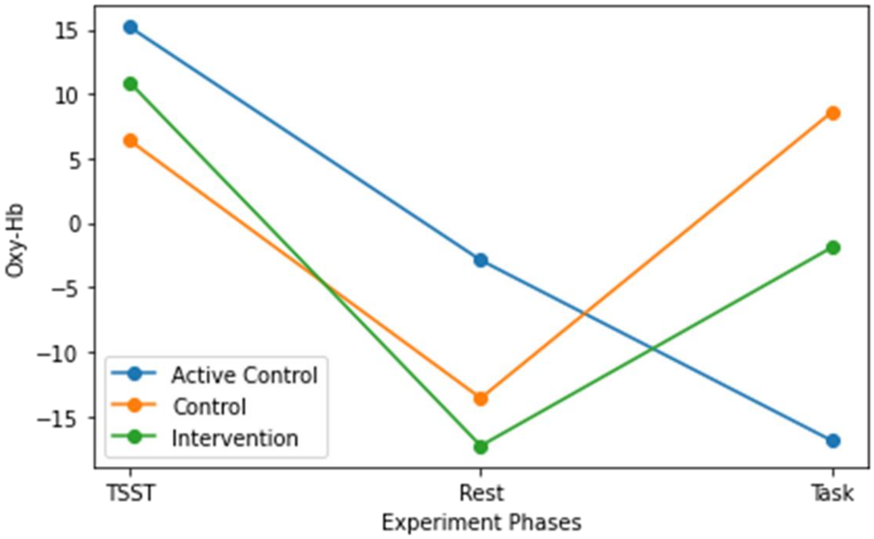


Figure 2.14 Mean Oxy-Hb recruitment across the PFC throughout each experiment phase, for each group.

Table 2.14 Statistical analysis for the Mean Oxy-Hb concentration across the PFC for all groups during each phase of the experiment. Outliers within groups were removed from analysis using the IQR method.

Phase	Group	n	Mean	SD	Shapiro-Wilk *p*-value	t	*p*-value
TSST	Active Control	27	15.219	22.190	0.320	0.580	0.562
	Control	31	6.353	38.946	0.175		
	Intervention	29	10.942	29.367	0.515		
Restoration Break	Active Control	29	-2.919	49.117	0.332	0.604	0.549
	Control	32	-13.627	52.994	0.703		
	Intervention	31	-17.265	54.583	0.818		
Design Task	Active Control	30	-16.881	31.520	0.153	6.110	0.003*
	Control	32	8.634	29.387	0.621		
	Intervention	30	-1.910	25.128	0.859		

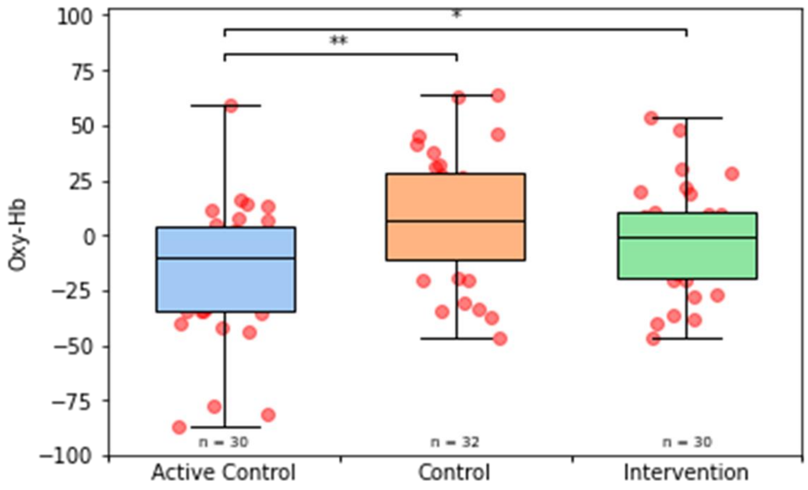


Figure 2.15 Mean Oxy-Hb across the PFC during the Design Task.

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the Design Task, the mean Oxy-Hb concentration across the PFC for the Active Control group was significantly lower than the Control group ($p < 0.005$), with a large effect size (Cohen's $d = 0.838$). However, the Intervention group did not significantly differ from the Active Control and Control groups.

2.3.3.2 Mean Oxy-Hb in ROIs

The mean Oxy-Hb recruitment during the TSST was calculated for the right and left DMPFC, DLPFC, Frontopolar Cortex, VLPFC, and OFC. No significant differences ($p < 0.05$) between groups were found during the TSST.

The mean Oxy-Hb recruitment during the Restoration Break was calculated for the right and left DMPFC, DLPFC, Frontopolar Cortex, VLPFC, and OFC. A parametric ANOVA test indicated a significant difference ($p < 0.05$) between groups for activity in the right VLPFC (see Table 2.15).

Table 2.15 Statistical analysis for the Mean Oxy-Hb concentration in the rVLPFC for all groups during the Restoration Break. Outliers within groups were removed from analysis using the IQR method.

Phase	Group	n	Mean	SD	Shapiro-Wilk *p*-value	t	*p*-value
Restoration Break	Active Control	30	2.911	121.894	0.760	3.125	0.049^{*}
	Control	30	-18.538	62.682	0.920		
	Intervention	31	-53.158	69.270	0.651		

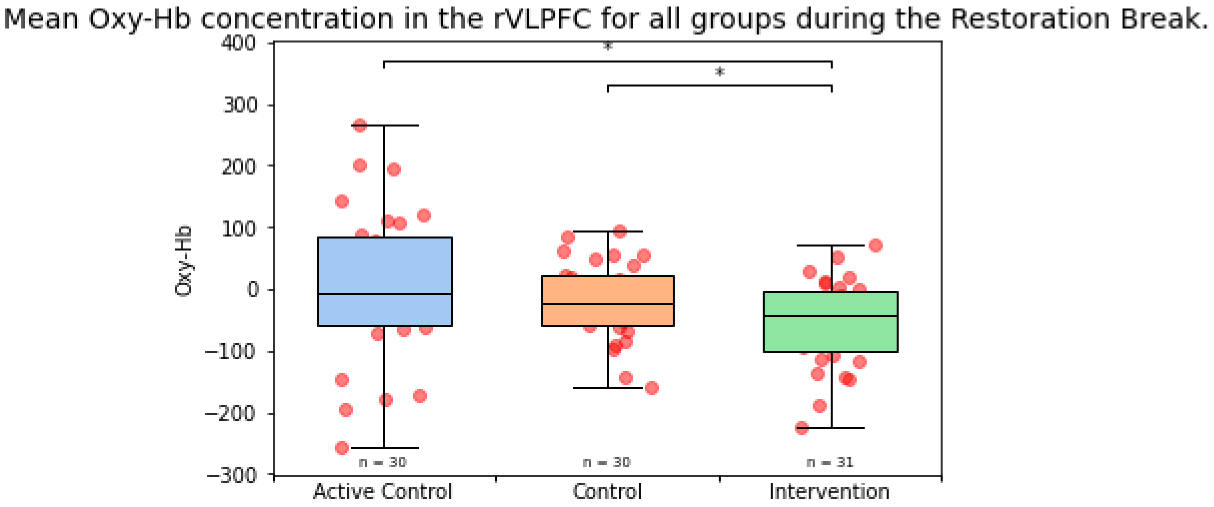


Figure 2.16 Mean Oxy-Hb recruitment to the rVLPFC during the Restoration Break.

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that the mean Oxy-Hb in the rVLPFC did not differ significantly between groups during the Restoration Break. The test returned the *p*-values 0.091 (Intervention vs Control), 0.091 (Intervention vs Active Control), and 0.395 (Control vs Active Control).

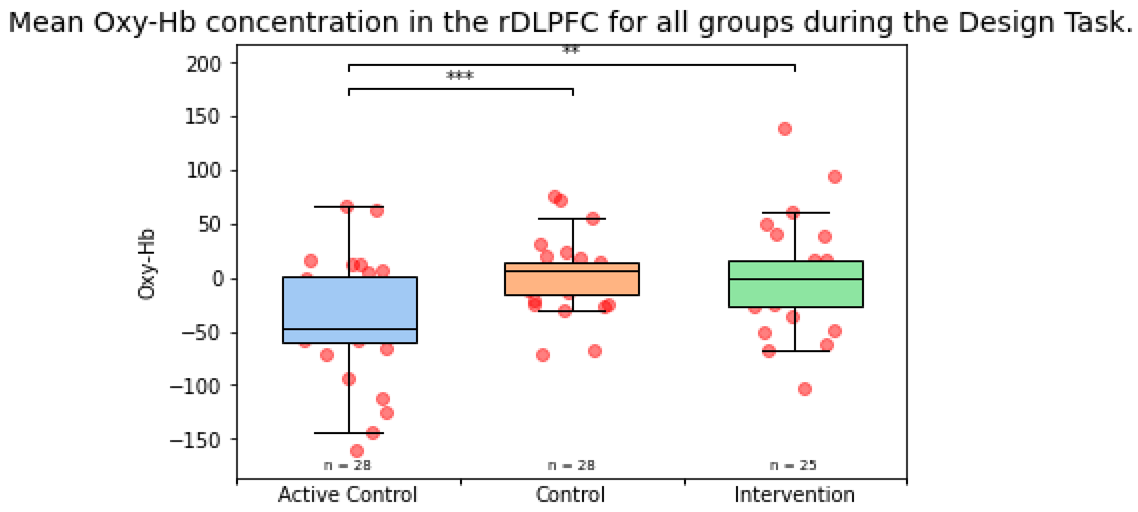


Figure 2.17 Mean Oxy-Hb recruitment to the rDLPFC during the Design Task.

The mean Oxy-Hb recruitment during the Design Task was calculated for the right and left DMPFC, DLPFC, Frontopolar Cortex, VLPFC, and OFC. A parametric ANOVA test indicated a significant difference ($p < 0.05$) between groups for activity in the right DLPFC (see Table 2.16).

Table 2.16 Statistical analysis for the Mean Oxy-Hb concentration in the rDLPFC for all groups during the Design Task. Outliers within groups were removed from analysis using the IQR method.

Phase	Group	n	Mean	SD	Shapiro-Wilk *p*-value	t	*p*-value
Design Task	Active Control	28	-40.876	55.321	0.497	7.049	0.002^{*}
	Control	28	2.057	33.488	0.168		
	Intervention	25	-0.099	52.254	0.662		

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the Design Task, the mean Oxy-Hb in the rDLPFC for the Active Control group was significantly lower than both the Control ($p = 0.003$, Cohen's $d = 0.939$) and the Intervention ($p = 0.016$, Cohen's $d = 0.757$) groups, with large and medium to large effect sizes.

Activation in the rVLPFC during the Restoration Break and in the rDLPFC during the Design Task were tested for correlations for all groups. Results indicated a negative correlation between activation in these two ROIs in the two experiment phases. A strong negative correlation was found for the Intervention group (r = -0.545, *p* = 0.006). The Active Control group had a moderate strength correlation (r = -0.311, *p* = 0.122), while the Control group had a weak correlation (r = -0.271, *p* = 0.172).

2.3.4 Subjective data

2.3.4.1 In the moment feeling

2.3.4.1.1 Baseline Stress Level

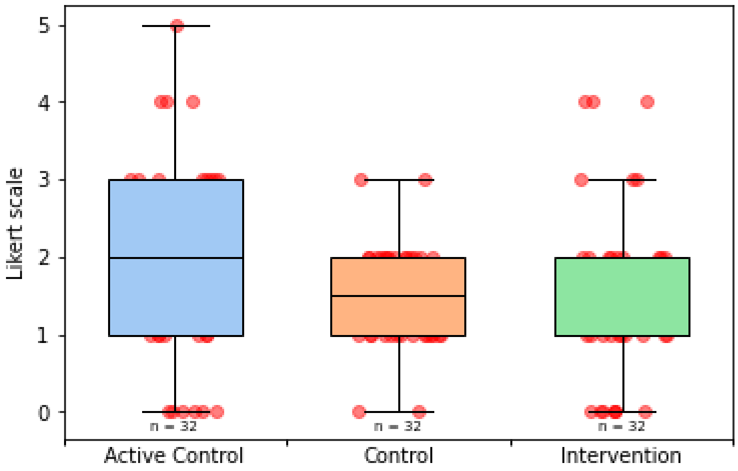


Figure 2.18 Self-reported baseline stress level.

No significant difference (*t* = 2.150, *p* = 0.341) was found between the Active Control (M = 1.938, SD = 1.390), Control (M = 1.500, SD = 0.718), and Intervention (M = 1.531, SD = 1.218) groups for the self-reported baseline stress level.

2.3.4.1.2 Post TSST Stress Level

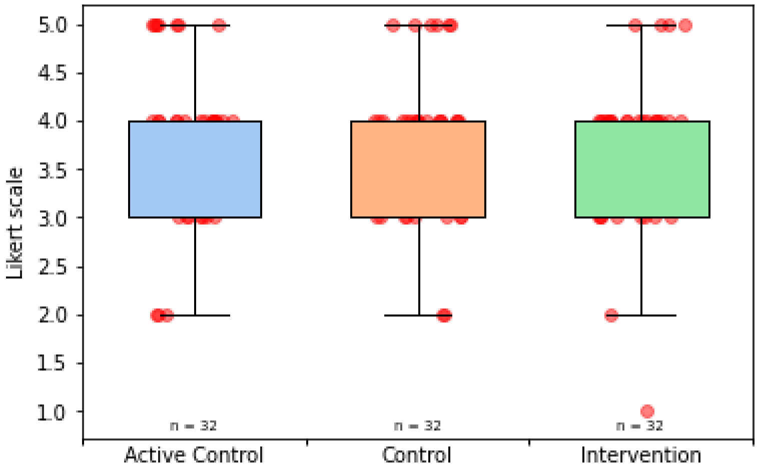


Figure 2.19 Self-reported stress level post-TSST.

No significant difference (*t* = 0.205, *p* = 0.903) was found between the Active Control (M = 3.813, SD = 0.896), Control (M = 3.813, SD = 0.821), and Intervention (M = 3.719, SD = 0.851) groups for the self-reported stress level post TSST.

2.3.4.1.3 Relaxation Level Post Restoration Break

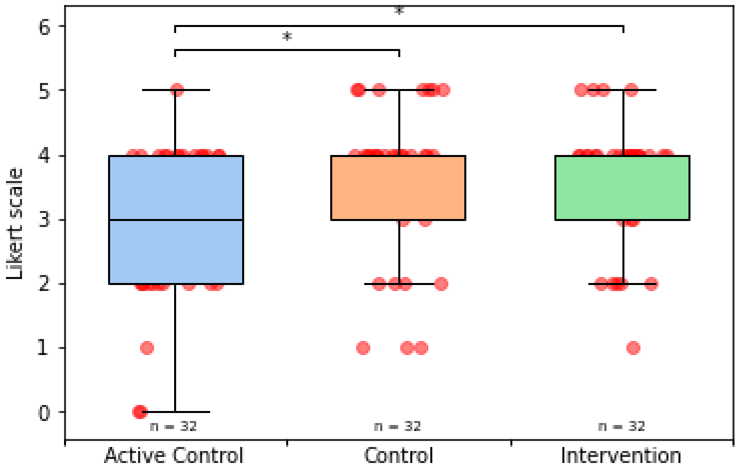


Figure 2.20 Self-reported relaxation level post Restoration Break.

A non-parametric ANOVA test indicated that a significant difference (*t* = 7.267, *p* = 1.238) existed between groups for the self-reported relaxation level post restoration break. A post hoc

T-test indicated that both the Control (M = 3.625, SD = 1.238) and the Intervention (M = 3.625, SD = 1.008) groups reported a higher relaxation level than the Active Control group (M = 2.938, SD = 1.268). The comparison between the Control and the Active Control groups returned a *p*-value of 0.032 and a Cohen's *d* of 0.549. The comparison between the Intervention and the Active Control groups returned a *p*-value of 0.019 and a Cohen's *d* of 0.600. When the Holm-Bonferroni p-value adjustment was applied, p-values were 0.064 (Active Control vs Control) and 0.058 (Active Control vs Intervention).

2.3.4.1.4 Mental Demand from Design Task

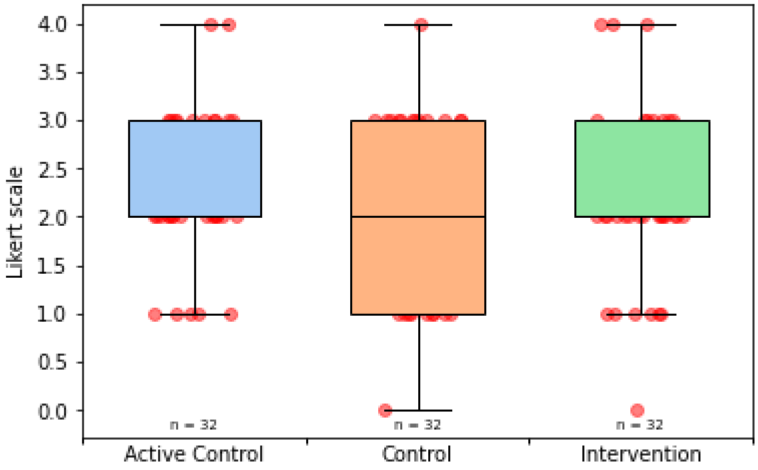


Figure 2.21 Self-reported mental demand from Design Task.

No significant difference ($t = 0.526$, $p = 0.769$) was found between the Active Control (M = 2.281, SD = 0.813), Control (M = 2.094, SD = 0.963), and Intervention (M = 2.156, SD = 0.954) groups for the self-reported mental demand from the design task.

2.3.4.2 Connectedness to Nature

Table 2.17 Statistical analysis for the scores in the pre- and post- experiment NR-6.

Phase	Group	n	Mean	SD	Shapiro-Wilk *p*-value	t	*p*-value
Pre-experiment	Active Control	32	3.786	0.565	0.051	1.502	0.228
	Control	32	3.792	0.558	0.124		
	Intervention	32	3.557	0.717	0.520		
Post-experiment	Active Control	32	3.745	0.629	0.684	2.450	0.092
	Control	32	3.667	0.709	0.390		
	Intervention	32	3.365	0.825	0.498		

Statistical analysis utilizing the mean scores for the NR-6 showed that no significant difference existed between groups either before or after the experiment.

2.4 Discussion

The goal of this study was to expand the available literature on the restorative potential of biophilic auditory experiences by investigating effects to body and brain post induced psychological stress. Our hypotheses were formulated on the basis of the SRT (Ulrich et al., 1991), the ART (Kaplan & Kaplan, 1989; Kaplan, 1995), and findings from previous research, which had shown that listening to nature sounds could induce physiological restoration by reducing cortisol levels (Thoma et al., 2013, 2018), reducing SCL (Alvarsson et al., 2010), and increasing HRV (Song et al., 2023) and also induce neurocognitive restoration by reducing Oxy-Hb concentrations both in the left and the right side of the PFC (Jo et al., 2019; Song et al., 2023). We expected to see similar levels of physiological arousal and brain activity in between groups during the TSST. Then, due to the different auditory experiences, neurocognitive and physiological resources would be restored at different rates throughout the Restoration Break. Lastly, we expected the restorative effects to be carried over into the Design Task, with the Intervention group seeing the task as less mentally demanding given potential differences in availability of neurocognitive resources.

During the TSST, all predictions were confirmed by the data. No significant differences existed between groups for any of the dependent variables. Given all subjects had gone through the exact same procedure, and the sample size was large enough to normalize any individual differences, the findings were cohesive with expectations. During the Restoration Break, it was hypothesized that both EDA and HRV data would indicate higher PNS and lower SNS activity for the

Intervention Group. Nonetheless, our results show that the complete opposite happened. Furthermore, it happened with statistical significance and large effect size. While listening to birdsong and water sounds during the Restoration Break, participants in the Intervention Group had significantly higher SCL (see Table 2.4 and Fig. 2.4) and LF/HF (see Tables 2.6 and Fig. 2.6) when compared to both of the other groups. The Intervention Group also had significantly lower mean RMSSD (see Table 2.7). These results suggest that participants in the Intervention Group were induced to greater physiological arousal during the Restoration Break.

Unexpected results that go on the opposite direction of what has been hypothesized can stem from three possible reasons: (1) our understanding of the world is incomplete; (2) these results are just an artifact of some hidden underlying cause; or (3) the experiment is flawed. Our understanding of the mechanics behind the restorative effects of biophilic experiences is indeed incomplete and many knowledge gaps exist in the literature. One of them is the relationship between perceived stress and physiological arousal. For example, the idea that the body's response to an environmental demand can either be accompanied by unpleasant ("distress") or pleasant ("eustress") feelings has been discussed for decades (Cronholm, 1976). From the perspective of Hans Selye, independent of the "stressor", the stressful state will be built and processed by the individual, giving room for a range of different factors (e.g. genetic or environmental) to influence the behavioral response. Given this theoretical background, hidden underlying causes for the contradictory results could include individual differences in stress adaptation between participants or another missing confounding variable. For example, when investigating responses to naturalistic versus artificial sounds, Gould van Praag et al. (2017) found a relationship between physiological arousal and baseline neural connectivity.

The contradiction observed in our study is not unprecedented. In 2023, Ojala et al. conducted a study that compared the effects of exposure to natural versus artificial materials. Participants in the wooden room presented higher physiological arousal during the rest period, albeit indicating greater feelings of restoration and higher positive affect (Ojala et al., 2023). In our study, after the Restoration Break, participants that listened to nature sounds reported their relaxation level at a 3.625 out 5, significantly higher than participants who listened to traffic noise (see Fig. 2.19). Even though participants in the Intervention Group felt more relaxed, their physiological data tell us something about the birdsong and water sounds elicited more arousal.

In Medvedev et al.'s 2015 study, participants were asked to rate four different soundscapes (birdsong, ocean, road noise, and construction) on the metrics of pleasantness, arousal, familiarity, eventfulness, and dominance. Participants rated the natural soundscapes (birdsong and ocean sounds) as the most pleasant, but, at the same time, the most arousing. A possible explanation for the conflicting results found in our study in regards to physiological responses could lie within the context of core affect, "which is defined as an integral blend of the dimensions displeasure-pleasure (valence) and passive-active (arousal)" (Andringa & Lanser, 2013). In this context, a pleasant and passive experience could induce relaxation and enable the restoration of resources, whereas a pleasant and eventful experience can increase arousal and interest (Russell, 2003). By being pleasant and arousing at the same time, birdsong and water sounds could have elicited a stimulating, rather than a relaxing, state. A possible flaw within our experiment design was to not have included metrics of valence and arousal as potential confounding variables. Participants should have been given an opportunity to assess the quality of their experience during the restoration break, beyond reporting how relaxed they felt after it.

Hypothesis 2 was partially supported by the fNIRS data. Although the mean Oxy-Hb concentration across the PFC was the lowest for participants who received the biophilic auditory experience during the Restoration Break, the differences between groups were not statistically significant. During the Design Task, the active control group showed a significantly lower recruitment of Oxy-Hb across the PFC when compared to the control group, with a large effect size (see Table 2.14). By looking at the diagram in Figure 13, depicting the changes in brain activity throughout the experiment's phases, one should notice how the transition from the Restoration Break to the Design Task had a completely different effect on participants who listened to the traffic noises, when compared to the other two groups. A possible explanation for this rather interesting observation is that even being as cognitively demanding as a task could be, the Design Task inflicted less mental load on the active control group than the processes of cognitive appraisal of threat and inhibitory control triggered by the urban auditory experience. Both Jo et al. (2019) and Song et al. (2023) had found significant differences when splitting the PFC between left and right sides. The number of channels of our fNIRS device allowed us to tap into the granularity of the data by splitting the PFC into different ROIs. During the Restoration Break, the active control group had higher activation in the right VLPFC, a region believed to be associated with inhibitory control and the regulation of cognitive and emotional responses (Depue et al., 2016; Friedman & Robbins, 2022; Laird et al., 2011). These results suggest that participants in active control group had to spend significantly more neurocognitive resources during the supposed restoration break in order to adapt to and cope with the salience of the urban sounds (Kohn et al., 2014). On the other hand, the group that listened to birdsong and water sounds had the lowest activation in the right VLPFC, indicating that the pleasantness of the auditory experience spared these participants' brains from putting much effort towards emotional or cognitive regulation. Directed attention is exercised when distractions are ignored through inhibitory control (S. Kaplan, 1995). The lower activation in the right VLPFC indicates the rest of directed attention during exposure to nature sounds, adding confirmatory evidence to the ART.

With the absence of external stimuli, regions of the brain associated with inhibitory control were expected to rest during the Design Task, while the recruitment of resources for performing the task could vary depending on the availability of resources. During the Design Task, significant differences were again found between groups in a right-lateralized fronto-parietal region. The active control group recruited significantly less Oxy-Hb to the right DLPFC, a region associated with attention control (Kohn et al., 2014), than both the control and the intervention groups. Right-lateralized fronto-parietal regions are not only associated with inhibitory control, but are also engaged in other cognitive abilities and processes such as "working memory, … the capacity to focus attention and screen out the effects of interfering information, and the ability to formulate and to adjust action plans", which are arguably essential for design (Mezzacappa, 2017). After having the neurocognitive resources available consumed by the right VLPFC during the (tentative) Restoration Break, participants in the active control group could not engage an essential brain region for the Design Task, the rDLPFC, as well as the other groups. Both the Control and the Intervention groups, under the given auditory stimulus during the Restoration Break, did not need to regulate salient signals and were consequently better able to recruit their cognitive resources for the Design Task, utilizing the resources in the rDLPFC more efficiently.

Even though no statistically significant differences were found between groups for Connectedness to Nature, it was interesting to notice changes within groups from the pre-experiment NR-6 to the after the experiment NR-6. It was anticipated that the group that listened to birdsong and water sounds would potentially score higher in the NR-6 after the experiment. Exposure biophilic experiences have been shown to improve connectedness to nature, as well as increase pro-environmental awareness (Leung et al., 2022; Mackay & Schmitt, 2019). In spite of that, the intervention group saw a decrease in their NR-6 score after the experiment. This decrease is contradictory to the findings of Leung et al. (2022), who found that "virtual nature exposure had small to medium effects on increasing connectedness to nature among individuals with low CN at baseline."

2.4.1 Limitations

One limitation of this study is the absence of a subjective measure of the auditory experiences' quality. Even though participants were asked how relaxed they felt after the Restoration Break, information about how they perceived the auditory experience could have supported the analysis of the physiological responses by revealing their affective states, as suggested by Medvedev et al. (2015). In light of this, future research should give participants an opportunity to assess the auditory experience in terms of pleasantness, arousal, familiarity, eventfulness, and dominance (Axelsson et al., 2010). Another limitation is the absence of another potentially pleasant auditory experience that is not biophilic. As most published studies (Alvarsson et al., 2010; Jo et al., 2019; Krzywicka & Byrka, 2017; I. Song et al., 2023) exploring the restorative potential of biophilic auditory experiences, we utilized traffic/urban noises and silence as control exposures. The addition of music as one of the auditory experiences, specifically as another "pleasant" experience, could have expanded the possibility of discussion on the role of biophilia in the restorative potential of auditory experiences, adding on to the works of Thoma et al. (2013) and Medvedev et al. (2015). However, studies published so far show that when compared, biophilic auditory experiences yielded greater restorative effects than "calming" music (Thoma et al., 2013).

Given all participants in the study were engineering students, the sample characteristics is yet another limitation. For the findings to be truly generalizable, more data needs to be collected with professionals in design-related careers. Although one could argue that the high variance for some of the variables also presents a limitation to the study results, the several precautions made during the statistical analysis safeguard the validity of the findings. Some of the steps used as precaution include (1) removing outliers using the IQR method, (2) calculating the effect size using Cohen's d, and (3) applying the Holm-Bonferroni *p*-value adjustment.

2.4.2 Future work

As a next step in assessing the restorative potential of biophilic auditory experiences to cognition, we plan to assess the quality of the design concepts produced in the study. We are interested in exploring if the different types of auditory experience influenced participants' design ideas and allowed differential engagement of brain networks. Could the availability of neurocognitive resources and differences in brain functional connectivity influence the production of more original design ideas? Could the different auditory experiences influence the incorporation of natural or urban elements in the design ideas?

2.5 Conclusion

The goal for this study was to explore the effects of a biophilic auditory experience on the restoration of physiological and neurocognitive resources post induced psychological stress. A total of 96 participants, randomly split into three groups, had their physiological and neurocognitive responses tracked throughout a three-phase experiment, including a social stress test, a restoration break, and a design task. Results were partially contradictory. The data indicated that the biophilic auditory experience had the lowest restoration effect to physiological resources, but the highest restoration effect on neurocognitive resources. Subjective data showed that participants who listened to traffic noises felt the least relaxed, while those who enjoyed the silence or the natural sounds tied at the same level of relaxation. The findings presented in this paper demonstrate that more research is needed to understand the restorative effects of biophilic auditory experiences, especially as it relates to how the subjective experience affects the neurocognitive and physiological responses.

Credit authorship contribution statement

Ignacio Jr. contributed to the development of the research questions, data collection, data analysis, and manuscript writing. Shealy contributed to the development of the research question, grant management, feedback on data analysis, and manuscript writing.

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BioBuild.

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Declaration of competing interest

None.

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Appendix A. Screening survey

Thank you for your interest in participating in our study. The questions below help us to identify potential participants that fit our study design. Please answer all questions to the best of your knowledge. All the information shared in this form will be kept confidential.

First Name

Last Name

Phone

Email Address

Have you ever been diagnosed with any cardiovascular conditions?

1. Yes
2. No

Have you ever been diagnosed with any neurological conditions?

1. Yes
2. No

Have you ever been diagnosed with any psychiatric condition?

1. Yes
2. No

Do you have any auditory impairment?

1. Yes
2. No

Do you have any vision impairment?

1. Yes
2. No

Do you take any prescription drugs for anxiety, depression, or stress-related conditions?

1. Yes
2. No

Have you ever dealt with alcohol dependency?

1. Yes
2. No

Have you ever dealt with illegal drugs dependency?

1. Yes
2. No

References

Alvarsson, J. J., Wiens, S., & Nilsson, M. E. (2010). Stress Recovery during Exposure to Nature Sound and Environmental Noise. *International Journal of Environmental Research and Public Health*, *7*(3), Article 3. https://doi.org/10.3390/ijerph7031036

Andringa, T. C., & Lanser, J. J. L. (2013). How Pleasant Sounds Promote and Annoying Sounds Impede Health: A Cognitive Approach. *International Journal of Environmental Research and Public Health*, *10*(4), Article 4. https://doi.org/10.3390/ijerph10041439

Annerstedt, M., Jönsson, P., Wallergård, M., Johansson, G., Karlson, B., Grahn, P., Hansen, Å. M., & Währborg, P. (2013). Inducing physiological stress recovery with sounds of nature in a virtual reality forest—Results from a pilot study. *Physiology & Behavior*, *118*, 240–250. https://doi.org/10.1016/j.physbeh.2013.05.023

Aristizabal, S., Byun, K., Porter, P., Clements, N., Campanella, C., Li, L., Mullan, A., Ly, S., Senerat, A., Nenadic, I. Z., Browning, W. D., Loftness, V., & Bauer, B. (2021). Biophilic office design: Exploring the impact of a multisensory approach on human well-being. *Journal of Environmental Psychology*, *77*, 101682. https://doi.org/10.1016/j.jenvp.2021.101682

Arnsten, A. F. (1998). Catecholamine modulation of prefrontal cortical cognitive function. *Trends in Cognitive Sciences*, *2*(11), 436–447. https://doi.org/10.1016/s1364-6613(98)01240-6

Arnsten, A. F. T. (2009). Stress signalling pathways that impair prefrontal cortex structure and function. *Nature Reviews. Neuroscience*, *10*(6), 410–422. https://doi.org/10.1038/nrn2648

Axelsson, Ö., Nilsson, M. E., & Berglund, B. (2010). A principal components model of soundscape perception. *The Journal of the Acoustical Society of America*, *128*(5), 2836–2846. https://doi.org/10.1121/1.3493436

Barton, J., & Pretty, J. (2010). What is the Best Dose of Nature and Green Exercise for Improving Mental Health? A Multi-Study Analysis. *Environmental Science & Technology*, *44*(10), 3947–3955. https://doi.org/10.1021/es903183r

Basil, M. D. (2012). Multiple Resource Theory. In N. M. Seel (Ed.), *Encyclopedia of the Sciences of Learning* (pp. 2384–2385). Springer US. https://doi.org/10.1007/978-1-4419-1428-6_25

Berman, M. G., Jonides, J., & Kaplan, S. (2008). The Cognitive Benefits of Interacting With Nature. *Psychological Science*, *19*(12), 1207–1212. https://doi.org/10.1111/j.1467-9280.2008.02225.x

Beversdorf, D. Q., Hughes, J. D., Steinberg, B. A., Lewis, L. D., & Heilman, K. M. (1999). Noradrenergic modulation of cognitive flexibility in problem solving: *NeuroReport*, *10*(13), 2763–2767. https://doi.org/10.1097/00001756-199909090-00012

Bratman, G. N., Hamilton, J. P., Hahn, K. S., Daily, G. C., & Gross, J. J. (2015). Nature experience reduces rumination and subgenual prefrontal cortex activation. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(28), 8567–8572. https://doi.org/10.1073/pnas.1510459112

Calvo, M. G., & Gutiérrez-García, A. (2016). Chapter 16—Cognition and Stress. In G. Fink (Ed.), *Stress: Concepts, Cognition, Emotion, and Behavior* (pp. 139–144). Academic Press. https://doi.org/10.1016/B978-0-12-800951-2.00016-9

Coughlan, A., Ross, E., Nikles, D., De Cesare, E., Tran, C., & Pensini, P. (2022). Nature guided imagery: An intervention to increase connectedness to nature. *Journal of Environmental Psychology*, *80*, 101759. https://doi.org/10.1016/j.jenvp.2022.101759

Cronholm, B. (1976). Concluding Remarks. In G. Serban (Ed.), *Psychopathology of Human Adaptation* (pp. 359–362). Springer US. https://doi.org/10.1007/978-1-4684-2238-2_22

Dantzer, R. (2016). Chapter 6 - Behavior: Overview. In G. Fink (Ed.), *Stress: Concepts, Cognition, Emotion, and Behavior* (pp. 57–63). Academic Press. https://doi.org/10.1016/B978-0-12-800951-2.00006-6

Delos Living LLC. (2020). *MindBreaks—Relax & Recharge* (1.0.12) [Computer software]. Delos Living LLC. https://apps.apple.com/us/app/mindbreaks-relax-recharge/id1498782851

Deng, L., Luo, H., Ma, J., Huang, Z., Sun, L.-X., Jiang, M.-Y., Zhu, C.-Y., & Li, X. (2020). Effects of integration between visual stimuli and auditory stimuli on restorative potential and aesthetic preference in urban green spaces. *Urban Forestry & Urban Greening*, *53*, 126702. https://doi.org/10.1016/j.ufug.2020.126702

Depue, B. E., Orr, J. M., Smolker, H. R., Naaz, F., & Banich, M. T. (2016). The Organization of Right Prefrontal Networks Reveals Common Mechanisms of Inhibitory Regulation Across Cognitive, Emotional, and Motor Processes. *Cerebral Cortex*, *26*(4), 1634–1646. https://doi.org/10.1093/cercor/bhu324

Ergan, S., Radwan, A., Zou, Z., Tseng, H., & Han, X. (2019). Quantifying Human Experience in Architectural Spaces with Integrated Virtual Reality and Body Sensor Networks. *Journal of Computing in Civil Engineering*, *33*(2), 04018062. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000812

Ernst, G. (2017). Heart-Rate Variability—More than Heart Beats? *Frontiers in Public Health*, *5*. https://www.frontiersin.org/article/10.3389/fpubh.2017.00240

Fishburn, F. A., Ludlum, R. S., Vaidya, C. J., & Medvedev, A. V. (2019). Temporal Derivative Distribution Repair (TDDR): A motion correction method for fNIRS. *NeuroImage*, *184*, 171–179. https://doi.org/10.1016/j.neuroimage.2018.09.025

Friedman, N. P., & Robbins, T. W. (2022). The role of prefrontal cortex in cognitive control and executive function. *Neuropsychopharmacology*, *47*(1), Article 1. https://doi.org/10.1038/s41386-021-01132-0

Gaekwad, J. S., Sal Moslehian, A., & Roös, P. B. (2023). A meta-analysis of physiological stress responses to natural environments: Biophilia and Stress Recovery Theory perspectives. *Journal of Environmental Psychology*, *90*, 102085. https://doi.org/10.1016/j.jenvp.2023.102085

Goldstein, D. S. (2013). Chapter 2—Differential responses of components of the autonomic nervous system. In R. M. Buijs & D. F. Swaab (Eds.), *Handbook of Clinical Neurology* (Vol. 117, pp. 13–22). Elsevier. https://doi.org/10.1016/B978-0-444-53491-0.00002-X

Goodman, W. K., Janson, J., & Wolf, J. M. (2017). Meta-analytical assessment of the effects of protocol variations on cortisol responses to the Trier Social Stress Test. *Psychoneuroendocrinology*, *80*, 26–35. https://doi.org/10.1016/j.psyneuen.2017.02.030

Gould van Praag, C. D., Garfinkel, S. N., Sparasci, O., Mees, A., Philippides, A. O., Ware, M., Ottaviani, C., & Critchley, H. D. (2017). Mind-wandering and alterations to default mode network connectivity when listening to naturalistic versus artificial sounds. *Scientific Reports*, *7*(1), Article 1. https://doi.org/10.1038/srep45273

Hedblom, M., Gunnarsson, B., Iravani, B., Knez, I., Schaefer, M., Thorsson, P., & Lundström, J. (2019). Reduction of physiological stress by urban green space in a multisensory virtual experiment. *Scientific Reports*, *9*. https://doi.org/10.1038/s41598-019-46099-7

Igarashi, M., Yamamoto, T., Lee, J., Song, C., Ikei, H., & Miyazaki, Y. (2014). Effects of stimulation by three-dimensional natural images on prefrontal cortex and autonomic nerve activity: A comparison with stimulation using two-dimensional images. *Cognitive Processing*, *15*(4), 551–556. https://doi.org/10.1007/s10339-014-0627-z

Ignacio Junior, P., & Shealy, T. (2023). EFFECTS OF BIOPHILIC RESTORATIVE EXPERIENCES ON DESIGNERS' BODIES, BRAINS, AND MINDS. *Proceedings of the Design Society*, *3*, 1565–1574. https://doi.org/10.1017/pds.2023.157

Jo, H., Song, C., Ikei, H., Enomoto, S., Kobayashi, H., & Miyazaki, Y. (2019). Physiological and Psychological Effects of Forest and Urban Sounds Using High-Resolution Sound Sources. *International Journal of Environmental Research and Public Health*, *16*(15), Article 15. https://doi.org/10.3390/ijerph16152649

Kahneman, D. (1973). *Attention and effort.* Prentice-Hall.

Kaplan, R., & Kaplan, S. (1989). *The experience of nature: A psychological perspective*. Cambridge University Press.

Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology*, *15*(3), 169–182. https://doi.org/10.1016/0272-4944(95)90001-2

Kellert, S. R. (2005). *Building for life: Designing and understanding the human-nature connection* (1–1 online resource (x, 250 pages) : illustrations). Island Press. http://site.ebrary.com/id/10149925

Kellert, S. R., Heerwagen, J., & Mador, M. (2011). *Biophilic Design: The Theory, Science and Practice of Bringing Buildings to Life*. John Wiley & Sons.

Kellert, S. R., & Wilson, E. O. (1993). *The Biophilia Hypothesis*. Island Press.

Kim, H.-G., Cheon, E.-J., Bai, D.-S., Lee, Y. H., & Koo, B.-H. (2018). Stress and Heart Rate Variability: A Meta-Analysis and Review of the Literature. *Psychiatry Investigation*, *15*(3), 235–245. https://doi.org/10.30773/pi.2017.08.17

Kim, J., Cha, S. H., Koo, C., & Tang, S. (2018). The effects of indoor plants and artificial windows in an underground environment. *Building and Environment*, *138*, 53–62. https://doi.org/10.1016/j.buildenv.2018.04.029

Kocsis, L., Herman, P., & Eke, A. (2006). The modified Beer–Lambert law revisited. *Physics in Medicine & Biology*, *51*(5), N91. https://doi.org/10.1088/0031-9155/51/5/N02

Krzywicka, P., & Byrka, K. (2017). Restorative Qualities of and Preference for Natural and Urban Soundscapes. *Frontiers in Psychology*, *8*. https://www.frontiersin.org/articles/10.3389/fpsyg.2017.01705

Labuschagne, I., Grace, C., Rendell, P., Terrett, G., & Heinrichs, M. (2019). An introductory guide to conducting the Trier Social Stress Test. *Neuroscience & Biobehavioral Reviews*, *107*, 686–695. https://doi.org/10.1016/j.neubiorev.2019.09.032

Laird, A. R., Fox, P. M., Eickhoff, S. B., Turner, J. A., Ray, K. L., McKay, D. R., Glahn, D. C., Beckmann, C. F., Smith, S. M., & Fox, P. T. (2011). Behavioral interpretations of intrinsic connectivity networks. *Journal of Cognitive Neuroscience*, *23*(12), 4022–4037. https://doi.org/10.1162/jocn_a_00077

Lederbogen, F., Kirsch, P., Haddad, L., Streit, F., Tost, H., Schuch, P., Wüst, S., Pruessner, J. C., Rietschel, M., Deuschle, M., & Meyer-Lindenberg, A. (2011). City living and urban upbringing affect neural social stress processing in humans. *Nature*, *474*(7352), Article 7352. https://doi.org/10.1038/nature10190

Leung, G., Hazan, H., & Chan, C. S. (2022). Exposure to nature in immersive virtual reality increases connectedness to nature among people with low nature affinity. *Journal of Environmental Psychology*, 101863. https://doi.org/10.1016/j.jenvp.2022.101863

Li, D., & Sullivan, W. C. (2016). Impact of views to school landscapes on recovery from stress and mental fatigue. *Landscape and Urban Planning*, *148*, 149–158. https://doi.org/10.1016/j.landurbplan.2015.12.015

Liston, C., McEwen, B. S., & Casey, B. J. (2009). Psychosocial stress reversibly disrupts prefrontal processing and attentional control. *Proceedings of the National Academy of Sciences*, *106*(3), 912–917. https://doi.org/10.1073/pnas.0807041106

Liszio, S., Graf, L., & Masuch, M. (2018). The relaxing effect of virtual nature: Immersive technology provides relief in acute stress situations. *Annual Review of CyberTherapy and Telemedicine*, *16*, 87–93.

Luo, L., & Jiang, B. (2022). From oppressiveness to stress: A development of Stress Reduction Theory in the context of contemporary high-density city. *Journal of Environmental Psychology*, *84*, 101883. https://doi.org/10.1016/j.jenvp.2022.101883

Mackay, C. M. L., & Schmitt, M. T. (2019). Do people who feel connected to nature do more to protect it? A meta-analysis. *Journal of Environmental Psychology*, *65*, 101323. https://doi.org/10.1016/j.jenvp.2019.101323

Maller, C., Townsend, M., Pryor, A., Brown, P., & St Leger, L. (2006). Healthy nature healthy people: 'Contact with nature' as an upstream health promotion intervention for populations. *Health Promotion International*, *21*(1), 45–54. https://doi.org/10.1093/heapro/dai032

Marques, S., & Lima, M. L. (2011). Living in grey areas: Industrial activity and psychological health. *Journal of Environmental Psychology*, *31*(4), 314–322. https://doi.org/10.1016/j.jenvp.2010.12.002

Mayer, F., Frantz, C., Bruehlman-Senecal, E., & Dolliver, K. (2009). Why Is Nature Beneficial?The Role of Connectedness to Nature. *Environment and Behavior - ENVIRON BEHAV*, *41*, 607–643. https://doi.org/10.1177/0013916508319745

McCarty, R. (2016). Chapter 4 - The Fight-or-Flight Response: A Cornerstone of Stress Research. In G. Fink (Ed.), *Stress: Concepts, Cognition, Emotion, and Behavior* (pp. 33–37). Academic Press. https://doi.org/10.1016/B978-0-12-800951-2.00004-2

McSweeney, J., Johnson, S., Sherry, S., Singleton, J., & Rainham, D. (2021). Indoor nature exposure and influence on physiological stress markers. *International Journal of Environmental Health Research*, *31*(6), 636–650. https://doi.org/10.1080/09603123.2019.1679357

Medvedev, O., Shepherd, D., & Hautus, M. J. (2015). The restorative potential of soundscapes: A physiological investigation. *Applied Acoustics, 96*, 20–26. https://doi.org/10.1016/j.apacoust.2015.03.004

Mezzacappa, E. (2017). Executive Function. In *Reference Module in Neuroscience and Biobehavioral Psychology*. Elsevier. https://doi.org/10.1016/B978-0-12-809324-5.06001-6

Milovanovic, J., Hu, M., Shealy, T., & Gero, J. (2020, November 3). *Evolution of Brain Network Connectivity in the Prefrontal Cortex During Concept Generation Using Brainstorming for a Design Task.* ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. https://doi.org/10.1115/DETC2020-22563

Miyazaki, Y., Park, B.-J., & Lee, J. (2011). Nature therapy. In *Designing our future: Local perspectives on bioproduction, ecosystems and humanity* (pp. 407–412). UN University Press. https://digitallibrary.un.org/record/698814

Nisbet, E. K., & Zelenski, J. M. (2013). The NR-6: A new brief measure of nature relatedness. *Frontiers in Psychology*, *4*, 813. https://doi.org/10.3389/fpsyg.2013.00813

Ojala, A., Kostensalo, J., Viik, J., Matilainen, H., Wik, I., Virtanen, L., & Muilu-Mäkelä, R. (2023). Psychological and physiological effects of a wooden office room on human well-being: Results from a randomized controlled trial. *Journal of Environmental Psychology, 89*, 102059. https://doi.org/10.1016/j.jenvp.2023.102059

Ojala, A., Neuvonen, M., Kurkilahti, M., Leinikka, M., Huotilainen, M., & Tyrväinen, L. (2022). Short virtual nature breaks in the office environment can restore stress: An experimental study. *Journal of Environmental Psychology*, *84*, 101909. https://doi.org/10.1016/j.jenvp.2022.101909

Park, B.-J., Tsunetsugu, Y., Lee, J., Kagawa, T., & Miyazaki, Y. (2011). Effect of the forest environment on physiological relaxation using the results of field tests at 35 sites throughout Japan. *Forest Medicine*, 57–67.

Peltola, M. (2012). Role of editing of R-R intervals in the analysis of heart rate variability. *Frontiers in Physiology, 3*. https://www.frontiersin.org/articles/10.3389/fphys.2012.00148

Pinti, P., Scholkmann, F., Hamilton, A., Burgess, P., & Tachtsidis, I. (2019). Current Status and Issues Regarding Pre-processing of fNIRS Neuroimaging Data: An Investigation of Diverse Signal Filtering Methods Within a General Linear Model Framework. *Frontiers in Human Neuroscience, 12,* 505. https://doi.org/10.3389/fnhum.2018.00505

Rajendra Acharya, U., Paul Joseph, K., Kannathal, N., Lim, C. M., & Suri, J. S. (2006). Heart rate variability: A review. *Medical and Biological Engineering and Computing, 44*(12), 1031–1051. https://doi.org/10.1007/s11517-006-0119-0

Rashid, M., & Zimring, C. (2008). A Review of the Empirical Literature on the Relationships Between Indoor Environment and Stress in Health Care and Office Settings: Problems and

Prospects of Sharing Evidence. *Environment and Behavior*, *40*(2), 151–190. https://doi.org/10.1177/0013916507311550

Ratcliffe, E., Gatersleben, B., & Sowden, P. T. (2013). Bird sounds and their contributions to perceived attention restoration and stress recovery. *Journal of Environmental Psychology*, *36*, 221–228. https://doi.org/10.1016/j.jenvp.2013.08.004

Russell, J. A. (2003). Core affect and the psychological construction of emotion. *Psychological Review*, *110*(1), 145–172. https://doi.org/10.1037/0033-295X.110.1.145

Santosa, H., Zhai, X., Fishburn, F., & Huppert, T. (2018). The NIRS Brain AnalyzIR Toolbox. *Algorithms*, *11*(5), Article 5. https://doi.org/10.3390/a11050073

Schnell, I., Potchter, O., Epstein, Y., Yaakov, Y., Hermesh, H., Brenner, S., & Tirosh, E. (2013). The effects of exposure to environmental factors on Heart Rate Variability: An ecological perspective. *Environmental Pollution*, *183*, 7–13. https://doi.org/10.1016/j.envpol.2013.02.005

Shealy, T., Gero, J., Ignacio Junior, P., & Song, I. (2023). CHANGES IN COGNITION AND NEUROCOGNITION WHEN THINKING ALOUD DURING DESIGN. *Proceedings of the Design Society*, *3*, 867–876. https://doi.org/10.1017/pds.2023.87

Song, C., Ikei, H., Kagawa, T., & Miyazaki, Y. (2020). Effect of Viewing Real Forest Landscapes on Brain Activity. *Sustainability*, *12*(16), Article 16. https://doi.org/10.3390/su12166601

Song, C., Ikei, H., & Miyazaki, Y. (2021). Effects of forest-derived visual, auditory, and combined stimuli. *Urban Forestry & Urban Greening*, *64*, 127253. https://doi.org/10.1016/j.ufug.2021.127253

Song, I., Baek, K., Kim, C., & Song, C. (2023). Effects of nature sounds on the attention and physiological and psychological relaxation. *Urban Forestry & Urban Greening*, *86*, 127987. https://doi.org/10.1016/j.ufug.2023.127987

Stevenson, M. P., Schilhab, T., & Bentsen, P. (2018). Attention Restoration Theory II: A systematic review to clarify attention processes affected by exposure to natural environments. *Journal of Toxicology and Environmental Health, Part B*, *21*(4), 227–268. https://doi.org/10.1080/10937404.2018.1505571

Thayer, J. F., Åhs, F., Fredrikson, M., Sollers, J. J., & Wager, T. D. (2012). A meta-analysis of heart rate variability and neuroimaging studies: Implications for heart rate variability as a marker of stress and health. *Neuroscience & Biobehavioral Reviews*, *36*(2), 747–756. https://doi.org/10.1016/j.neubiorev.2011.11.009

Thoma, M. V., Marca, R. L., Brönnimann, R., Finkel, L., Ehlert, U., & Nater, U. M. (2013). The Effect of Music on the Human Stress Response. *PLOS ONE*, *8*(8), e70156. https://doi.org/10.1371/journal.pone.0070156

Thoma, M. V., Mewes, R., & Nater, U. M. (2018). Preliminary evidence: The stress-reducing effect of listening to water sounds depends on somatic complaints. *Medicine, 97*(8), e9851. https://doi.org/10.1097/MD.0000000000009851

Ulrich, R. S. (1981). Natural Versus Urban Scenes: Some Psychophysiological Effects. *Environment and Behavior*, *13*(5), 523–556. https://doi.org/10.1177/0013916581135001

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

United Nations, Department of Economic and Social Affairs, P. D. (2019). *World Urbanization Prospects: The 2018 Revision*. United Nations. https://doi.org/10.18356/b9e995fe-en

Vadlamudi, R. (2018). *LAZY BOYS PRODUCTIONS - YouTube* [YouTube]. https://www.youtube.com/

van den Berg, M. M. H. E., Maas, J., Muller, R., Braun, A., Kaandorp, W., van Lien, R., van Poppel, M. N. M., van Mechelen, W., & van den Berg, A. E. (2015). Autonomic Nervous System Responses to Viewing Green and Built Settings: Differentiating Between Sympathetic and Parasympathetic Activity. *International Journal of Environmental Research and Public Health*, *12*(12), 15860–15874. https://doi.org/10.3390/ijerph121215026

Wang, X., Shi, Y., Zhang, B., & Chiang, Y. (2019). The Influence of Forest Resting Environments on Stress Using Virtual Reality. *International Journal of Environmental Research and Public Health*, *16*(18), Article 18. https://doi.org/10.3390/ijerph16183263

Wickens, C. D. (1980). The structure of attentional resources. In *Attention and Performance: Vol. VIII* (1st ed., pp. 239–257).

Wong, D. L., Tai, T. C., Wong-Faull, D. C., Claycomb, R., Meloni, E. G., Myers, K. M., Carlezon, W. A., & Kvetnansky, R. (2012). Epinephrine: A Short- and Long-Term Regulator of Stress and Development of Illness. *Cellular and Molecular Neurobiology, 32*(5), 737–748. https://doi.org/10.1007/s10571-011-9768-0

Yin, J., Arfaei, N., MacNaughton, P., Catalano, P. J., Allen, J. G., & Spengler, J. D. (2019). Effects of biophilic interventions in office on stress reaction and cognitive function: A randomized crossover study in virtual reality. *Indoor Air*, *29*(6), 1028–1039. https://doi.org/10.1111/ina.12593

Yin, J., Yuan, J., Arfaei, N., Catalano, P. J., Allen, J. G., & Spengler, J. D. (2020). Effects of biophilic indoor environment on stress and anxiety recovery: A between-subjects experiment in virtual reality. *Environment International*, *136*, 105427. https://doi.org/10.1016/j.envint.2019.105427

Yin, J., Zhu, S., MacNaughton, P., Allen, J. G., & Spengler, J. D. (2018). Physiological and cognitive performance of exposure to biophilic indoor environment. *Building and Environment*, *132*, 255–262. https://doi.org/10.1016/j.buildenv.2018.01.006

Yücel, M. A., Selb, J., Aasted, C. M., Lin, P.-Y., Borsook, D., Becerra, L., & Boas, D. A. (2016). Mayer waves reduce the accuracy of estimated hemodynamic response functions in functional near-infrared spectroscopy. *Biomedical Optics Express*, *7*(8), 3078–3088. https://doi.org/10.1364/BOE.7.003078

Chapter 3 - Effects of nature-based auditory stimuli on the mind and brain when designing

Introduction

Broadly defined, design is the process of transforming current situations into future, preferred ones, often by creatively envisioning and planning[1]. From this perspective, design plays an important role in shaping our society. By exploring means and methods for enhancing designers' performance, design cognition research aims to contribute to advancement of the human society. Design is a complex and resource intensive process that involves different cognitive abilities, such as divergent thinking, planning, abstract reasoning, and working memory[2,3]. The iterative nature of the process, which can alternate between stages of problem identification, conceptualization, analysis, synthesis, and evaluation, inflict a high cognitive load on the designer[4–6]. Previous research suggests that the high cognitive load associated with design correlates with increased functional connectivity in a region of the brain called prefrontal cortex (PFC)[7]. Specific regions called the dorsolateral prefrontal cortex (DLPFC), the dorsomedial prefrontal cortex (DMPFC), and the ventrolateral prefrontal cortex (VLPFC) are often cited as the main regions engaged during design[7–9]. These brain regions of interest (ROI) are part of distinct networks. While the DMPFC is regarded as the central hub for the default-mode network (DMN), the DLPFC and the VLPFC are main components of the executive control network (ECN)[10–12].

The coupling between these two networks supports the generation of ideas, depending on the constraints established for the task at hand[10,13]. While the spontaneous generation of ideas, facilitated by mind wandering[14–16] and associative processes, is enabled with engagement of the DMN, the evaluation of ideas, in a sort of quality assessment/control fashion, is subject to the ECN[10]. In the context of design cognition, as designers frame and reframe design problems throughout the evolution of the problem-solution space[5,17,18], alternation between DMN and ECN engagement supports the production of creative design concepts, that is, concepts that are novel and useful within that context[19–21].

As a disruptor of prefrontal cortical function, stress, both from acute instances or chronic exposure, can negatively affect knowledge workers performance[22]. Daily life demands can induce psychosocial stress[23], impairing PFC regulated cognitive functions such as creative thought[24], decision-making, and working memory[22,25]. Psychosocial stress can also impair attentional control, and this impairment is correlated with a disruption in the functional connectivity between ROIs in the frontoparietal network[26]. Considering the essentiality of prefrontal cortical functioning in design cognition, designers are subject to performance decrements when stress is built up. Two existing theories in the environmental psychology literature, the Stress Reduction Theory (SRT)[27,28] and the Attention Restoration Theory (ART)[29,30] suggest that positive nature experiences could help one recover from stressful states and restore cognitive resources. Positive interactions with nature-based stimuli, or biophilic experiences, can also facilitate engagement of the DMN, enabling mind wandering processes that can support creativity[16,31,32]. Nonetheless, as the share of the world's population living in urban areas keeps rising, reaching an expected 68% by 2050[33], access to biophilic experiences throughout the work day, which could provide the restoration of resources, becomes limited, if not inexistent[34,35].

Emerging evidence suggests that biophilic experiences through symbolic contact with nature can yield some of the restorative outcomes proposed by the ART and the SRT. For instance, studies utilizing pictures[36,37] or videos[38] of nature, as well as natural environments in virtual reality[39,40], have observed enhancements in cognitive performance and stress reduction post-biophilic experience. To a lesser extent, prior studies have explored the restorative effects of nature sounds, finding birdsong and water sounds to drive the most restorative potential[41–43]. In a sound-focused study exploring mind-wandering and DMN connectivity, subjects were exposed to either naturalistic, artificial, or no-soundscape auditory experiences, while researchers measured behavioral, neural, and physiological effects[44]. Results showed that the naturalistic condition led to higher parasympathetic nervous system activity, indicating lower physiological arousal, as well as better attentional monitoring when compared to the artificial sounds condition. Although results from the fMRI scans did not offer evidence of increased DMN engagement during the naturalistic condition, and albeit limitations due to measurements being made only during the exposure period rather than during and after, findings from this study[44] support the ART and the SRT and encourage further exploration of biophilic auditory experiences.

The cognitive and neurocognitive effects of biophilic experiences have been mainly explored in the context of discrete constrained tasks, such as the Remote Associates Task[31], the Digit Span Backwards test[45], and the Operation Span test[46]. While these standardized tests serve their purpose in assessing individual cognitive capacities, such as working memory or divergent thinking, they do not have the power to inform how biophilic experiences could affect performance in complex tasks that require the simultaneous engagement of different cognitive functions[2,3]. The "neurological patterns of designing tend to differ from problem-solving ones"[5]. Little to no studies have investigated the potential effects on design cognition. Exploring the use of nature-based auditory stimuli for stress-restoration purposes, we investigated how exposure to either birdsong and water sounds, traffic sounds, or silence post induced psychosocial stress can affect neurocognitive mechanisms associated with design cognition and design performance. Derived from findings of previous studies[42,44,47–49], our main idea is that through enhanced restoration from a depleted, stressful state, participants who received the biophilic auditory experience would have more cognitive resources available for the subsequent design task, facilitating better performance. Specifically, we hypothesized that participants in the biophilic condition would (I) show improved functional connectivity in the PFC, which would consequently facilitate associative processes that could (II) enhance the exploration of the design space. We also hypothesized that due to a potential priming effect, participants in the biophilic condition would (III) incorporate more nature in their design concepts.

In an experiment including three phases – stress induction, restoration break, and design task – brain activity was measured by functional near-infrared spectroscopy (fNIRS) throughout all phases. A cohort of healthy college students was randomly split into three groups which would either receive a different auditory experience during the restoration break. After being induced to a stressful state by means of the Trier Social Stress Test (TSST)[50], participants were exposed to either birdsong and water sounds (intervention), heavy traffic sounds (active control), or silence (control).

Following the restoration break, participants were asked to develop a design concept for a playground for young children inside an existing park. Explanations of the design concepts were analyzed semantically to assess originality. fNIRS data was analyzed to assess changes in prefrontal cortical functional connectivity. We observed (I) significantly higher brain functional connectivity, in terms of network density, for participants who listened to nature sounds during the restoration break. In addition, participants in the intervention group showed a larger distribution of central nodes during the design task. When assessing potential temporal changes in prefrontal cortical network engagement throughout the design task period, we found that the intervention group had significantly higher network density during two out of ten evenly split segments. Effects to neurocognition were not reflected on design cognition. No significant differences were found between groups for exploration of the design space. Assessment of the design products for the incorporation of biophilic design showed that connectedness to nature acted as the main influencing factor. However, although contradictory, significant effects were found for the intervention and the active control groups, with participants in the intervention group incorporating significantly less *Material Connection with Nature*, and participants in the active control group incorporating significantly more *Visual Connection with Nature* and *Non-Rhythmic Sensory Stimuli* in their design concepts.

Results

Effects on functional connectivity in the PFC

All participants were induced to a state of heightened psychosocial stress by means of the Trier Social Stress Test (TSST)[50]. The different treatments given during the restoration break consisted of biophilic sounds (birdsong and water sounds, intervention group), heavy road traffic sounds (active control group), or silence (control group). Participants were randomly assigned to one out of the three groups. The restoration break consisted of an 8-minute period in which participants received the auditory stimulus through headphones, while having their eyes closed. Following the restoration break, participants were given the open-ended design task. Changes in the recruitment of oxygenated hemoglobin (Oxy-Hb) to the PFC were recorded throughout the whole experiment through fNIRS. Functional connectivity analysis was utilized to assess the integration between different ROIs in the PFC. The main measure of integration utilized was the network density. The network density score goes from 0 to 1, where the higher the number of edges (i.e. correlations between ROIs), the higher the density.

Previous studies correlate psychosocial stress with a disruption in prefrontal cortical function[22] and functional connectivity in the frontoparietal network[26]. During the TSST, the mean network density was the lowest for all three groups, and no significant differences existed between them ($p > 0.05$) (Fig. 3.1). Linear mixed effects models utilizing a random intercept for participants and adjusted for age, gender, and caffeine consumption within 2 hours prior to the experiment indicated that none of these factors had a confounding effect (models provided in Appendix B).

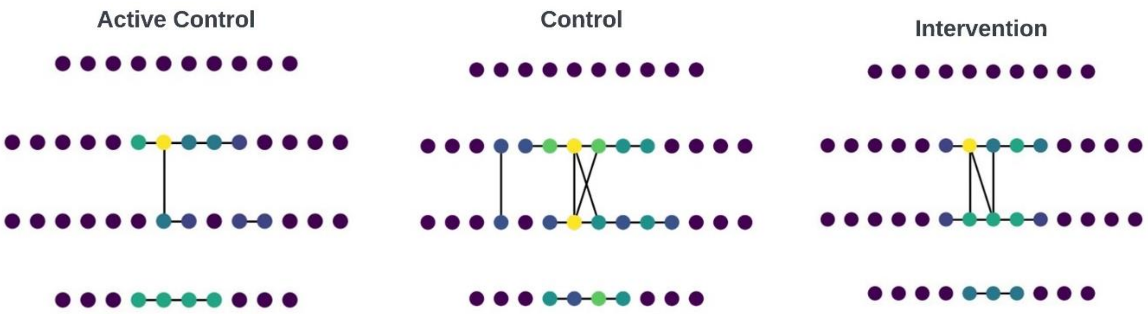
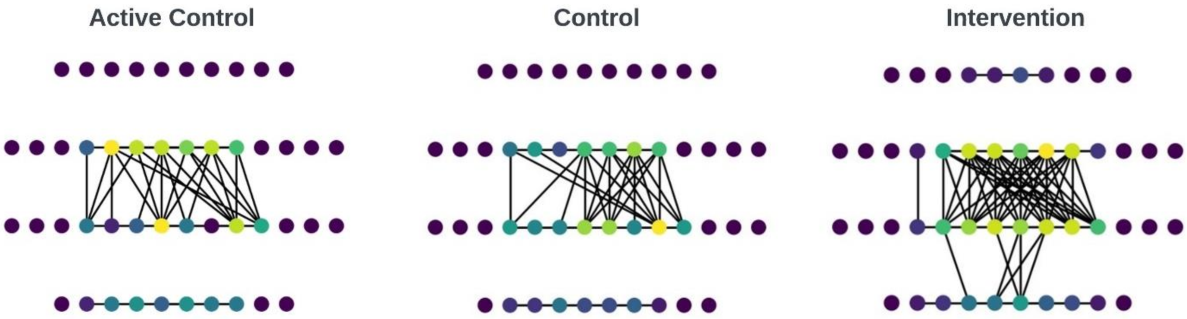
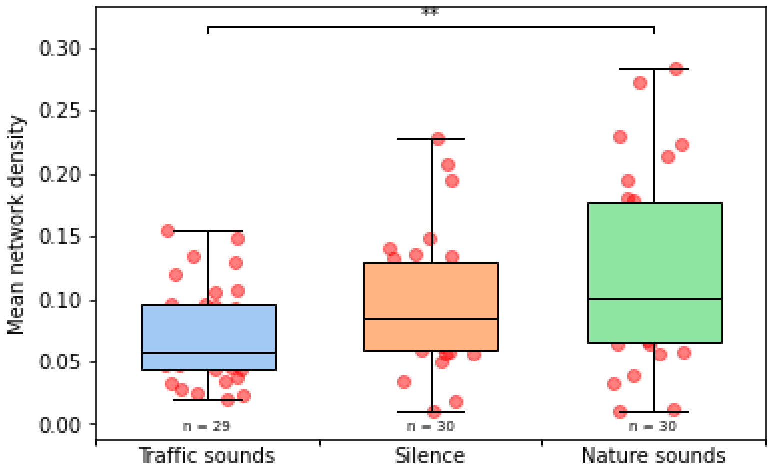


Figure 3.1 All groups showed similar, low functional connectivity during the TSST.

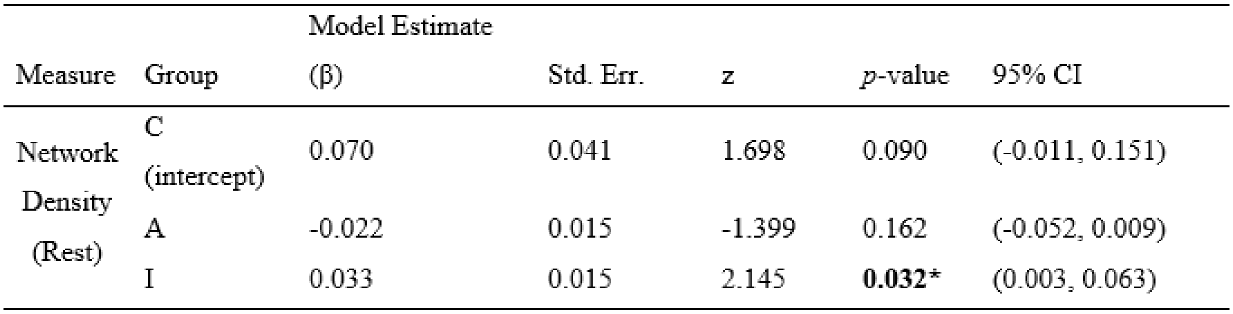
a



b



c



Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Network Density (Rest)	C (intercept)	0.070	0.041	1.698	0.090	(-0.011, 0.151)
	A	-0.022	0.015	-1.399	0.162	(-0.052, 0.009)
	I	0.033	0.015	2.145	**0.032***	(0.003, 0.063)

Figure 3.2 Functional connectivity in the PFC for all groups during the Restoration Period.

a. Networks graphs depicting the correlations between different ROIs in the PFC. Color coding is used to represent degree centrality (i.e. number of connected edges), with warmer colors indicating higher centrality. **b.** Mean network density in the PFC whilst listening to either traffic or nature sounds, or no auditory stimulus. The group that listened to nature sounds had significantly higher network density when compared to the group in the traffic sounds condition ($p = 0.0079$), with a large effect size (Cohen's $d = 0.8196$). However, although also having a higher score, the intervention group did not significantly differ from the control group ($p = 0.1234$). *Note.* Group: A – Active Control; C – Control; I – Intervention; Std. Err. – Standard Error; CI – Confidence Interval

As expected, listening to nature sounds during the restoration break had a positive effect on prefrontal cortical functional connectivity. Brain network graphs (Fig. 3.2a) show that while correlations happened mainly within the frontopolar PFC, with isolated correlations between channels in the orbitofrontal cortex (OFC), for the groups in the traffic and silence conditions, the group that listened to nature sounds showed integration between frontopolar PFC and OFC, as well as isolated correlation within the DMPFC. The visual differences in functional connectivity between groups was confirmed by the network density scores (Fig. 3.2b). After controlling for individual differences and repeated measures, as well as random effects from age, gender, and caffeine consumption, the main effect of listening to nature sounds significantly increased functional connectivity in the PFC, measured in terms of network density (Fig. 3.2c).

Effects from the biophilic auditory experience were carried over to the design task. Even though no significant differences were found between groups for the overall network density during the design task ($t = 0.4365$, $p = 0.8039$), main effects were found when splitting the design task period into equal deciles (Fig. 3.3). Splitting the period in which participants are engaged with a design task into equal parts is a previously used approach to explore temporal changes in Oxy-Hb recruitment patterns during design[9,51,52]. Linear mixed effects models indicated that the group that listened to nature sounds had significantly denser brain networks during the 5th and 8th deciles. Age, as a confounding variable, also had a significant effect on network density during both the 5th ($\beta = 0.003$, $p < 0.001$) and 8th deciles ($\beta = 0.003$, $p = 0.003$). After controlling for age, the nature sounds condition still had a significant main effect on network density (see models in Appendix B).

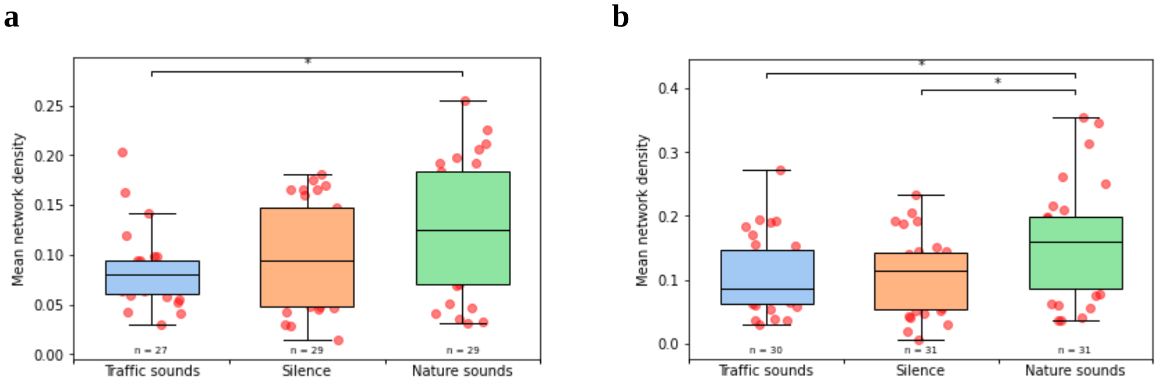


Figure 3.3 Mean network density during the design task (5th and 8th deciles).

a. During the 5th decile, the group in the nature sounds condition had significantly higher network density than the group in the traffic sounds condition, with a large effect size (p = 0.0121, Cohen's d = 0.8032). Although having a higher mean network density, the intervention group did not significantly differ from the control group (p = 0.1398). **b.** The nature sounds condition led to significantly higher network density during the 8th decile when compared to both the traffic sounds (p = 0.0267, Cohen's d = 0.6919) and the silence conditions (p = 0.0267, Cohen's d = 0.6868), with medium to large effect sizes.

Effects on design cognition

Semantic distance analysis can be used to quantitatively measure the exploration of the semantic space[53], where the semantic space is used as proxy for the space in which design ideas exist. As one travels further out in the semantic space when designing, by visualizing associations between remote concepts, the design space is expanded and new ideas can emerge[17,54,55]. Effects of different auditory experiences on design cognition were measured by the mean semantic similarity and divergent semantic integration (DSI) scores for participants explanations of their design concepts. One-way ANOVA tests were used to compare the scores between groups.

No significant differences were found for either the semantic similarity scores (t = 0.3037, p = 0.7388) or the DSI scores (t = 0.1568, p = 0.9246). Nonetheless, linear mixed effects models controlling for age, gender, native language, and caffeine consumption within two hours prior to the experiment indicated that being a non-native English speaker and the consumption of caffeine had significant main effects on the semantic similarity scores, with the language barrier increasing the semantic similarity between words used (β = 0.011, p = 0.034, 95% CI = [0.001, 0.021]) and caffeine consumption having the opposite effect (β = -0.013, p = 0.029, 95% CI = [-0.024, -0.001]).

For the DSI scores, the model indicated that native language and gender were significant confounding variables. Non-native English speakers had significantly lower DSI scores (β = -0.004, p = 0.006, 95% CI = [-0.007, -0.001]), while male participants had significantly higher DSI scores (β = 0.004, p = 0.012, 95% CI = [0.001, 0.007]).

Table 3.1 Linear mixed-effects models' results for incorporation of biophilic design.

Results suggest that hypothesis III should be rejected. Participants that listened to nature sound had significantly lower scores for the incorporation of Material Connection with Nature in their design concepts. Also, against expectations, participants who listened to traffic sounds had significantly higher scores for the incorporation of Visual Connection with Nature and Non-Rhythmic Sensory Stimuli. Previous work experience with design, previous knowledge about biophilic design, and higher baseline connectedness to nature all had positive main effects on the incorporation of different patterns. Higher post-experiment connectedness to nature had a negative main effect on the incorporation of 7 out of the 14 patterns. Descriptions and examples for the patterns extracted from the "14 Patterns of Biophilic Design"[56].

	Nature Sounds	**Traffic Sounds**	**Design Experience**	**Biophilic Design Knowledge**	**Baseline Connectedness to Nature**	**Post-experiment Connectedness to Nature**
Visual Connection with Nature		**$\beta = 0.400$, $p = 0.016$**				**$\beta = -0.168$, $p = 0.026$**
Non-Visual Connection with Nature			**$\beta = 0.393$, $p = 0.029$**			
Non-Rhythmic Sensory Stimuli		**$\beta = 0.420$, $p = 0.029$**			**$\beta = 0.319$, $p < 0.001$**	**$\beta = -0.353$, $p = 0.007$**
Thermal and Airflow Variability						**$\beta = -0.229$, $p < 0.001$**
Presence of Water						**$\beta = -0.217$, $p = 0.023$**
Dynamic and Diffuse Light					**$\beta = 0.172$, $p < 0.001$**	**$\beta = -0.259$, $p = 0.009$**
Connection with Natural Systems						
Biomorphic Forms & Patterns						

Material Connection with Nature	**β = -0.277, $p = 0.012$**		**β = 0.201, $p = 0.034$**			
Complexity & Order						
Prospect				**β = 0.721, $p = 0.036$**		
Refuge					**β = 0.149, $p = 0.001$**	**β = -0.231, $p = 0.003$**
Mystery						**β = -0.229, $p < 0.001$**
Risk/Peril					**β = 0.142, $p < 0.001$**	

Qualitative analysis of the design concepts generated was conducted utilizing a modified version of the Biophilic Design Matrix (BDM)[57–60]. This tool facilitates the assessment of the extent to which biophilic design is present in a design product. Raters are asked to rate the presence of each of the "14 Patterns of Biophilic Design"[56] on a scale of 0 (not present at all) to 3 (strongly present), leading into an overall BDM score with a maximum of 42 points. Two academics trained in biophilic design volunteered as raters. Inter-rater reliability was calculated through a weighted Cohen's Kappa, which indicated a fair agreement between Rater 1 and Rater 2 ($\kappa = 0.29$). Results from linear mixed-effects models adjusted for design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature showed that confounders had more significant effects on the dependent variables (i.e. scores for the incorporation of each of the 14 Patterns of Biophilic Design) than the different auditory stimuli. Participants who reported higher connectedness to nature post-experiment had significantly lower scores for the incorporation of the Visual Connection with Nature (β = -0.168, $p = 0.026$, 95% CI = [-0.315, -0.020]), Non-Rhythmic Sensory Stimuli (β = -0.353, $p = 0.007$, 95% CI = [-0.610, -0.096]), Thermal and Airflow Variability (β = -0.229, $p = < 0.001$, 95% CI = [-0.269, -0.189]), Presence of Water (β = -0.217, $p = 0.023$, 95% CI = [-0.404, -0.030]), Dynamic and Diffuse Light (β = -0.259, $p = 0.009$, 95% CI = [-0.453, -0.065]), Refuge (β = -0.231, $p = 0.003$, 95% CI = [-0.386, -0.077]), and Mystery (β = -0.229, $p = < 0.001$, 95% CI = [-0.248, -0.209]) patterns. Alternatively, participants who reported higher baseline connectedness to nature had significantly higher scores for the incorporation of the Non-Rhythmic Sensory Stimuli (β = 0.319, $p = < 0.001$, 95% CI = [0.251, 0.387]), Dynamic and Diffuse Light (β = 0.172, $p = < 0.001$, 95% CI = [0.128, 0.216]), Refuge (β = 0.149, $p = 0.001$, 95% CI = [0.062, 0.235]), and Risk/Peril (β = 0.142, $p = < 0.001$, 95% CI = [0.080, 0.204]) patterns.

Previous work experience with design had a significant positive effect on the incorporation of the Non-Visual Connection with Nature (β = 0.393, $p = 0.029$, 95% CI = [0.040, 0.746]) and Material Connection with Nature (β = 0.201, $p = 0.034$, 95% CI = [0.015, 0.387]) patterns. Previous knowledge about biophilic design led to significantly higher scores to the incorporation of only one pattern, Prospect (β = 0.721, $p = 0.036$, 95% CI = [0.048, 1.393]).

Finally, after controlling for all confounders, the models indicated that participants who listened to traffic sounds had significantly higher scores for the incorporation of the Visual Connection with Nature ($\beta = 0.400$, $p = 0.016$, 95% CI = [0.076, 0.725]) and the Non-Rhythmic Sensory Stimuli ($\beta = 0.420$, $p = 0.029$, 95% CI = [0.044, 0.796]) patterns, while participants who listened to nature sounds had significantly lower scores for the incorporation of the Material Connection with Nature pattern ($\beta = -0.277$, $p = 0.012$, 95% CI = [-0.493, -0.062]).

Discussion

In the present study, we tested the extent to which cognitive benefits derived from biophilic restorative experiences can be influential in the performance of real-world scenario tasks, by exploring effects on the mind and the brain when designing. It was hypothesized that a biophilic auditory experience would lead to (I) improved functional connectivity within the DMN, consequentially facilitating associative cognitive processes that would lead to (II) improved performance in design. It was also hypothesized that due to a potential priming effect, participants in the biophilic condition would (III) incorporate more nature in their design concepts. We assessed the functional connectivity between ROIs within the PFC when participants went through the three phases of the experiment: (1) induced psychosocial stress by means of the TSST; (2) a restoration break listening to either birdsong and water sounds (intervention), heavy traffic sounds (active control), or no sounds (control); and (3) an open-ended design task. Potential effects on design cognition were assessed by the exploration of the design space, measured by distributional semantic models that quantify the semantic similarity between concepts, and by the incorporation of biophilic design patterns, measured by a modified version of the BDM tool. Functional connectivity analysis showed that, as expected[22,26], prefrontal cortical functions were disrupted during the TSST across all groups (Fig. 3.1). Next, during the restoration break, participants who listened to birdsong and water sounds had a significantly higher mean network density when compared to the traffic sounds condition (Fig. 3.2b), indicating improved functional connectivity for the intervention group. We also observed a difference between the network graphs for all groups during the restoration break period (Fig. 3.2a), which show that the intervention group was the only group to exhibit correlations in activity between the frontopolar PFC and the OFC, as well as isolated instances of correlated activity within the DMPFC.

During the design task, no significant differences were observed between groups for the mean network density. However, differences were found when the design task period was evenly split into deciles[9,51,52]. The intervention group had a significantly denser network in the 5th decile, when compared to the active control group, and in the 8th decile, when compared to both the active control and the control groups, with central activity distributed between channels in the left and right sides of the frontopolar PFC and left OFC (channels 22, 23, 26, 27, and 31). Differences were significant even after controlling for age as a confounding variable. Aging causes alterations in the DMN[61]. Findings from the functional connectivity analysis confirmed hypothesis I. Results showed that during both the restoration break and the design task, correlated activity was centered in the frontopolar PFC, also known as Brodmann area 10 (BA 10)[62,63]. This area is believed to be one of the main hubs of the DMN within the PFC[64] and involved in introspective processes like mind-wandering [15,65]. The frontopolar PFC is also believed to have a major role in “unstructured settings where the correct response is not readily known”[66], like in the case of an open-ended design task. Even though a coupling between the

DMN and the ECN can be expected during creative thought when the task at hand is bounded by specific constraints or parameters[10], our results indicate that during the design task, which had little to no constraints, all groups had consistently more engagement of central regions of the PFC that are part of the DMN.

DMN activity is "correlated with behavioral measures of divergent thinking"[53], facilitating associative processes that enable one to travel further into semantic memory. With the increase in functional connectivity within the DMN for the intervention group (hypothesis I), it was expected that participants from this group would be able to explore a larger semantic space when describing their design concepts (hypothesis II). Assessment of the design concepts produced could tell us if the effects on subjects' brain were accompanied by changes in subjects' minds. Semantic analysis results showed no significant differences between groups for either semantic similarity or DSI scores, rejecting hypothesis II. Why were there significant differences between groups in terms of functional connectivity in the PFC, but not in the design products? As noted by McDonnell & Strayer (2024), "neurophysiological measures may detect changes that are not large enough to affect behavior, which often requires a change to pass a certain threshold before it is reflected in task performance." However, linear mixed effects models showed that non-native English speakers explored a significantly smaller semantic space when describing their design concepts, whereas male subjects and subjects that consumed any caffeine within two hours of the experiment explored a significantly larger semantic space. The effects of the confounders can be explained by a couple deductions. Non-native English speakers' exploration of the semantic space might have been hindered by the vocabulary available to them to describe playgrounds and their features. As international students, these subjects might have learned English at a time past their childhood and might not have been exposed to this type of vocabulary. For example, this is how one participant described a merry-go-round: "*I'm not sure what the little circle of spinny thing is, but I remember playing with that when I was a kid"*. Male subjects might have been more comfortable when describing their design concepts given that the researcher conducting the experiment was also a male. Although previous research indicates that caffeine consumption does not affect divergent thinking capabilities[68], in the case of this study it helped participants explore a larger semantic space when describing their design concepts. However, only 18 out of 96 participants reported having consumed caffeine before the experiment, so this finding should be observed with caution.

Assessment of the design concepts produced utilizing the modified version of the BDM[57,60] led to a rejection of hypothesis III. Opposite to expectations, exposure to nature sounds led to a significant lower score for the incorporation of *Material Connection with Nature*, while exposure to traffic sounds led to significantly higher scores for the incorporation of *Visual Connection with Nature* and *Non-Rhythmic Sensory Stimuli*, even after controlling for design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature. These findings could suggest a possible role of the human negativity bias[69] on how the different auditory experiences influenced the design concepts. The negative experience of listening to heavy traffic sounds had a larger impact than the positive experience of listening to birdsong and water sounds. In a possible attempt to counteract the negative experience with the traffic sounds, participants in the active control group might have be inspired to create a playground environment that could serve as a refuge or escape from the unpleasant urban environment they experienced. Confounders also had a significant influence on the incorporation of biophilic design. Previous experience working with design, as well as previous knowledge about biophilic design, were positively associated with the incorporation of three biophilic design patterns (*Non-*

Visual Connection with Nature, *Material Connection with Nature*, and *Prospect*). Out of 96 participants, 37 reported having experience in design. Experience with design might have helped these participants take into consideration sensory engagement (other than visual) and material selection. The effect of baseline connectedness to nature supports previous findings. Feelings of connectedness to nature are associated with pro-environmental behavior[70,71], as well as with willingness to spend more time immersed in natural environments[72–74]. Participants with higher baseline connectedness to nature designed playgrounds that incorporated more *Non-Rhythmic Sensory Stimuli* and *Dynamic and Diffuse Light*, as well as more spaces that facilitated a sense of *Refuge* and *Risk/Peril*. The confounder with the most main effects on the incorporation of biophilic design was the post-experiment connectedness to nature. Participants that reported higher connectedness to nature after the experiment had significantly lower scores for the incorporation of 7 out of the 14 Pattern of Biophilic Design[56]. One possible explanation is that after realizing they did not incorporate much nature in their design concepts, these participants attempted to compensate by rating themselves as more connected to nature.

From an evolutionary perspective, birdsong may indicate the absence of predators, while running water sounds offer the promise of a freshwater source nearby. On the other hand, silence may raise red flags for a potential threat, and traffic noises can signal the imminence of danger. From this framework, it was hypothesized that participants in the intervention group would have better chances of recovering from the induced stressful state and engaging in a restful state. Previous studies had observed greater functional connectivity within the DMN for participants listening to naturalistic versus artificial sounds[44] and results from our study replicate and further validate these findings. We observed (I) increased functional connectivity within BA 10 for participants who received the biophilic auditory experience, both during the exposure period as well as in a subsequent design task. Higher engagement of the DMN did not however lead to (II) better performance in design, in terms of exploration of the design space. Surprisingly, listening to nature sounds led to less, and listening to traffic sounds led to more (III) incorporation of biophilic design patterns in the design concepts. Our findings reiterate the restorative potential of biophilic auditory experiences to prefrontal cortical functioning, building on the empirical evidence of effects on the DMN. Impacts on behavior need to be further explored.

Methods

Overview of the experiment design

This randomized controlled trial employed a between-subjects factor to investigate the impact of a biophilic auditory experience on engineering students' design cognition and neurocognition. Data collection spanned February to May 2023 at Virginia Tech, Blacksburg, VA. Eligible participants were randomly assigned to one of three groups: active control, control, and intervention. The experiment comprised three phases: stress induction, restoration, and a design task (Fig. 3.4). Stress was induced via a social stress test. The restoration phase included an 8-minute break with different auditory stimuli: biophilic sounds for the intervention group, urban noise for the active control, and silence for the control group. Subjects were instructed to close their eyes during restoration to eliminate visual stimuli. Design task completion time was unrestricted. Participants were asked to explain their design concept and the design process utilized to develop it. Neurocognitive responses were captured via a wireless brain-imaging device worn throughout the experiment. Perceived stress levels pre- and post-stressor, post-restoration relaxation level, and perceived mental demand during the design task were assessed using Likert scales after each phase. Post-experiment survey questions gathered demographic data. Indoor environmental quality (IEQ) factors and nature connectedness were considered as potential confounding variables.

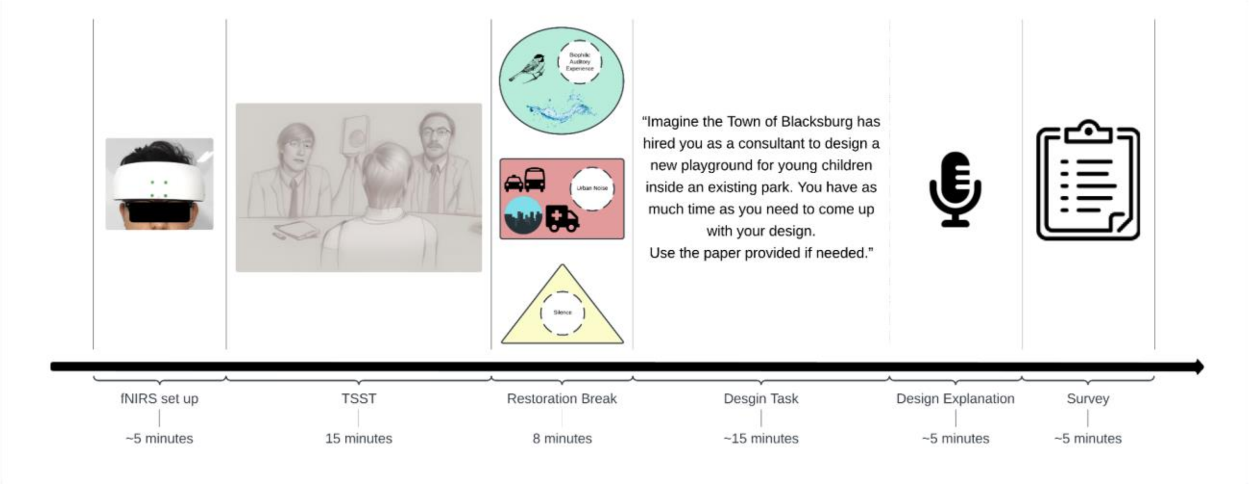


Figure 3.4 Timeline of events in the experiment.

Participants

Virginia Tech engineering students were recruited via department listservs, class visits, and campus flyers. All recruitment efforts and experimental procedures were approved by the Institutional Review Board (IRB #22-448). Eligibility was determined through a screening survey (see on Chapter 2, Appendix A), assessing pre-existing conditions potentially affecting the study outcomes: cardiovascular, neurological, and psychiatric disorders, severe hearing and/or vision impairments, substance use history, anxiety/depression episodes, and alcohol/illicit drug dependency. The short-form version of the nature relatedness scale (NR-6)[75] was also included in the screening survey to measure potential participants' baseline connectedness to nature. A power analysis based on pilot study data (Ignacio Junior & Shealy, 2023) suggested a minimum of 21 subjects per group for 80% power at a 5% significance level. A target of 30 subjects per group was set. Two extra participants per group were included to offset potential data losses with equipment malfunction. Ninety-six participants (aged 18-39; 21 females, 74 males, 1 transman; 6 left-handed, 90 right-handed) passed screening and were randomly assigned to the active control, control, or intervention cohorts. A consent form was signed by all participants prior to participation. Monetary compensation in the form of a $20 Amazon gift card was provided to all participants, independently of study completion.

Demographic data including age, gender, handedness, and first language were collected post-experiment. Given the potential for changes due to the different treatments in the experiment, participants' connectedness to nature was measured again post-experiment. Additional background information potentially influencing treatment response/ and task performance was solicited. Most participants (81%) reported no caffeine consumption within 2 hours pre-experiment. Average pre-experiment stress level was low (1.66/5). Refer to Table 3.2 for participants' background and demographic details.

Table 3.2 Characteristics of the sample (n = 96).

Demographics and Environmental Factors	Mean ± SD or n (%)			
	Overall	Active Control	Control	Intervention
N	96	32	32	32
Age	22 ± 4	23 ± 4	23 ± 4	22 ± 3
Gender	-	-	-	-
Female	21 (22)	8 (25)	7 (22)	6 (19)
Male	74 (77)	24 (75)	25 (78)	25 (78)
Trans	1 (1)	-	-	1 (3)
Handedness	-	-	-	-
Right	90 (94)	29 (91)	29 (91)	32 (100)
Left	6 (6)	3 (9)	3 (9)	-

English is first language	-	-	-	-
Yes	67 (70)	22 (69)	20 (63)	25 (78)
No	29 (30)	10 (31)	12 (37)	7 (22)
Caffeine intake (up to 2 hours before experiment)	-	-	-	-
Yes	18 (19)	3 (9)	8 (25)	7 (22)
No	78 (81)	29 (91)	24 (75)	25 (78)
Time of the day	-	-	-	-
Morning (8am-12pm)	40 (42)	15 (47)	12 (37)	13 (41)
Afternoon (12-5pm)	56 (58)	17 (53)	20 (63)	19 (59)
Self-reported baseline stress level (0-lowest to 5-highest)	1.66 ± 1.15	1.94 ± 1.39	1.50 ± 0.72	1.53 ± 1.22

Treatment

Stress induction. The experiment started with the researcher providing participants with instructions for the initial task, the Trier Social Stress Test (TSST). The TSST, recognized for its efficacy in eliciting both physiological and psychological stress[39,40,50,76,77], serves as a robust method to deplete cognitive, physiological, and psychological resources. Notably, the three components of the test—anticipatory stress, public speaking, and mental arithmetic—can simulate cognitively demanding situations encountered in daily life, such as those experienced in work settings, academic pursuits, or routine social interactions[50,78]. During the TSST, participants are first asked to imagine they are being interviewed for their dream job. They are then given five minutes to prepare notes for a five-minute talk, in which they have to convince a judge why they are the best candidate for the position. Participants are told that they will be recorded, that their brain activity will be monitored, and that the judges are trained in behavioral analysis and will be taking notes. During the five-minute speech period, participants are told to keep talking every time they pause for more than 20 seconds. When the five-minute speech portion is over, participants are asked to sequentially subtract the number 13 from 1022, reporting their answers out loud. For the entire five-minute mental arithmetic portion, every time a mistake is made, participants are asked to start over from the beginning. The mental arithmetic portion concludes the TSST. After that, participants are asked to sit down and the judge leaves the room.

Restoration Break. After being induced to a state of psychosocial stress by the TSST, participants were given an opportunity to relax before going into the design task. During the 8-minute restoration break, all participants were asked to close their eyes - ruling out any sort of visual stimulus - and each of the groups received a different type of auditory stimulus. As a control condition, participants in the control group sat in silence for the whole period. As a means to compare the experience of seeking restoration in an urban area with an outing into a natural landscape, researchers[42,47–49] have utilized recordings of road traffic as well as recordings of tweeting birds and different types of water flows. Therefore, in this study, participants in the active control group listened to a binaural recording of a heavily trafficked urban area, and participants in the intervention group listened to binaural recordings of birdsong and water sounds. Both recordings (nature sounds and urban sounds) are available to the general public, enhancing the replicability and applicability of this study. The urban sounds are available as virtual traffic 3D audio on YouTube[79]. The biophilic sounds come from the Castaway track in the MindBreaks mobile app[80]. Auditory experiences were delivered through over-the-ear headphones. Following recommendations from the literature, participants were allowed to adjust the audio volume to their comfort level[81]. The length of the restoration break fits within the range (5 to 10 minutes) of prior, similar studies[73,82–84].

Outcome measures

To assess the potential effects of the independent variable, the biophilic auditory experience, on how participants' brains behaved during the design task, as well as on what design ideas they came up with, two dependent variables were tracked: design cognition and neurocognition. The design concepts participants produced were analyzed both qualitatively and quantitatively. A semantic analysis was conducted on the recorded design explanations. Volunteer raters assessed the incorporation of biophilic design in the design products utilizing a modified version of the Biophilic Interior Design Matrix (BID-M). Neurocognitive responses were tracked during each of the experiment phases. Different metrics for functional connectivity and temporal dynamics of Oxy-Hb recruitment in the PFC were analyzed. The combination of objective and subjective data helps us understand the interaction between behavioral and physiological responses.

Measurement of exploration of the design (semantic) space. Researchers have explored the potential benefits of biophilic experiences to creative cognition utilizing a wide range of established cognitive tests. Positive effects have been observed when study participants performed the Remote Associates Task (RAT)[31,85], the Torrance Test for Creative Thinking[86–88], and the Test for Creative Thinking - Drawing Production[37]. Nonetheless, less is known about how these potential benefits could translate into better performance in real-world tasks. While no studies have assessed how biophilic experiences affect knowledge workers performance at work, it is known that some professionals seek creative inspiration through contact with nature. One study[89] found that Danish professionals engaged in creative work seek immersion in nature to help them through the creative process, especially during the early stages of preparation and incubation. One of the cognitive mechanisms engaged during nature experience that may enhance creativity is mind wandering[31]. Mind wandering can be explained as an introspective process in which the lack of attention-demanding external stimuli enables the retrieval of previously ignored memories and facilitates associations between seemingly unrelated concepts and ideas[14,32]. Drawing on the associative theory of creativity[90,91], as the mind wanders across the semantic memory, new associations can be made, and creative thought emerges as the semantic space considered expands[17,55].

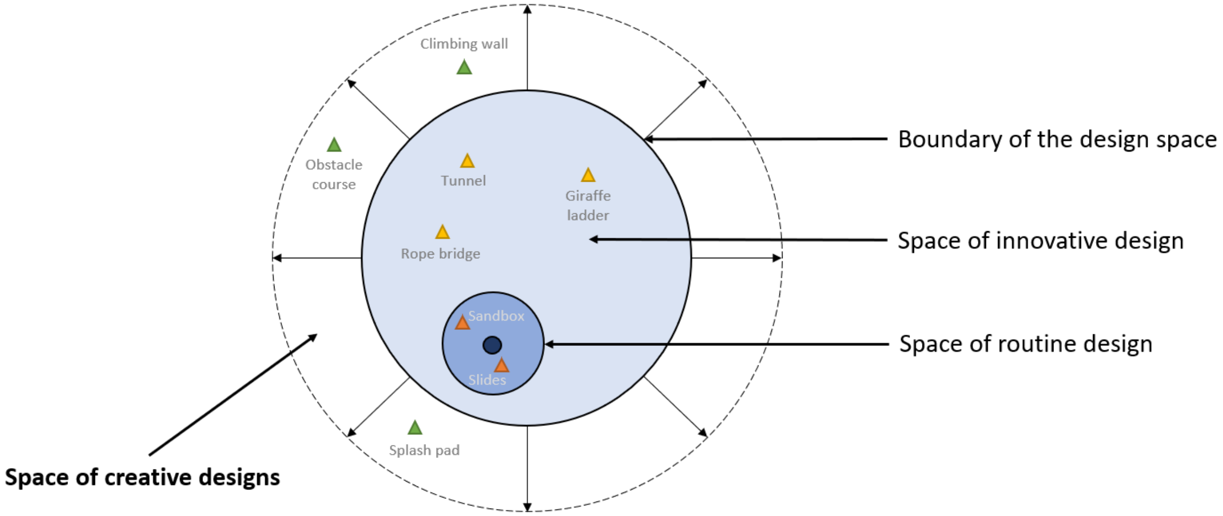


Figure 3.5 Metaphor for the expansion of the design space through associative semantic processes.

The smaller, darker circle represents the word “playground”, while the triangles around it represent different features that can added to a playground for young children. Words - or features - that are more commonly associated with the word - or concept of - “playground” appear in the space of routine design. As associations are made between concepts that are not as similar in their meaning, the boundaries of the semantic space, and also, in this case, of the design space, are expanded.

Design space was measured by the scores for the average semantic similarity between the words used by each participant when explaining their design concepts. In this approach, the exploration of the design space is compared to the exploration of the semantic space. A person’s ability to use semantically distant words (or concepts) while explaining their design products demonstrates their originality and capacity to think in a divergent way[93,94]. Divergent semantic integration (DSI) scores were also utilized as a measurement of exploration of the design space. DSI is “defined as the extent to which a narrative connects divergent ideas”[95]. The chosen model employed Bidirectional Encoder Representations Transformers (BERT).

Measurement of incorporation of Biophilic Design. Exposure to different environmental stimuli can influence the designer's mindset. The physical setting can mold design outcomes; for instance, students working on a design task in certified sustainable buildings generated significantly more ideas infused with sustainability principles[96]. Any type of sensory stimuli can act as a primer[97]. Acting as a supraliminal primer, the biophilic auditory experience could unconsciously “influence the solution produced consciously” for the design task[98]. Furthermore, exposure to biophilic restorative experiences, even through short-term exposure[38], can increase feelings of connectedness with nature[73,99,100]. A greater sense of connectedness with nature can be positively associated with pro-environmental behavior[70,71], as well as with willingness to spend more time immersed in natural environments[72–74]. Acting as a priming intervention, the biophilic auditory experience could affect designers’ behavior[101,102]. Changes in behavior could be reflected on design choices. “The incorporation of newly acquired information and new experiences can be a source of priming in the design process”[103]. In order to measure to what extent a potential priming effect influenced participants’ design cognition, all design concepts were assessed for the incorporation of biophilic design.

Incorporation of Biophilic Design is being measured through a modified version of the Biophilic Interior Design Matrix (BID-M). The BID-M is a valid and reliable tool for measuring biophilic interior design[57,58,60]. Besides being applied in this study to the design of an outdoor park, the modified version switches to Browning et al.’s[56] “14 Patterns of Biophilic Design" in an attempt to simplify the BID-M and reduce the workload required to use it. The original BID-M was based on Kellert’s[104] extensive list of biophilic design elements and attributes. The extension and language technicality of the original BID-M could cause limitations to the proposed experiment design. In this modified version, design concepts are assessed for the strength of the presence of each of the “14 Patterns of Biophilic Design” on a scale of not present at all (0), weak presence (1), moderate presence (2), or strong presence (3). A post-doctoral researcher and a graduate student trained in Biophilic Design were used as raters. Mean scores for each design product were used as a measure for the incorporation of Biophilic Design.

Measurement of neurocognitive effects. Daily life demands can induce psychosocial stress, impairing prefrontal cortical cognitive functions such as creative thought[24], decision-making, and working memory[22,25]. Thus, the TSST, a social stress test, was employed to deliberately degrade subjects' cognitive and neurocognitive resources. One publication[26] identified that psychosocial stress can also impair attentional control, and that this impairment was correlated with a disruption in the functional connectivity between different regions of the PFC. A disruption in functional connectivity could also affect working memory abilities, given they “crucially depend on the precise activity of interconnected neuronal networks”[22].

By inducing mental fatigue uniformly across subjects, the Kaplans’ Attention Restoration Theory (ART)[29,30], derived from the "Biophilia Hypothesis"[105], was tested. ART posits that exposure to natural environments offers respite for directed attention—a resource vulnerable to fatigue. Given the prefrontal cortex's (PFC) role in executive cognitive processes[12,106], including attention, inhibition, and working memory, changes in oxygenated hemoglobin (Oxy-Hb) recruitment to the PFC were measured to assess the potential restorative effects of the biophilic auditory experience on cognitive and neurocognitive resources.

Data processing and analysis

Semantic analysis. Audio recordings of participants’ explanations of their design (1) products and (2) processes were transcribed into text. Punctuation, stop words, and repeated words were removed from the body of text utilizing the gensim[107], nltk[108], and re[109] Python libraries. Next, spaCy's[110] "en_core_wen_lb" pipeline, a large vocabulary trained on written text from the web, was utilized to calculate semantic similarity scores for all possible word pairings in the cleaned bodies of text for each participant (see Table 3.3 for an example). 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). The average semantic similarity score was calculated for each participant based on the scores for all combinations of words used in each design explanation.

Statistical analysis was performed using Python packages. Outliers within groups were identified and removed utilizing the interquartile range (IQR) method. A Shapiro-Wilk test was performed to determine the data distribution. For normally distributed datasets, a parametric ANOVA test (i.e. F-test) was utilized. If the dataset presented a skewed distribution, a non-parametric ANOVA test (i.e. Kruskal-Wallis) was performed. A p-value of 0.05 was set as threshold for significance. If the ANOVA results pointed out any statistically significant difference between the three groups, a post-hoc T-test with a Holm-Bonferroni *p*-value adjustment was performed to identify where the significant difference exists. The Cohen's *d* was computed and utilized to measure the effect size.

Table 3.3 Examples of pairwise comparison between words extracted from design explanations in a pilot study[110].

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

BID-M. Scores by all raters were compiled and an inter-rater reliability analysis was performed. An inter-rater reliability (IRR) analysis was performed using a quadratically weighted Cohen's Kappa metric, which is a measure of the agreement between two reviewers when using an ordinal scale to independently rate the same set of data. Both reviewers were given PDFs of all 96 design concepts, audio recordings and text transcripts of all participant descriptions, Terrapin Bright Green's handbook on the 14 Patterns of Biophilic Design, and the same survey instrument with identical comments to guide ratings of each design for each biophilic pattern from 0 (not present at all) to 3 (Strong presence). The weighted Cohen's Kappa showed that there was a fair agreement between Rater 1 and Rater 2 with $\kappa = 0.29 \pm 0.03$ (CI = [0.22, 0.35], $p < 0.001$). This value indicates a low probability that the observed agreement is due to random chance. IRR could be improved through iterative dialogue between reviewers focused on the responses with the highest rates of divergence. Informed updates to the comments in the survey instrument and a supplemental guide to ranking playground designs could also help improve IRR.

Table 3.4 Distribution of scores and agreement between raters.

		Rater 1				
		0	1	2	3	Total
Rater 2	0	404	390	95	62	951
	1	51	85	64	26	226
	2	11	50	32	27	120
	3	4	13	10	20	47
	Total	470	538	201	135	1344

Table 2 tallies how reviewers scored each of the 96 designs on each of the 14 patterns for a total of 1344 responses. For example, if both reviewers ranked a design zero indicating their opinion that a given pattern was 'not present at all', one was added to the number in the top-left corner. As shown in Table 1, this happened 404 times and was the most frequent scenario in the review. If Rater 1 ranked a design one for a given pattern and Rater 2 ranked the same design zero for the same pattern, one was added to the number in the first row, second column of the table. This was the second most frequent scenario in the review, occurring a total of 390 times. Large improvements to IRR could be achieved by encouraging a dialogue between reviewers focused on instances when one rater ranked the design 'not present at all' and the other gave the same design a rating of one for the same biophilic pattern. These discrepancies could be due to factors such as playing fields and the presence of grass interpreted as a biophilic feature by one reviewer and not the other. After communicating clarifications on common discrepancies, another round of reviews would likely improve IRR.

Design neurocognition. Raw fNIRS data for each participant had outliers removed utilizing z-scores (threshold = 2 standard deviations). Next, the data was pre-processed utilizing the Matlab-based NIRS Brain AnalyzIR Toolbox[112]. First, the data sampling rate was reduced from 8 Hz to 5 Hz. Light intensity was then converted to optical density. Motion artifacts were then removed using the Temporal Derivative Distribution Repair (TDDR) method[113]. Following the motion correction, bandpass filtering was performed. An 1000th order finite impulse response (FIR) bandpass filter was applied. The applied cutoff range - 0.01–0.25Hz - corresponds to the range in which hemodynamic responses happen[114]. Next, changes in optical density were converted to hemoglobin (Hb) concentration utilizing the MBLL method (Kocsis et al., 2006). The last step in the data preparation process was removing other physiological noise. The Mayer wave noise (from blood pressure) was removed by regressing out the median time series[115]. Functional connectivity analysis was performed in Python. Pearson's correlation matrices were developed using the mean oxy-Hb in each channel (n = 48) during each phase of the experiment (TSST, Restoration Break, Design Task), for each cohort. Then, values from each correlation matrix were transformed into a binary matrix with connected nodes and edges. A global threshold value of 0.65 was applied, following prior studies[9]. In these previous studies, the threshold value (0.65) was obtained empirically. Here, during the analysis process, a range of threshold numbers (± 0.10) around 0.65 was explored, but results did not differ significantly. Network graphs were generated utilizing the NetworkX Python package[116]. Using functions from the same package, the degree centrality and the network density were calculated. To assess the temporal dynamics of Oxy-Hb recruitment and brain functional connectivity, the Design Task period was also evenly split into 10 non-overlapping segments, an approach previously used in design cognition research[9,51]. The mean Oxy-Hb recruitment during each decile was utilized to create plots of the temporal dynamics of brain activation. Functional connectivity analysis was also performed for each decile, allowing for the assessment of changes in centrality and density throughout the Design Task.

Statistical analysis was conducted using Python. The mean network density was calculated for all groups during each of the experiment phases. Outliers within groups (outside IQR) were removed from statistical analysis. All datasets were tested for normality utilizing the Shapiro-Wilk test. A parametric or a non-parametric ANOVA was used depending on normality. For normally distributed datasets, a parametric ANOVA test (i.e. F-test) was utilized. If the dataset presented a skewed distribution, a non-parametric ANOVA test (i.e. Kruskal-Wallis) was performed. A p-value of 0.05 was set as threshold for significance. If the ANOVA results pointed out any statistically significant difference between the three groups, a post-hoc test with a Holm-Bonferroni p-value adjustment was performed to identify where the significant difference exists. The Cohen's d was computed and utilized to measure the effect size.

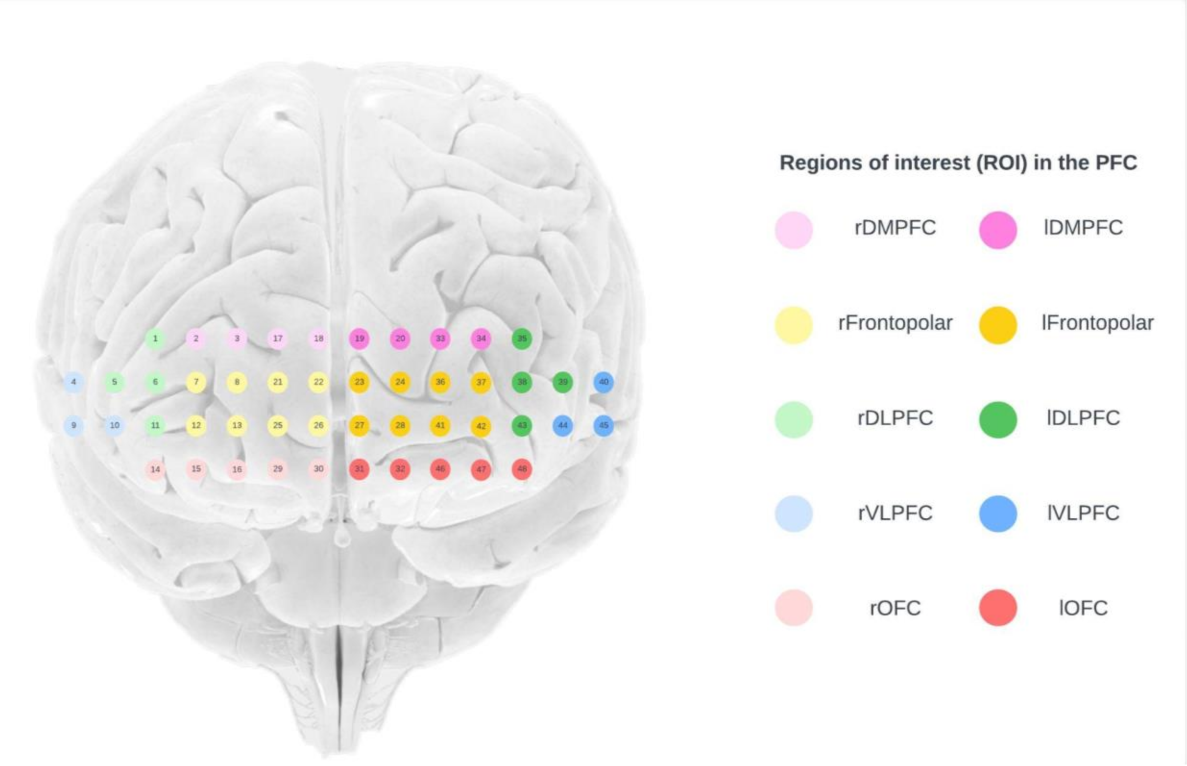


Figure 3.6 Spatial distribution of ROIs with the OBELAB NIRSIT channel configuration.

References

1. Klotz, L. *et al.* Beyond rationality in engineering design for sustainability. *Nat Sustain* **1**, 225–233 (2018).
2. Gero, J. S. & Milovanovic, J. A framework for studying design thinking through measuring designers' minds, bodies and brains. *Design Science* **6**, e19 (2020).
3. Shealy, T., Grohs, J. R., Hu, M., Maczka, D. K. & Panneton, R. Investigating Design Cognition during Brainstorming Tasks with Freshmen and Senior Engineering Students using Functional Near Infrared Spectroscopy. in (2017).
4. Basil, M. D. Multiple Resource Theory. in *Encyclopedia of the Sciences of Learning* (ed. Seel, N. M.) 2384–2385 (Springer US, Boston, MA, 2012). doi:10.1007/978-1-4419-1428-6_25.
5. Gero, J. & Milovanovic, J. A design thinker's mind: insights on the neurocognitive processes of ideation. in *Research Handbook on Design Thinking* 7–24 (Edward Elgar Publishing, 2023).
6. Vieira, S. L. da S. *et al.* Comparing the Design Neurocognition of Mechanical Engineers and Architects: A Study of the Effect of Designer's Domain. *Proceedings of the Design Society: International Conference on Engineering Design* **1**, 1853–1862 (2019).
7. Alexiou, K., Zamenopoulos, T., Johnson, J. H. & Gilbert, S. J. Exploring the neurological basis of design cognition using brain imaging: some preliminary results. *Design Studies* **30**, 623–647 (2009).

8. Fink, A. *et al.* The creative brain: Investigation of brain activity during creative problem solving by means of EEG and FMRI. *Human Brain Mapping* **30**, 734–748 (2009).
9. Milovanovic, J., Hu, M., Shealy, T. & Gero, J. Evolution of Brain Network Connectivity in the Prefrontal Cortex During Concept Generation Using Brainstorming for a Design Task. in (American Society of Mechanical Engineers Digital Collection, 2020). doi:10.1115/DETC2020-22563.
10. Beaty, R. E., Benedek, M., Silvia, P. J. & Schacter, D. L. Creative Cognition and Brain Network Dynamics. *Trends Cogn Sci* **20**, 87–95 (2016).
11. Friedman, N. P. & Robbins, T. W. The role of prefrontal cortex in cognitive control and executive function. *Neuropsychopharmacol.* **47**, 72–89 (2022).
12. Mezzacappa, E. Executive Function. in *Reference Module in Neuroscience and Biobehavioral Psychology* (Elsevier, 2017). doi:10.1016/B978-0-12-809324-5.06001-6.
13. Beaty, R. E., Benedek, M., Barry Kaufman, S. & Silvia, P. J. Default and Executive Network Coupling Supports Creative Idea Production. *Sci Rep* **5**, 10964 (2015).
14. Baird, B. *et al.* Inspired by Distraction: Mind Wandering Facilitates Creative Incubation. *Psychol Sci* **23**, 1117–1122 (2012).
15. Mason, M. F. *et al.* Wandering Minds: The Default Network and Stimulus-Independent Thought. *Science* **315**, 393–395 (2007).
16. Smallwood, J. & Schooler, J. W. The science of mind wandering: empirically navigating the stream of consciousness. *Annual review of psychology* **66**, 487–518 (2015).
17. Gero, J. Design Prototypes : A Knowledge Representation Schema for Design. *AI Magazine. 1990, vol. 11: pp. 26-36* **11**, (1990).
18. Simon, H. A. *The Sciences of the Artificial*. (MIT Press, Cambridge, MA, USA, 1969).
19. Diedrich, J., Benedek, M., Jauk, E. & Neubauer, A. C. Are creative ideas novel and useful? *Psychology of Aesthetics, Creativity, and the Arts* **9**, 35–40 (2015).
20. Runco, M. A. *Creativity: Theories and Themes: Research, Development, and Practice*. (Elsevier Science & Technology, San Diego, UNITED STATES, 2007).
21. Runco, M. & Jaeger, G. The Standard Definition of Creativity. *Creativity Research Journal - CREATIVITY RES J* **24**, 92–96 (2012).
22. Arnsten, A. F. T. Stress signalling pathways that impair prefrontal cortex structure and function. *Nat Rev Neurosci* **10**, 410–422 (2009).
23. Luo, L. & Jiang, B. From oppressiveness to stress: A development of Stress Reduction Theory in the context of contemporary high-density city. *Journal of Environmental Psychology* **84**, 101883 (2022).
24. Beversdorf, D. Q., Hughes, J. D., Steinberg, B. A., Lewis, L. D. & Heilman, K. M. Noradrenergic modulation of cognitive flexibility in problem solving: *NeuroReport* **10**, 2763–2767 (1999).
25. Arnsten, A. F. T. Catecholamine modulation of prefrontal cortical cognitive function. *Trends Cogn Sci* **2**, 436–447 (1998).
26. Liston, C., McEwen, B. S. & Casey, B. J. Psychosocial stress reversibly disrupts prefrontal processing and attentional control. *Proceedings of the National Academy of Sciences* **106**, 912–917 (2009).
27. Ulrich, R. S. Natural Versus Urban Scenes: Some Psychophysiological Effects. *Environment and Behavior* **13**, 523–556 (1981).
28. Ulrich, R. S. *et al.* Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology* **11**, 201–230 (1991).

29. Kaplan, R. & Kaplan, S. *The Experience of Nature: A Psychological Perspective*. (Cambridge University Press, Cambridge ;, 1989).
30. Kaplan, S. The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology* **15**, 169–182 (1995).
31. Atchley, R. A., Strayer, D. L. & Atchley, P. Creativity in the Wild: Improving Creative Reasoning through Immersion in Natural Settings. *PLOS ONE* **7**, e51474 (2012).
32. Williams, K. J. H. *et al.* Conceptualising creativity benefits of nature experience: Attention restoration and mind wandering as complementary processes. *Journal of Environmental Psychology* **59**, 36–45 (2018).
33. United Nations, Department of Economic and Social Affairs, P. D. *World Urbanization Prospects: The 2018 Revision*. (United Nations, 2019). doi:10.18356/b9e995fe-en.
34. Bratman, G. N., Hamilton, J. P., Hahn, K. S., Daily, G. C. & Gross, J. J. Nature experience reduces rumination and subgenual prefrontal cortex activation. *Proceedings of the National Academy of Sciences of the United States of America* **112**, 8567–72 (2015).
35. Maller, C., Townsend, M., Pryor, A., Brown, P. & St Leger, L. Healthy nature healthy people: ‘contact with nature’ as an upstream health promotion intervention for populations. *Health Promotion International* **21**, 45–54 (2006).
36. Song, C., Ikei, H. & Miyazaki, Y. Effects of forest-derived visual, auditory, and combined stimuli. *Urban Forestry & Urban Greening* **64**, 127253 (2021).
37. van Rompay, T. J. L. & Jol, T. Wild and free: Unpredictability and spaciousness as predictors of creative performance. *Journal of Environmental Psychology* **48**, 140–148 (2016).
38. Mayer, F., Frantz, C., Bruehlman-Senecal, E. & Dolliver, K. Why Is Nature Beneficial?The Role of Connectedness to Nature. *Environment and Behavior - ENVIRON BEHAV* **41**, 607–643 (2009).
39. Liszio, S., Graf, L. & Masuch, M. The relaxing effect of virtual nature: Immersive technology provides relief in acute stress situations. *Annual Review of CyberTherapy and Telemedicine* **16**, 87–93 (2018).
40. Wang, X., Shi, Y., Zhang, B. & Chiang, Y. The Influence of Forest Resting Environments on Stress Using Virtual Reality. *International Journal of Environmental Research and Public Health* **16**, 3263 (2019).
41. Deng, L. *et al.* Effects of integration between visual stimuli and auditory stimuli on restorative potential and aesthetic preference in urban green spaces. *Urban Forestry & Urban Greening* **53**, 126702 (2020).
42. Krzywicka, P. & Byrka, K. Restorative Qualities of and Preference for Natural and Urban Soundscapes. *Frontiers in Psychology* **8**, (2017).
43. Ratcliffe, E., Gatersleben, B. & Sowden, P. T. Bird sounds and their contributions to perceived attention restoration and stress recovery. *Journal of Environmental Psychology* **36**, 221–228 (2013).
44. Gould van Praag, C. D. *et al.* Mind-wandering and alterations to default mode network connectivity when listening to naturalistic versus artificial sounds. *Sci Rep* **7**, 45273 (2017).
45. Yin, J., Zhu, S., MacNaughton, P., Allen, J. G. & Spengler, J. D. Physiological and cognitive performance of exposure to biophilic indoor environment. *Building and Environment* **132**, 255–262 (2018).

46. Aristizabal, S. *et al.* Biophilic office design: Exploring the impact of a multisensory approach on human well-being. *Journal of Environmental Psychology* **77**, 101682 (2021).
47. Alvarsson, J. J., Wiens, S. & Nilsson, M. E. Stress Recovery during Exposure to Nature Sound and Environmental Noise. *International Journal of Environmental Research and Public Health* **7**, 1036–1046 (2010).
48. Jo, H. *et al.* Physiological and Psychological Effects of Forest and Urban Sounds Using High-Resolution Sound Sources. *International Journal of Environmental Research and Public Health* **16**, 2649 (2019).
49. Song, I., Baek, K., Kim, C. & Song, C. Effects of nature sounds on the attention and physiological and psychological relaxation. *Urban Forestry & Urban Greening* **86**, 127987 (2023).
50. Labuschagne, I., Grace, C., Rendell, P., Terrett, G. & Heinrichs, M. An introductory guide to conducting the Trier Social Stress Test. *Neuroscience & Biobehavioral Reviews* **107**, 686–695 (2019).
51. Gero, J. Generalizing Design Cognition Research. in (Sydney, Australia, 2010). doi:10.13140/2.1.3756.5128.
52. Shealy, T. & Gero, J. The Neurocognition of Three Engineering Concept Generation Techniques. *Proceedings of the Design Society: International Conference on Engineering Design* **1**, 1833–1842 (2019).
53. Beaty, R. E. & Kenett, Y. N. Associative thinking at the core of creativity. *Trends in Cognitive Sciences* **27**, 671–683 (2023).
54. Brown, D. C. & Chandrasekaran, B. Expert systems for a class of mechanical design activity. *Knowledge Engineering in …* (1985).
55. Schon, D. A. *The Reflective Practitioner - How Professionals Think in Action*. (Basic Books, 1983).
56. Browning, W., Ryan, C. & Clancy, J. *14 Patterns of Biophilic Design*. http://www.terrapinbrightgreen.com/reports/14-patterns-of-biophilic-design/ (2014).
57. Marte, E. *et al.* Testing Reliability of Biophilic Design Matrix Within Urban Residential Playrooms. *Frontiers in Psychology* **11**, (2020).
58. McGee, B., Park, N.-K., Portillo, M., Bosch, S. & Swisher, M. Diy Biophilia: Development of the Biophilic Interior Design Matrix as a Design Tool. *Journal of Interior Design* **44**, 201–221 (2019).
59. McGee, B., Jin, X., Park, N.-K., Ball, S. & Carr, A. Designers' perceptions of biophilia and testing of the biophilic interior design matrix in China. *Archnet-IJAR: International Journal of Architectural Research* **16**, 517–535 (2022).
60. McGee, B. & Marshall-Baker, A. Loving Nature From the Inside Out: A Biophilia Matrix Identification Strategy for Designers. *HERD : Health Environments Research & Design Journal* **8**, 115–130 (2015).
61. Goelman, G., Dan, R., Bezdicek, O., Jech, R. & Ekstein, D. Directed functional connectivity of the default-mode-network of young and older healthy subjects. *Sci Rep* **14**, 4304 (2024).
62. Burgess, P. W., Gilbert, S. J. & Dumontheil, I. Function and localization within rostral prefrontal cortex (area 10). *Philosophical Transactions of the Royal Society B: Biological Sciences* **362**, 887–899 (2007).

63. Burgess, P. W. & Wu, H.-C. Rostral Prefrontal Cortex (Brodmann Area 10): Metacognition in the Brain. in *Principles of Frontal Lobe Function* (eds. Burgess, P. W., Stuss, D. T. & Knight, R. T.) 0 (Oxford University Press, 2013). doi:10.1093/med/9780199837755.003.0037.
64. Peng, K., Steele, S. C., Becerra, L. & Borsook, D. Brodmann area 10: Collating, integrating and high level processing of nociception and pain. *Progress in Neurobiology* **161**, 1–22 (2018).
65. Benedek, M. *et al.* Brain mechanisms associated with internally directed attention and self-generated thought. *Sci Rep* **6**, 22959 (2016).
66. Davey, C. G., Pujol, J. & Harrison, B. J. Mapping the self in the brain's default mode network. *NeuroImage* **132**, 390–397 (2016).
67. McDonnell, A. S. & Strayer, D. L. Immersion in nature enhances neural indices of executive attention. *Sci Rep* **14**, 1845 (2024).
68. Zabelina, D. L. & Silvia, P. J. Percolating ideas: The effects of caffeine on creative thinking and problem solving. *Consciousness and Cognition* **79**, 102899 (2020).
69. Rozin, P. & Royzman, E. B. Negativity Bias, Negativity Dominance, and Contagion. *Pers Soc Psychol Rev* **5**, 296–320 (2001).
70. Klaniecki, K., Leventon, J. & Abson, D. J. Human–nature connectedness as a 'treatment' for pro-environmental behavior: making the case for spatial considerations. *Sustain Sci* **13**, 1375–1388 (2018).
71. Parker, J. & Simpson, G. D. A Theoretical Framework for Bolstering Human-Nature Connections and Urban Resilience via Green Infrastructure. *Land* **9**, 252 (2020).
72. Hartig, T., Kaiser, F. G. & Strumse, E. Psychological restoration in nature as a source of motivation for ecological behaviour. *Environmental Conservation* **34**, 291–299 (2007).
73. Leung, G., Hazan, H. & Chan, C. S. Exposure to nature in immersive virtual reality increases connectedness to nature among people with low nature affinity. *Journal of Environmental Psychology* 101863 (2022) doi:10.1016/j.jenvp.2022.101863.
74. Mackay, C. M. L. & Schmitt, M. T. Do people who feel connected to nature do more to protect it? A meta-analysis. *Journal of Environmental Psychology* **65**, 101323 (2019).
75. Nisbet, E. K. & Zelenski, J. M. The NR-6: a new brief measure of nature relatedness. *Front Psychol* **4**, 813 (2013).
76. Annerstedt, M. *et al.* Inducing physiological stress recovery with sounds of nature in a virtual reality forest — Results from a pilot study. *Physiology & Behavior* **118**, 240–250 (2013).
77. Thoma, M. V. *et al.* The Effect of Music on the Human Stress Response. *PLOS ONE* **8**, e70156 (2013).
78. Goodman, W. K., Janson, J. & Wolf, J. M. Meta-analytical assessment of the effects of protocol variations on cortisol responses to the Trier Social Stress Test. *Psychoneuroendocrinology* **80**, 26–35 (2017).
79. Vadlamudi, R. LAZY BOYS PRODUCTIONS - YouTube. https://www.youtube.com/ (2018).
80. Delos Living LLC. MindBreaks - Relax & Recharge. Delos Living LLC (2020).
81. Rashid, M. & Zimring, C. A Review of the Empirical Literature on the Relationships Between Indoor Environment and Stress in Health Care and Office Settings: Problems and Prospects of Sharing Evidence. *Environment and Behavior* **40**, 151–190 (2008).

82. Barton, J. & Pretty, J. What is the Best Dose of Nature and Green Exercise for Improving Mental Health? A Multi-Study Analysis. *Environ. Sci. Technol.* **44**, 3947–3955 (2010).
83. Ojala, A. *et al.* Short virtual nature breaks in the office environment can restore stress: An experimental study. *Journal of Environmental Psychology* **84**, 101909 (2022).
84. Thoma, M. V., Mewes, R. & Nater, U. M. Preliminary evidence: the stress-reducing effect of listening to water sounds depends on somatic complaints. *Medicine (Baltimore)* **97**, e9851 (2018).
85. Ferraro, F. M. Enhancement of Convergent Creativity Following a Multiday Wilderness Experience. *Ecopsychology* **7**, 7–11 (2015).
86. Dul, J., Ceylan, C. & Jaspers, F. Knowledge workers' creativity and the role of the physical work environment. *Human Resource Management* **50**, 715–734 (2011).
87. McCoy, J. M. & Evans, G. W. The Potential Role of the Physical Environment in Fostering Creativity. *Creativity Research Journal* **14**, 409–426 (2002).
88. Yeh, C.-W., Hung, S.-H. & Chang, C.-Y. The influence of natural environments on creativity. *Frontiers in Psychiatry* **13**, (2022).
89. Plambech, T. & Konijnendijk van den Bosch, C. C. The impact of nature on creativity – A study among Danish creative professionals. *Urban Forestry & Urban Greening* **14**, 255–263 (2015).
90. Beaty, R. E., Silvia, P. J., Nusbaum, E. C., Jauk, E. & Benedek, M. The roles of associative and executive processes in creative cognition. *Mem Cogn* **42**, 1186–1197 (2014).
91. Mednick, S. The associative basis of the creative process. *Psychological Review* **69**, 220–232 (1962).
92. Beaty, R. E. & Johnson, D. R. Automating creativity assessment with SemDis: An open platform for computing semantic distance. *Behav Res* **53**, 757–780 (2021).
93. Beaty, R. E., Silvia, P. J., Nusbaum, E. C., Jauk, E. & Benedek, M. The roles of associative and executive processes in creative cognition. *Mem Cogn* **42**, 1186–1197 (2014).
94. Dumas, D., Organisciak, P. & Doherty, M. Measuring Divergent Thinking Originality with Human Raters and Text-Mining Models: A Psychometric Comparison of Methods. *Psychology of Aesthetics Creativity and the Arts* (2020) doi:10.1037/aca0000319.
95. Johnson, D. R. *et al.* Divergent Semantic Integration (DSI): Extracting Creativity from Narratives with Distributional Semantic Modeling. Preprint at https://doi.org/10.31234/osf.io/fmwgy (2021).
96. Shealy, T. Do Sustainable Buildings Inspire More Sustainable Buildings? *Procedia Engineering* **145**, 412–419 (2016).
97. Schacter, D. L. & Church, B. A. Auditory priming: Implicit and explicit memory for words and voices. *Journal of Experimental Psychology: Learning, Memory, and Cognition* **18**, 915–930 (1992).
98. Kakoun, N. A., Boy, F., Groves, C. & Xavier, P. Priming Civil Engineers Into Human-Centered Designing (and Its Unexpected Consequences). in (2021).
99. Richardson, M. & Butler, C. W. Nature connectedness and biophilic design. *Building Research & Information* **50**, 36–42 (2022).
100. Whitburn, J., Linklater, W. & Abrahamse, W. Meta-analysis of human connection to nature and proenvironmental behavior. *Conservation Biology* **34**, 180–193 (2020).

101. Bargh, J. A., Chen, M. & Burrows, L. Automaticity of social behavior: Direct effects of trait construct and stereotype activation on action. *Journal of Personality and Social Psychology* **71**, 230–244 (1996).
102. Hu, M. & Shealy, T. Priming Engineers to Think About Sustainability: Cognitive and Neuro-Cognitive Evidence to Support the Adoption of Green Stormwater Design. *Front Neurosci* **16**, 896347 (2022).
103. She, J. & MacDonald, E. Priming Designers to Communicate Sustainability. *Journal of Mechanical Design* **136**, (2013).
104. Kellert, S. R. Dimensions, Elements, and Attributes of Biophilic Design. in *Biophilic Design: The Theory, Science and Practice of Bringing Buildings to Life* (John Wiley & Sons, 2011).
105. Kellert, S. R. & Wilson, E. O. *The Biophilia Hypothesis*. (Island Press, 1993).
106. Laird, A. R. *et al.* Behavioral interpretations of intrinsic connectivity networks. *J Cogn Neurosci* **23**, 4022–4037 (2011).
107. Řehůřek, R. & Sojka, P. *Software Framework for Topic Modelling with Large Corpora*. 50 (2010). doi:10.13140/2.1.2393.1847.
108. Bird, S., Klein, E. & Loper, E. *Natural Language Processing with Python*. (2009).
109. Friedl, J. E. F. *Mastering Regular Expressions*. (O'Reilly Media, Inc., 2006).
110. Honnibal, M., Montani, I., Van Landeghem, S. & Boyd, A. spaCy: Industrial-strength Natural Language Processing in Python. 10.5281/zenodo.1212303 (2020).
111. Ignacio Junior, P. & Shealy, T. EFFECTS OF BIOPHILIC RESTORATIVE EXPERIENCES ON DESIGNERS' BODIES, BRAINS, AND MINDS. *Proceedings of the Design Society* **3**, 1565–1574 (2023).
112. Santosa, H., Zhai, X., Fishburn, F. & Huppert, T. The NIRS Brain AnalyzIR Toolbox. *Algorithms* **11**, 73 (2018).
113. Fishburn, F. A., Ludlum, R. S., Vaidya, C. J. & Medvedev, A. V. Temporal Derivative Distribution Repair (TDDR): A motion correction method for fNIRS. *NeuroImage* **184**, 171–179 (2019).
114. Pinti, P., Scholkmann, F., Hamilton, A., Burgess, P. & Tachtsidis, I. Current Status and Issues Regarding Pre-processing of fNIRS Neuroimaging Data: An Investigation of Diverse Signal Filtering Methods Within a General Linear Model Framework. *Front Hum Neurosci* **12**, 505 (2019).
115. Yücel, M. A. *et al.* Mayer waves reduce the accuracy of estimated hemodynamic response functions in functional near-infrared spectroscopy. *Biomed. Opt. Express, BOE* **7**, 3078–3088 (2016).
116. Hagberg, A. A., Schult, D. A. & Swart, P. J. Exploring Network Structure, Dynamics, and Function using NetworkX. in *Proceedings of the 7th Python in Science Conference* (eds. Varoquaux, G., Vaught, T. & Millman, J.) 11–15 (Pasadena, CA USA, 2008).

Chapter 4 - Effects of multisensory biophilic experiences on the body, brain, and mind

Abstract

The restorative effects of immersion in nature to cognitive and psychophysiological resources have been investigated in several contexts, from the Japanese forest-bathing practices to virtual reality biophilic office spaces. However, albeit the accumulating evidence of beneficial effects, little exploration has been pursued on the translational potential and applicability of biophilic restorative experiences to real world scenarios, as well as the differential effects between isolated and combined sensory experiences. This study aimed to explore the impact of multisensory biophilic experiences on how people feel, think, and design. Hypotheses predicted higher parasympathetic activity, increased functional connectivity within the prefrontal cortex (PFC), and greater incorporation of biophilic design elements in participants exposed to biophilic conditions. A randomized controlled trial including a stress induction task, a restoration break, and an open-ended design task was conducted, measuring physiological arousal, brain activity, and design outcomes. Results indicated that exposure to biophilic auditory stimuli led to higher physiological arousal levels, challenging expectations. The multisensory group showed intermediate arousal levels, suggesting nuanced effects of sensory combinations. Neurocognitive analyses revealed differential brain activation patterns across sensory conditions and higher resource consumption efficiency in the visual and multisensory groups. Furthermore, the visual group exhibited stronger incorporation of biophilic design elements, supporting our hypothesis. Our findings contribute the body of knowledge on the Attention Restoration Theory (ART) and the Stress Reduction Theory (SRT) while also introducing new perspectives to the literature on the effects of biophilic experiences.

Introduction

Modern indoor environments lack the sensory richness the human body evolved to experience. Residents of urban areas spend over 87% of their lives inside buildings[1], disconnected from sensory experiences in the natural world that shaped human perceptual and cognitive systems throughout evolutionary history[2]. This separation from nature occurs despite biophilia, the human innate tendency to affiliate with the natural world[3]. Although innate, the human biophilic tendencies can go dormant and need to be stimulated over time[4]. The lack of access to positive experiences of nature, or biophilic experiences, not only suppresses the human biophilic tendencies but also prevents humans from enjoying the restorative effects of nature-based stimuli.

The Attention Restoration Theory[5,6] (ART) proposes that nature exposure allows fatigued directed-attention mechanisms, part of top-down regulatory processes[7], to be replenished by exposure to softly fascinating stimuli that engages involuntary attention[8]. Prior studies utilizing brain imaging techniques have identified changes in prefrontal cortical activity due to exposure to biophilic experiences[9], providing objective evidence of the ART. Yet, relatively few studies have explored the differential patterns of activation within the prefrontal cortex (PFC) during and following biophilic experiences. A field study comparing views to a forest area and to an urban area found reduced concentration of oxygenated hemoglobin (Oxy-Hb) in the right and left sides of the PFC while viewing the forest[10]. Another study utilizing the same brain imagining technique found similar results, but this time with nature sounds.

Participants Oxy-Hb concentration in both the right and left sides of the PFC were significantly lower when listening to forest sounds, as compared to city sounds[11]. A limitation for these studies is the lack of granularity for the neurocognitive data. Splitting the PFC into right and left sides fails to account for different regions of interest (ROIs) that are part of distinct networks. For example, while the dorsolateral prefrontal cortex (DLPFC) is engaged with the fronto-parietal network, the ventrolateral prefrontal cortex (VLPFC) is part of the cingulo-opercular network, and the dorsomedial prefrontal cortex (DMPFC) is a hub of the default-mode network[7] (DMN). With all ROIs being involved in distinctive processes within their respective networks, more granular brain imaging data is needed to understand the neurocognitive mechanisms behind the ART.

Gould van Praag and colleagues[9] identified the need for exploring how different networks are engaged during biophilic experiences and investigated effects to the DMN during exposure to naturalistic versus artificial sounds. Previous research had suggested that exposure to nature-based stimuli could be associated with an engagement of the DMN, enabling an introspective mind state referred to as mind wandering[12]. Analysis of data collected through functional magnetic resonance imaging (fMRI) indicated no evidence of differential engagement of the DMN during exposure to naturalistic sounds[9]. Nonetheless, evidence of a switch from top-down to bottom-up regulatory processes was found by metrics of heart rate variability (HRV). The naturalistic condition led to an increase in peak high frequency (HF) HRV, indicating an increase in parasympathetic activity, and therefore supporting the Stress Reduction Theory[9,13] (SRT). The SRT proposes that biophilic experiences can aid the body’s stress regulation by promoting parasympathetic nervous system (PNS) activity and enabling the restoration of psychophysiological resources[13–16]. Just as for the ART, numerous studies[17–22] have utilized physiological measurements to objectively test the SRT, finding exposure to nature-based stimuli to promote changes in HRV[21] and electrodermal activity[23] (EDA). With increasing evidence of the neurocognitive and physiological effects of biophilic experiences, a gap in knowledge that still remains concerns how the positive effects on body and brain ultimately affect the mind.

Prior studies heavily relied on basic cognitive tests like the Digit Span Backwards test[8,24,25], the Operation Span test[18], or the Remote Associates Task[12] for assessing the impact of biophilic experiences on cognitive performance. The impacts on complex cognitive abilities like design thinking, which integrate creativity, abstraction and goal-directed reasoning, is underexplored despite its centrality to disciplines shaping society[26–29]. To address this gap, we used a novel open-ended architectural design task to capture the cognitive effects of biophilic experiences on design thinking. Here, we explore the effects of biophilic experiences on how people *feel*, *think*, and *design*, while also assessing the differences between auditory and visual experiences, as well as the potential cumulative effects of multisensory experiences. Our main idea is that, when compared to a control scenario, participants who are exposed to biophilic experiences would enjoy enhanced restoration of depleted cognitive, neurocognitive, and physiological resources, which in turn would enable better performance in a design task. Specifically, we hypothesized that participants in the biophilic conditions would (1) enjoy higher parasympathetic activity and (2) increased functional connectivity within the DMN both during the exposure period and during the subsequent design task. Furthermore, we hypothesized that participants in the biophilic conditions would (3) incorporate more biophilic design elements in their design products. Lastly, we hypothesized that the combination of different sensory experiences would lead to a cumulative effect and (4) participants in the multisensory condition would enjoy the most significant effects.

In an experiment including three phases – stress induction, restoration break, and design task – brain activity was measured by functional near-infrared spectroscopy (fNIRS) throughout all phases. EDA and HRV were also continuously tracked by a wrist-worn device. A cohort of healthy college students was randomly split into four groups which either received a different sensory experience during the restoration break. After being induced to a stressful state by means of the Trier Social Stress Test[30] (TSST) – depleting cognitive, neurocognitive, and physiological resources - participants were exposed to either a biophilic auditory experience, a biophilic visual experience, or a biophilic multisensory experience (auditory + visual). The control group had no auditory nor visual stimulation during this period. Following the restoration break, participants were asked to develop a design concept of a playground for young children inside an existing park. Design concepts were assessed for the incorporation of biophilic design by two different raters. fNIRS data was analyzed to assess changes in prefrontal cortical functional connectivity. EDA and HRV data were analyzed to assess changes in the autonomic nervous system (ANS). We observed that (I) during the exposure period, the auditory condition drove the most significant physiological changes, inducing high arousal; (2) both the visual and the multisensory group presented significantly less centrality in ROIs part of the fronto-parietal, the cingulo-opercular, and the default-mode networks, suggesting potential support to the Neural Efficiency Hypothesis[31–33] (NEH); lastly, (3) the visual group incorporated significantly more of 3 out of 14 patterns of biophilic design.

Results

Nature sounds increase physiological arousal

Participants were randomly assigned to either a control group (n = 32), the auditory group (n = 32), the visual group (n = 29), or the multisensory group (n = 29). All participants were induced to a heightened state of psychosocial stress through the Trier Social Stress Test[30]. Following the stressor, each group was exposed to different environmental conditions during an 8-minute restoration break. The exposure conditions consisted of: no auditory stimulus and no visual stimulus (control group); biophilic auditory experience with no visual stimulus (auditory group); biophilic visual experience with no auditory stimulus (visual group); combined auditory and visual biophilic experience (multisensory group). Lastly, participants were given an open-ended design task with no time restrictions, which prompted them to design a playground for young children.

Throughout all experiment phases, participants' electrodermal activity (EDA) and heart rate variability (HRV) were continuously monitored by a wristband with medical-grade photoplethysmography (PPG) and EDA sensors. During the restoration break, the skin conductance level (SCL) for the auditory group was significantly higher than the visual (p = 0.006, Cohen's d = 0.925) and the control (p = 0.014, Cohen's d = 0.850) groups, with large effect sizes (Fig. 1). Even though age was found to be a confounder (β = -0.054, 95% CI = (-0.095, -0.014), p = 0.008), after controlling for age, gender, caffeine consumption within two hours of the experiment, time of the day, baseline stress level and baseline connectedness to nature, the linear mixed effects model still indicated a significant main effect for the auditory group (β = 1.702, 95% CI = (0.404, 3.001), *p* = 0.010) for SCL during the restoration break, suggesting higher physiological arousal[34].

Also, during the restoration break, the mean frequency of skin conductance responses (nSCR) for the auditory group was significantly higher than the visual group (*p* = 0.030), with a medium to large effect size (Cohen's *d* = 0.749), however no main effects remained after controlling for confounders.

As a metric of the sympathovagal balance, the ratio of the low frequency to the high frequency (LF/HF) components of HRV can indicate changes in physiological arousal by sympathetic modulations[35–37]. During the restoration break, the LF/HF ratio for the auditory group was significantly higher than the visual (*p* = 0.010, Cohen's *d* = 0.861) and the control (*p* = 0.017, Cohen's *d* = 0.773) groups, with large and medium to large effect sizes. Linear mixed effects model indicated a significant main effect for the auditory group (β = 0.824, 95% CI = (0.338, 1.310), *p* = 0.001) even after controlling for all potential confounders. The HF component of HRV is associated with parasympathetic activity[38]. During the restoration break, a linear mixed effects model indicated significant main effects of age (β = -17.286, 95% CI = (-33.433, -1.139), *p* = 0.036) and baseline connectedness to nature (β = 61.126, 95% CI = (3.736, 118.515), *p* = 0.037) on the HF component of HRV, where individuals with high baseline connectedness to nature experienced an increase, and older individuals experienced a decrease in parasympathetic activity.

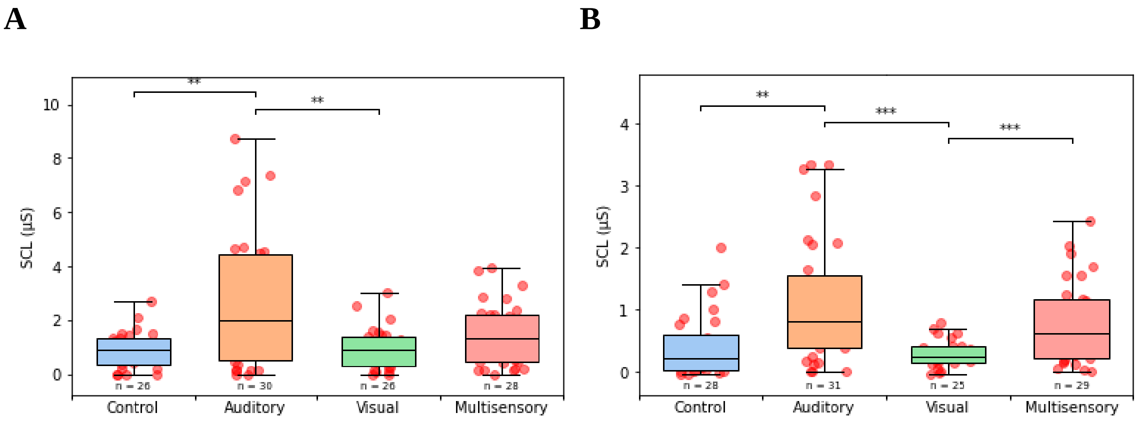


Figure 4.1. Mean SCL during the restoration break (A) and design task (B) for all groups.

During the design task, a significant main effect was again found for the auditory group. SCL for the auditory group was significantly higher than the visual (*p* = 0.0008, Cohen's *d* = 1.109) and the control (*p* = 0.010, Cohen's *d* = 0.839) groups, with large effect sizes. Also, the mean SCL for the multisensory group was significantly higher than the visual group (*p* = 0.003), with a large effect size (Cohen's *d* = 1.007). A linear mixed effects model indicated that, as a confounder, baseline stress level had a significant main effect (β = 0.185, 95% CI = (0.017, 0.353), *p* = 0.031). However, a significant main effect for the auditory group (β = 0.517, 95% CI = (0.059, 0.974), *p* = 0.027) existed even after controlling for all confounders. Analysis of the mean nSCR showed a significant main effect for the visual group (β = -80.650, 95% CI = (-151.416, -9.885), *p* = 0.026). As a confounder, again age had a significant main effect (β = -

12.409, 95% CI = (-19.511, -5.307), $p = 0.001$). Analysis of the HF component of HRV also significant effects of age (β = -10.546, 95% CI = (-17.815, -3.277), $p = 0.004$) on the dependent variable.

Effects on neurocognition

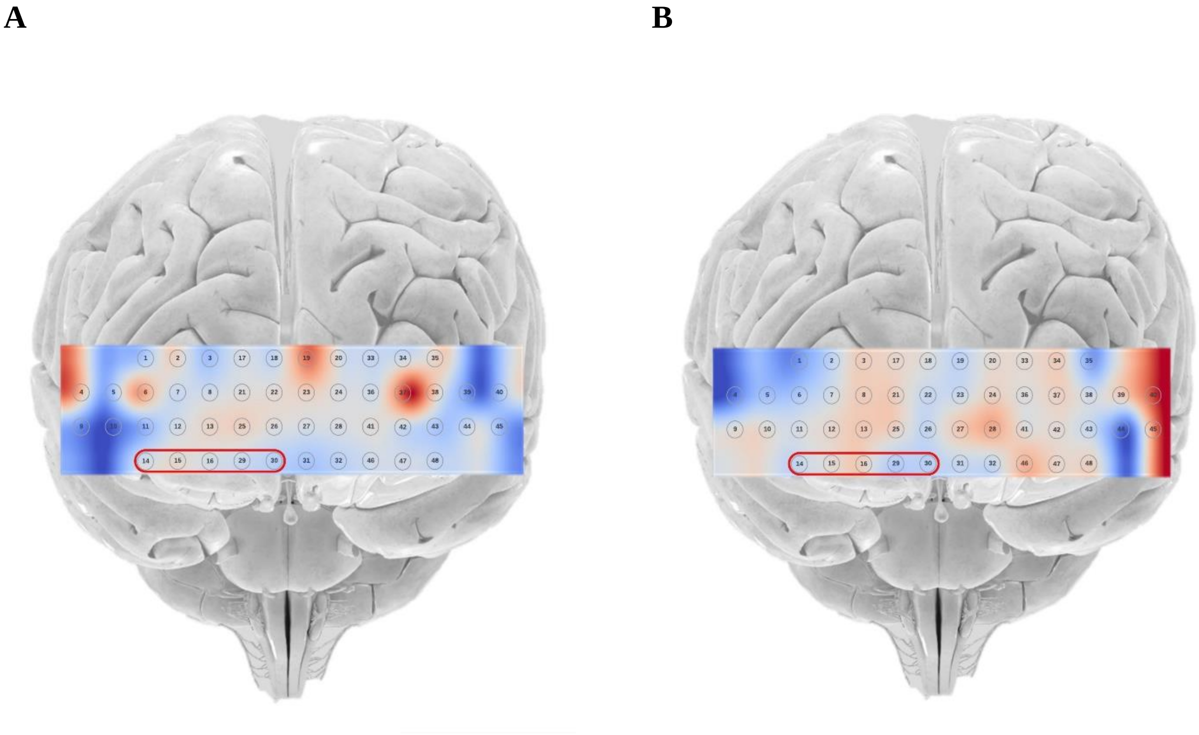


Figure 4.2 Heat maps for the mean recruitment of Oxy-Hb to the PFC during the restoration break.

A linear mixed effects models indicated significant main effects for the multisensory (A) and visual (B) groups for activation of the rOFC, region represented by channels 14, 15, 16, 29, and 30 (highlighted in red).

Neurocognitive responses were recorded throughout the experiment using fNIRS. Data for the changes in recruitment of oxygenated hemoglobin (Oxy-Hb) to the PFC were analyzed for ten different regions of interest (ROI), including right and left dorsomedial (DM), dorsolateral (DL), and ventrolateral (VL) prefrontal cortex, as well as the right and left frontopolar cortex and orbitofrontal cortex. During the restoration break, the mean recruitment of Oxy-Hb to the rOFC for the multisensory group was significantly higher than the auditory group ($p = 0.029$), with medium to large (Cohen’s $d = 0.781$) effect size. Although baseline connectedness to nature was found to have main effect (β = 16.906, 95% CI = (9.397, 24.415), $p < 0.001$), significant main effects were found for the multisensory (β = 65.513, 95% CI = (18.060, 106.967), $p = 0.006$) and visual (β = 49.110, 95% CI = (3.794, 94.426), $p = 0.034$) groups, even after controlling for age, gender, caffeine consumption within two hours of the experiment, time of the day (AM/PM), baseline stress level and connectedness to nature.

Confounders were found to have main effects on five additional ROIs. Baseline connectedness to nature also had a positive effect on the recruitment of Oxy-Hb to the lDLPFC (β = 26.922, 95% CI = (8.591, 45.253), *p* = 0.004) and the lDMPFC (β = 39.262, 95% CI = (17.461, 61.063). On the other hand, it had a negative main effect on activation of the rDLPFC (β = -35.780, 95% CI = (-59.465, -12.095), *p* = 0.003). Other main effects from confounders included the effects of age on the rVLPFC (β = 3.154, 95% CI = (0.352, 5.957), *p* = 0.027), gender on the lVLPFC (Male, β = 136.221, 95% CI = (58.945, 213.497), *p* = 0.001), and baseline stress level on the rDLPFC (β = 24.539, 95% CI = (0.440, 48.638), *p* = 0.046).

During the design task, a linear mixed effects model tracking activation of the lOFC as the dependent variable indicated a significant main effect for the visual group (β = -24.342, 95% CI = (-48.168, -0.515), *p* = 0.045) after controlling for all potential confounders. Analysis for other ROIs indicated baseline connectedness to nature to be a confounder once again. Baseline connectedness to nature had a negative main effect on activation of the rOFC (β = -12.389, 95% CI = (-18.587, -6.192), *p* = 0.000) and a positive main effect on activation of the right frontopolar cortex (β = 9.085, 95% CI = (0.403, 17.768), *p* = 0.040) during the design task.

Functional connectivity analysis was utilized to assess the dynamics of simultaneous engagement of different ROIs. Network density and node degree centrality were the two metrics utilized for statistical comparisons. The network density score is given on a scale of 0 to 1, and refers to a topological metric indicating the ratio of actual edges (i.e. correlations between nodes) present in a network to the total possible number of edges[39]. Higher density therefore indicates enhanced connectivity between ROIs. A node's degree centrality describes the number of nodes it is connected to as a proportion of the total amount of nodes, where nodes with high degree centrality are acting as main hubs within the network[40].

During the restoration break, the mean network density for the auditory group was significantly higher than the visual group (*p* = 0.006), with a large effect size (Cohen's *d* = 0.928). After controlling for potential confounders, no main effects were found.

During the design task, a linear mixed effects model indicated a main effect of gender on network density (Male, β = -0.030, 95% CI = (-0.049, -0.011), *p* = 0.002). Splitting the period in which participants are engaged with a design task into even segments is an approach utilized to explore temporal changes in functional connectivity during design[41–43]. Analysis of different deciles indicated main effects in the first and second deciles. During the first decile, age had a significant main effect on density as a confounder (β = 0.004, 95% CI = (0.002, 0.006), $p <$ 0.001). During the second decile, the mean network density for the auditory group was significantly higher than the visual (*p* = 0.0174) and the multisensory (*p* = 0.0016) groups, with medium to large (Cohen's *d* = 0.782) and large (Cohen's *d* = 1.060) effect sizes. Also, the mean network density for the control group was significantly higher than the multisensory group (*p* = 0.0039), with a large effect size (Cohen's *d* = 0.977). After controlling for confounders, no main effects remained but the effect of age (β = 0.007, 95% CI = (0.002, 0.006), $p < 0.001$).

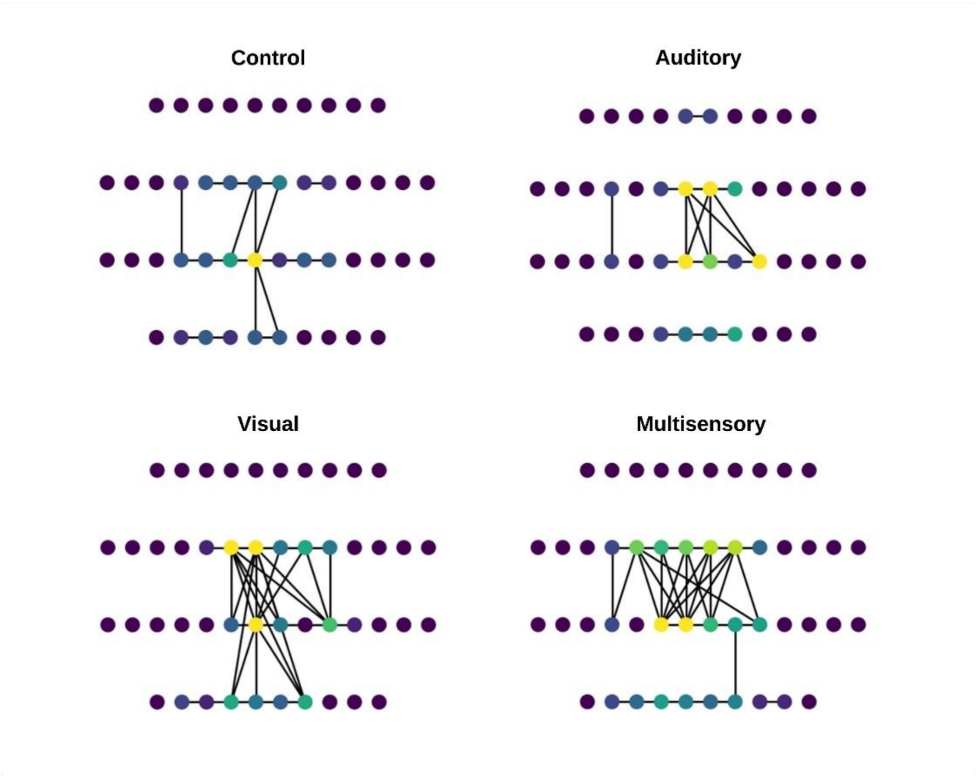


Figure 4.3 Brain network graphs for all groups during the design task.

Analysis of node degree centrality indicated that both the visual and the multisensory group had significant lower concentration of activation in different ROIs, suggesting a possible effect of the treatments on neural efficiency[31,32] during the design task.

Mean degree centrality for each ROI was calculated by averaging the degree centrality scores for nodes within each region. Main effects were found for both the visual and the multisensory groups, as well as for caffeine and baseline connectedness to nature as confounders. Consumption of caffeine within two hours of the experiment had a positive main effect on degree centrality for the left frontopolar cortex (β = 0.067, 95% CI = (0.005, 0.128), *p* = 0.035) and the rOFC (β = 0.067, 95% CI = (0.004, 0.130), *p* = 0.038) during the restoration break. Baseline connectedness to nature had a negative main effect on degree centrality for the the rDMPFC (β = -0.026, 95% CI = (-0.045, -0.007), *p* = 0.009) and the lOFC (β = -0.009, 95% CI = (-0.016, -0.003), *p* = 0.003) during the design task.

During the restoration break, after controlling for potential confounders, the visual group had negative main effects on the degree centrality for the rDMPFC (β = -0.052, 95% CI = (-0.097, -0.006), *p* = 0.026) and the lVLPFC (β = -0.046, 95% CI = (-0.082, -0.011), *p* = 0.010), and so did the multisensory group for the lVLPFC (β = -0.039, 95% CI = (-0.074, -0.004), *p* = 0.028). During the design task, negative main effects were also found visual and multisensory groups. The visual group had a negative main effect on degree centrality for the rDMPFC (β = -0.059, 95% CI = (-0.099, -0.020), *p* = 0.003), the rDLPFC (β = -0.055, 95% CI = (-0.096, -0.013), *p* = 0.010), the lDLPFC (β = -0.062, 95% CI = (-0.119, -0.005), *p* = 0.034), and the lVLPFC (β = -0.062, 95% CI = (-0.106, -0.017), *p* = 0.007). The multisensory group had a negative main effect on degree centrality for the right (β = -0.052, 95% CI = (-0.090, -0.013), *p* = 0.008) and left (β = -0.051, 95% CI = (-0.101, -0.000), *p* = 0.048) DMPFC.

Effects on design cognition

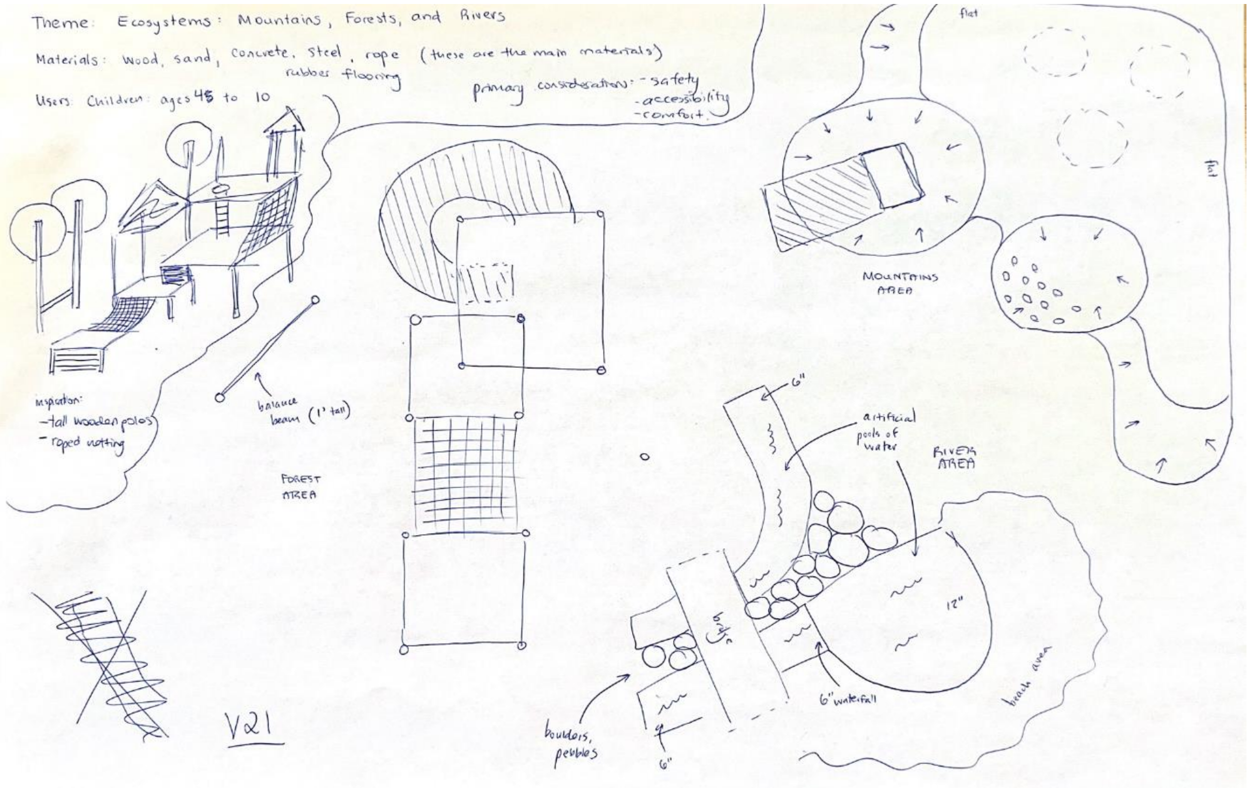


Figure 4.4 Example of design concept produced by the visual group.

The sketch shown above represents an example of a design concept that was given maximum scores (i.e. 3, strongly present) for the incorporation of *Visual Connection with Nature*, *Presence of Water*, and *Risk/Peril*. *Visual Connection with Nature* is described as “a view to elements of nature, living systems and natural processes.” *Presence of Water* is described as “a condition that enhances the experience of a place through the seeing, hearing or touching of water.” *Risk/Peril* is described as “an identifiable threat coupled with a reliable safeguard.”[44]

Qualitative analysis of the design concepts generated was conducted utilizing a modified version of the Biophilic Design Matrix[45–48] (BDM). This tool facilitates the assessment of the extent to which biophilic design is present in a design product. Raters are asked to rate the presence of each of the “14 Patterns of Biophilic Design”[44] on a scale of 0 (not present at all) to 3 (strongly present), leading into an overall BDM score with a maximum of 42 points. A post-doctoral researcher trained in biophilic design volunteered as rater. Results from linear mixed-effects models adjusted for age, gender, design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature showed that the visual group produce design concepts that incorporated significantly more *Visual Connection with Nature* ($\beta = 0.477$, 95% CI = (0.004, 0.950), $p = 0.048$), *Presence of Water* ($\beta = 0.948$, 95% CI = (0.346, 1.550), $p = 0.002$), and *Risk/Peril* ($\beta = 0.813$, 95% CI = (0.327, 1.300), $p = 0.001$). As a confounder, prior biophilic design knowledge had main effects on the *Thermal and Airflow Variability* ($\beta = 1.476$, 95% CI = (0.054, 2.898), $p = 0.042$) and the *Prospect* ($\beta = 1.251$, 95% CI = (0.008, 2.494), $p = 0.049$) patterns. Age had negative main effects on the incorporation of the *Material Connection with Nature* ($\beta = -0.051$, 95% CI = (-0.092, -0.010), $p = 0.014$) and *Complexity & Order* ($\beta = -0.068$, 95% CI = (-0.118, -0.018), $p = 0.008$) patterns.

Discussion

In an experiment exploring the effects of biophilic multisensory experiences on the body, brain, and mind, we showed that the type of sensory experience is a determinant of the type and magnitude of the effects. It was hypothesized that participants in the biophilic conditions would (1) enjoy higher parasympathetic activity and (2) increased functional connectivity within the DMN both during the exposure period and during the subsequent design task. Also, we hypothesized that through an increase in feelings of connectedness to nature following the exposure period, participants in the biophilic conditions would (3) incorporate more biophilic design elements in their design products. Lastly, we hypothesized that the combination of different sensory experiences would lead to a cumulative effect and (4) participants in the multisensory condition would enjoy the most significant effects.

We found that exposure to the biophilic auditory experience (birdsong and water sounds) drove significantly more physiological arousal than exposure to the biophilic visual or multisensory experiences, as well as to the no-stimulus condition (Fig. 4.1). Physiological arousal for the multisensory group was in between the auditory and the visual groups, indicating the possibility that the combined engagement of multiple senses does not necessarily lead to cumulative effects. Analysis of prefrontal cortical activity during both the exposure period and the subsequent design task showed that the neurocognitive effects of biophilic experiences are more sophisticated than a decrease or an increase in activity in the left or right PFC[10,11]. Differential effects were found for mean Oxy-Hb recruitment to the right and left OFC (Fig. 4.2).

Brain network analysis (Fig. 4.3) indicated that the auditory group had significantly denser brain networks, a proxy for enhanced functional connectivity, during both the restoration break and the design task. Analysis of degree centrality for each ROI showed consistently lower centrality across multiple ROIs (rDMPFC, lDMPFC, lVLPFC, rDLPFC, lDLPFC) for both the visual and the multisensory groups, indicating a potential effect on resource consumption efficiency[31–33]. Lastly, assessment of the design concepts utilizing the modified version of the BDM[45–47] showed that the concepts produced by the visual group had significantly stronger presence of 3 out of the “14 Patterns of Biophilic Design”[44], when compared to the other groups. The visual group incorporated significantly more of the *Visual Connection with Nature*, *Presence of Water*, and *Risk/Peril* patterns in their design concepts.

Previous research[9,17,18] exploring the stress reduction potential[13,14] of biophilic experiences have relied on behavioral and physiological measures to interpret changes in participants' stress level. Expectations are set for the self-reported stress levels and ANS activity (EDA and/or HRV data) to tell the same story. However, this is not always the case. One study[49] comparing the effects of exposure to natural versus artificial materials found that participants in the wooden room presented higher physiological arousal during the rest period, albeit indicating greater feelings of restoration and higher positive affect. Our results for both EDA and HRV analysis showed that the auditory group had significantly higher SNS activity during the exposure period when compared to the other groups. However, no significant differences were found for the self-reported relaxation level post restoration break. While the objective data provides evidence for a potential increase in stress level for participants in the auditory group, the subjective data creates an opportunity for discussion about potential drivers of physiological arousal other than stress.

One possible explanation lies within the context of core affect. Core affect can be split into two spectrums: valence, with displeasure and pleasure on the extremes; and arousal, with passive and active on the extremes[50]. While a pleasant and passive experience could induce relaxation and enable the restoration of resources, a pleasant and eventful experience could increase arousal and interest[51]. In a study that asked participants to rate four different soundscapes (birdsong, ocean, road noise, and construction) on the metrics of pleasantness, arousal, familiarity, eventfulness, and dominance, participants rated the natural soundscapes (birdsong and ocean sounds) as the most pleasant, but, at the same time, the most arousing[52]. In our case, with participants in the auditory group reporting feeling just as relaxed as the other groups while showing significantly higher physiological arousal, a plausible explanation could be that the birdsong and water sounds were perceived as pleasant and relaxing, but at the same time arousing and stimulating, driving physiological arousal. Another explanation could lie within individual differences in baseline parasympathetic activity. In previous research[9] exploring effects of nature-based stimuli on brain functional connectivity and physiological arousal, a correlation between physiological arousal effects and individual baseline parasympathetic activity was found. Although the use of a stressor (i.e. TSST) was intended to normalize the baseline arousal levels, individual differences could still affect how the stressor was perceived, consequently affecting baseline SNS/PNS activity going into the restoration break. Another possible explanation could be differences due to the time of the day when data was collected. Literature on the interactions between the hypothalamus-pituitary-adrenal (HPA) axis and the body's response to stress suggest that "the responsiveness of HPA axis is modulated by the time of day"[53]. The HPA axis should be more responsive during peak active phase[53,54] (i.e. middle of the day). However, main effects persisted even after controlling for time of the day.

Baseline connectedness to nature accumulated main effects on the recruitment of Oxy-Hb to multiple ROIs during both the restoration break and the design task. During the restoration break, baseline connectedness to nature had a significant negative effect on activation of the rDLPFC and significant positive effects on the lDLPFC, lDMPFC, and rOFC. During the design task, higher baseline connectedness to nature led to lower activation in the rOFC and higher activation in the right frontopolar cortex. With both the DLPFC and OFC being ROIs associated with processes of emotion processing and regulation[55,56] and the DMPFC being involved in the modulation of physiological arousal[7,56], it is possible that different emotional responses to the biophilic conditions, modulated by pre-existing feelings of connectedness to nature, influence the recruitment of neurocognitive resources (i.e. Oxy-Hb) to these regions.

It is worth noting that after controlling for confounding factors, positive main effects were found for both the visual and the multisensory group for recruitment of resources to the rOFC during the exposure period. Increased activation of the rOFC for the two groups that received a visual stimulus can be explained by the major visual input the OFC receives from the temporal lobe[57]. Main findings from functional connectivity analysis concerned the integration of some ROIs with other regions in their respective networks. During the restoration break, degree centrality for the rDMPFC for the visual and degree centrality for the lVLPFC for both the visual and the multisensory groups were significantly lower than other groups. This effect was expanded to other ROIs during the design task, with the visual group having significantly lower centrality for the rDMPFC, rDLPFC, lDLPFC, and lVLPFC, as well the right and left DMPFC for the multisensory group. This differential distribution and usage of neurocognitive resources introduces new nuances to the ART[5,6,8] and potentially connects it with the NEH[31]. Restorative effects of the biophilic visual and multisensory experiences potentially led to a more efficient use of resources during the design task. According to the NEH[31,32], high performers display more efficient brain activation while performing cognitive tasks. Our findings show that biophilic restorative experiences can indeed impact neurocognition and, consequently, cognitive performance.

Assessment of the design concepts produced highlights how the different treatments affected participants’ minds when designing. Specifically, the visual group was found to design playgrounds that incorporated significantly more visual connection with nature, presence of water, and risk/peril elements than other groups. These main effects were found even after controlling for pre-existing knowledge about biophilic design and feelings of connectedness to nature. Our findings suggest that the visual stimuli acted as a primer, subliminally shaping cognition[58]. The biophilic visual experience may have unconsciously influenced[59] participants to design playgrounds that would grant kids opportunities to connect with nature, granted that none of the participants in the visual group reported having any prior knowledge about biophilic design. Greater nature connectedness has been associated with pro-environmental behavior[60,61] and willingness to spend time outdoors[62–64]. Connectedness to nature could have been the factor influencing the incorporation of biophilic design, however the main effects found for the visual group stood even after controlling for participants’ baseline connectedness to nature.

In conclusion, our study investigated the effects of multisensory biophilic experiences on how people feel, think, and design. Our hypotheses predicted that participants exposed to biophilic conditions would (1) exhibit higher parasympathetic activity, (2) increased functional connectivity within the Default Mode Network (DMN), and (3) greater incorporation of biophilic design elements. Furthermore, we anticipated that (4) the multisensory condition would yield the most significant effects. Contrary to our expectations, exposure to biophilic auditory experiences led to higher physiological arousal levels compared to the control group, rebutting hypothesis 1.

Interestingly, the multisensory group's arousal levels fell between those of the auditory and visual groups, suggesting that combining auditory and visual stimuli may not always produce cumulative effects (hypothesis 4). Neurocognitive assessments using fNIRS revealed nuanced patterns of brain activation across different sensory conditions, with differential effects observed for recruitment of Oxy-Hb to the OFC. Brain network analysis demonstrated denser networks in the auditory group, indicative of enhanced functional connectivity, partially supporting hypothesis 2. Also, degree centrality analyses revealed lower centrality in multiple ROIs for the visual and multisensory groups, suggesting unexplored potential effects on resource consumption efficiency. Our study also revealed intriguing findings regarding the incorporation of biophilic design elements in participants' design concepts. The visual group exhibited significantly stronger presence of certain biophilic design patterns compared to other groups, even after controlling for pre-existing knowledge about biophilic design and feelings of connectedness to nature, partially confirming hypothesis 3.

Our study’s limitations should be taken into consideration. Firstly, our sample primarily consisted of engineering college students. Caution should be taken when generalizing our findings to broader populations. Secondly, our study design did not account for individual differences in baseline parasympathetic activity, which may have influenced physiological responses. In future research, it would be beneficial to investigate the long-term effects of multisensory biophilic interventions on cognitive performance and design outcomes. Additionally, exploring individual differences in response to biophilic stimuli and identifying potential moderators of these effects could provide a more nuanced understanding of the underlying mechanisms. Finally, incorporating ecological validity by studying design processes in professional settings would enhance the applicability of our findings to design practice.

Methods

Experiment design

This study employed a randomized controlled trial with a between-subjects design to investigate the impact of biophilic auditory, visual, and multisensory experiences on engineering students' bodies, brains, and minds. Two rounds of data collection were performed at Virginia Tech, Blacksburg, VA, between February and May 2023 and between February and April 2024. Eligible participants were randomly assigned to one of four conditions: control, auditory, visual, or multisensory. The experiment comprised three phases: stress induction, restoration, and a design task.

Stress induction. Stress was induced using the Trier Social Stress Test (TSST), a validated protocol involving anticipation, public speaking, and mental arithmetic tasks.

Restoration break. Following stress induction, participants underwent an 8-minute restoration break. During the break, participants in the control group sat in silence with their eyes closed, while participants in the auditory group listened to binaural recordings of birdsong and water sounds. Participants in the visual group sat in silence while being visually exposed to different biophilic design patterns in the room. The multisensory received a combination of auditory and visual exposure to the biophilic experiences.

Design task. Participants then completed and open-ended design task with no time restriction. No requirements were given to what method (e.g. sketching, taking notes) should be used. When participants signaled having finished the task, they were asked to explain their design concept and process.

Measurements. Perceived stress (pre-/post-stressor), relaxation (post-restoration), and mental demand (design task) were assessed using Likert scales. Physiological responses were measured through electrodermal activity (EDA), captured throughout the experiment by a medical-grade, wrist-worn device. Neurocognitive responses were measured in terms of changes in Oxy-Hb in the PFC, captured via a wireless functional near-infrared spectroscopy (fNIRS) device worn throughout all experiment phases. Design products were analyzed qualitatively (semantic analysis) and quantitatively (biophilic design incorporation).

Participants

Engineering students were recruited via department listservs, class visits, and Virginia Tech's newsletter. Interested potential participants were screened for eligibility. Eligible participants did not present pre-existing cardiovascular, neurological, or psychiatric conditions. Students who reported having severe hearing and/or vision impairment, substance use history, anxiety/depression episodes, and alcohol/illicit drug dependency were also deemed ineligible to participate. Sample size calculations suggested a minimum of 21 participants per group for 80% power ($\alpha = 0.05$). A target of 30 participants per group was set. A total of 122 participants aged 18-35 years (demographics in Table 4.1) passed screening, provided informed consent (IRB #22-448), and were randomly assigned to one of the four groups. Monetary compensation was provided in the form of a $20 Amazon gift card.

Table 4.1 Demographics (n = 122) and environmental factors.

	Mean ± SD or n (%)				
	Overall	Control	Auditory	Visual	Multisensory
N	122	32	32	29	29
Age	22 ± 4	23 ± 4	22 ± 3	23 ± 4	22 ± 4
Gender	-	-	-	-	-
Female	29 (24)	7 (22)	6 (19)	7 (24)	9 (31)
Male	92 (75)	25 (78)	25 (78)	22 (76)	20 (69)
Trans	1 (1)	-	1 (3)	-	-
Handedness	-	-	-	-	-
Right	113 (93)	29 (91)	32 (100)	27 (93)	25 (86)
Left	9 (7)	3 (9)	-	2 (7)	4 (14)
English is first language	-	-	-	-	-
Yes	79 (65)	20 (63)	25 (78)	14 (48)	20 (69)
No	43 (35)	12 (37)	7 (22)	15 (52)	9 (31)
Caffeine consumption*	-	-	-	-	-
Yes	21 (17)	8 (25)	7 (22)	2 (7)	4 (14)
No	101 (83)	24 (75)	25 (78)	27 (93)	25 (86)
Time of the day	-	-	-	-	-
AM (8am-12pm)	41 (34)	12 (38)	13 (41)	10 (34)	12 (41)
PM (12-5pm)	81 (66)	20 (62)	19 (59)	19 (66)	17 (59)
IEQ	-	-	-	-	-
CO2 (ppm)	758 ± 198	722 ± 106	778 ± 100	756 ± 242	762 ± 185
Temperature (°C)	19.6 ± 1.6	21.3 ± 1.0	22.1 ± 1.9	18.9 ± 0.8	19.1 ± 0.8
Relative humidity (%)	36 ± 9	40 ± 14	37 ± 9	35 ± 7	35 ± 7

Procedures

Equipment setup.

Stress induction. The TSST[30] was employed to induce psychosocial stress and deplete subjects' cognitive, physiological, and psychological resources. The TSST is an established protocol comprising three stress-inducting components: anticipation, public speaking, and mental arithmetic. This procedure elicits physiological arousal and psychological distress[65–68] by simulating cognitively demanding situation akin to real-world stressors in occupational, academic, or social settings[69].

Subjects were instructed to prepare a 5-minute speech convincing a panel of hypothetical judges they were the best candidate for their ideal job. After the 5-minute preparation period (anticipation), each subject stood up and delivered the speech (public speaking) while being video-recorded. Subjects were informed their nonverbal behavior would be scrutinized by experts and reminded that their physiological responses and brain activity were being monitored. During the speech, subjects were prompted to continue speaking after each pause longer than 20 seconds.

Following the speech, subjects were asked to sequentially subtract the number 13 from 1022 and report their answer aloud during a 5-minute period. Each arithmetic error required restarting from 1022. Upon completion, subjects were allowed to sit down while the judge left the room. Subjects were asked to report how stressed they felt during the previous tasks on a scale of 0 (not stressed at all) to 5 (extremely stressed). Lastly, subjects were congratulated for completing the “hard part of the study” and told they would now be given an opportunity to relax.

Restoration break. Participants in the control and in the auditory group sat facing a gray wall and were asked to keep their eyes closed throughout the whole 8-minute break in order to null any visual stimulus (Fig. 4.5). While participants in the control group were told to “enjoy the silence”, participants in the auditory group were told to “enjoy the soundtrack” that would be played on the headphones. The soundtrack comprised binaural recordings of birdsong and water sounds, which created a biophilic auditory experience.

Figure 4.5 Room setup for the control and auditory groups.

Participants in the visual and multisensory groups sat in a modified version of the room during the restoration break. The room was modified to include different patterns of biophilic design, including visual connection with nature (1), biomorphic forms and shapes (2), and dynamic and diffuse light (3) (Fig. 4.6). Participants in the visual group were told to "enjoy the silence and the views of the room" during the 8-minute break. Participants in the multisensory group were told to "enjoy the soundtrack being played on the headphones and the views of the room".

Figure 4.6 Room setup for the visual and multisensory groups.

At the end of the 8-minute period, all participants were asked to report how relaxed they felt on a scale of 0 (not relaxed at all) to 5 (extremely relaxed). For the visual and multisensory groups, a room divider was put in front of the desk to block views to the biophilic elements for the remainder of the experiment (Fig. 4.7).

Figure 4.7 Point of view for participants in the visual and multisensory groups post restoration break.

Design task.

The design task prompted participants to design a playground for young children inside an existing park in Blacksburg, VA. Participants were told that the task had no time restriction. Participants were also told that they could use the sheet of paper provided to develop their design concept utilizing whatever method they preferred (e.g. sketching or taking notes).

Measurements

To assess the potential cumulative effects of multisensory biophilic experiences on body, brain, and mind, three dependent variables were tracked: physiological responses (body), neurocognitive responses (brain) and design outcomes (mind).

Physiological responses. To assess autonomic nervous system (ANS) activity and physiological stress responses, we recorded electrodermal activity (EDA) and heart rate variability (HRV). The ANS regulates involuntary bodily functions by alternations between sympathetic nervous system (SNS) and parasympathetic nervous system (PNS) activity. The SNS dominates during stress-induced "fight-or-flight" responses[37,38,70]. Increases PNS activity indicates a relaxation state, also known as “rest-and-digest” mode[13,71]. EDA, or galvanic skin response (GSR), serves as a reliable index of physiological arousal[18,72,73]. It reflects sweat gland activity controlled by the SNS[34,74]. EDA comprises tonic (skin conductance level, SCL) and phasic (skin conductance response, SCR) components, indicating sustained stimulus exposure and transient arousal events, respectively[18,34]. HRV indexes parasympathetic regulation by quantifying beat-to-beat variations in heart rate, with higher variability reflecting greater parasympathetic "rest-and-digest" dominance[37,75,76]. Reduced HRV indicates sympathetic prevalence during stress responses[19,65,72].

Both EDA and HRV were recorded using an Empatica E4 wristband (Empatica Inc.), capable of real-time physiological data streaming. EDA was acquired from the wristband's electrodermal sensor (4 Hz), while HRV was derived from photoplethysmography readings of blood volume pulses (64 Hz). This multi-measure approach captured sympathetic and parasympathetic dynamics to characterize physiological responses elicited by the stress induction and potential stress reduction from the biophilic conditions.

Neurocognitive responses. Acute psychosocial stress can impair prefrontal cortical functions such as creativity, decision-making, and working memory[77–79]. To intentionally induce cognitive strain and subsequently assess the potential restorative effects of biophilic experiences to cognitive resources, we employed the Trier Social Stress Test (TSST) as a potent social-evaluative stressor. The biophilia hypothesis proposes that exposure to natural environments provides an opportunity to restore depleted directed attention resources[3,5,6]. Given the PFC’s role in executive functions like attention and working memory[7,80], we measured changes in PFC oxygenated hemoglobin (Oxy-Hb) levels to assess whether the biophilic auditory intervention restored neurocognitive resources.

Recruitment of Oxy-Hb to the PFC was monitored using an OBELAB NIRSIT wireless functional near-infrared spectroscopy (fNIRS) device. This forehead-mounted device has an array of near-infrared light sources and detectors to measure blood oxygenation level-dependent (BOLD) responses across 48 channels[81]. The 780-850 nm near-infrared light is differentially absorbed by Oxy-Hb and deoxygenated hemoglobin, allowing for the calculation of relative Oxy-Hb concentrations in the PFC, using either the Modified Beer-Lambert Law[82] (MBLL) or Diffuse Optical Tomography[83] (DOT) methods.

Design outcomes. Environmental stimuli can influence the designer's mindset and the design outcomes. For example, students generated more sustainability-focused designs when working in certified green buildings[84]. Sensory stimuli can act as a primer, subliminally shaping cognition[58]. The biophilic experiences could unconsciously "influence the solution produced consciously" for the design task[59]. Moreover, even short-term biophilic exposures can increase feelings of connectedness to nature[62,85–87]. Greater nature connectedness is associated with pro-environmental behavior[60,61] and willingness to spend time outdoors[62–64]. As priming interventions, the biophilic conditions could impact designers' behaviors and choices[88,89], with newly acquired experiences shaping the design process[90].

In order to measure the extent to which a potential priming effect influenced participants' design cognition, all design concepts were assessed for the incorporation of biophilic design using a modified version of Biophilic Interior Design Matrix (BID-M). The BID-M is a valid and reliable tool for quantifying the incorporation of biophilic design[45–47]. Besides being applied in this study to the design of an outdoor park, the modified version switches to Browning et al.'s "14 Patterns of Biophilic Design"[44] in an attempt to simplify the BID-M and reduce the workload required to use it. The original BID-M was based on Kellert's extensive list of biophilic design elements and attributes[91]. The extension and language technicality of the original BID-M did not fit our experiment design. In this modified version, design concepts were assessed for the strength of the presence of each of the "14 Patterns of Biophilic Design" on a scale of zero (not present at all) to three (strong presence). A post-doctoral researcher and a graduate student trained in Biophilic Design were used as raters. Mean scores for each design product were used as the metric for the incorporation of biophilic design.

Data processing and analysis

EDA data (pre-)processing and analyses. EDA data collected by the Empatica E4 wristbands was downloaded from the E4 connect web portal, where data was automatically uploaded to after each experiment session. Phasic and tonic components of the EDA data were extracted through a continuous decomposition analysis (CDA) over the length of each step in the experiment (TSST, restoration break, design task) utilizing the Matlab-based software Ledalab®[92]. A threshold of 0.01 µS was applied to the skin conductance response amplitude[18,34]. Ledalab's default settings for data filtering and smoothing were utilized. Outputs from the CDA presented in this study include the number of significant SCRs (nSCR), the mean phasic driver (SCR), and the mean tonic activity (SCL), all within the response window for each of the three steps in the experiment.

HRV-related data was processed utilizing the hrvanalysis Python module. The data processing procedure started with the removal of outliers and ectopic (i.e. irregular) heartbeats from the RR-intervals, transforming them into Normal to Normal (NN) intervals. RR-intervals below 300 and above 2000 milliseconds were removed. Linear interpolation was utilized to replace outliers[93]. After the transformation, frequency domain features were extracted.

Frequency domain features extracted included power at high frequency (HF, 0.15 to 0.40 Hz) and the LF/HF ratio, metrics used in previous biophilic experiences studies[22,72,94].

Statistical analysis was performed using Python packages. Outliers within groups were identified and removed utilizing the interquartile range (IQR) method. For normally distributed datasets, a parametric ANOVA test (i.e. F-test) was utilized. If the dataset presented a skewed distribution, a non-parametric ANOVA test (i.e. Kruskal-Wallis) was performed. A p-value of 0.05 was set as threshold for significance. If the ANOVA results pointed out any statistically significant difference between the three groups, a post-hoc T-test with a Holm-Bonferroni *p*-value adjustment was performed to identify where the significant difference exists. The Cohen's *d* was computed and utilized to measure the effect size. Linear mixed effects models were developed utilizing statsmodels' (https://www.statsmodels.org/dev/about.html) mixedLM procedure. The models were utilized to control for potential confounders. A random intercept for participants was included in all models to account for individual differences and repeated measures.

Neurocognitive data processing and analyses. Raw fNIRS data for each participant had outliers removed utilizing z-scores (threshold = 2 standard deviations). Next, the data was pre-processed utilizing the Matlab-based NIRS Brain AnalyzIR Toolbox[95]. First, the data sampling rate was reduced from 8 Hz to 5 Hz. Light intensity was then converted to optical density. Motion artifacts were then removed using the Temporal Derivative Distribution Repair (TDDR) method[96]. Following the motion correction, bandpass filtering was performed. An 1000th order finite impulse response (FIR) bandpass filter was applied. The applied cutoff range - 0.01–0.25Hz - corresponds to the range in which hemodynamic responses happen[97]. Next, changes in optical density were converted to hemoglobin (Hb) concentration utilizing the MBLL method[82]. The last step in the data preparation process was removing other physiological noise. The Mayer wave noise (from blood pressure) was removed by regressing out the median time series[98]. ROI analysis was performed in Python by averaging the mean Oxy-Hb for channels in each ROI (see spatial distribution in Fig. 8) during each phase of the experiment.

Functional connectivity analysis was also performed in Python. Pearson's correlation matrices were developed using the mean oxy-Hb in each channel (n = 48) during each phase of the experiment (TSST, Restoration Break, Design Task), for each cohort. Then, values from each correlation matrix were transformed into a binary matrix with connected nodes and edges. A global threshold value of 0.65 was applied, following previous research[42]. In these previous studies, the threshold value (0.65) was obtained empirically. Here, during the analysis process, a range of threshold numbers (± 0.10) around 0.65 was explored, but results did not differ significantly. Network graphs were generated utilizing the NetworkX Python package[99]. Using functions from the same package, the degree centrality and the network density were calculated. To assess the temporal dynamics of Oxy-Hb recruitment and brain functional connectivity, the Design Task period was also evenly split into 10 non-overlapping segments, an approach previously used in design cognition research[41,42]. Functional connectivity analysis was also performed for each decile.

Statistical analysis was conducted in Python. The mean recruitment of Oxy-Hb to each ROI, the mean network density, and the mean degree centrality for each channel were calculated for all groups during each of the experiment phases. Outliers within groups (outside IQR) were removed from statistical analysis. All datasets were tested for normality utilizing the Shapiro-Wilk test. A parametric or a non-parametric ANOVA was used depending on normality. For normally distributed datasets, a parametric ANOVA test (i.e. F-test) was utilized. If the dataset presented a skewed distribution, a non-parametric ANOVA test (i.e. Kruskal-Wallis) was performed. A p-value of 0.05 was set as threshold for significance. If the ANOVA results pointed out any statistically significant difference between the three groups, a post-hoc test with a Holm-Bonferroni p-value adjustment was performed to identify where the significant difference exists. The Cohen's d was computed and utilized to measure the effect size. Linear mixed effects models were developed utilizing statsmodels' (https://www.statsmodels.org/dev/about.html) mixedLM procedure. The models were utilized to control for potential confounders. A random intercept for participants was included in all models to account for individual differences and repeated measures.

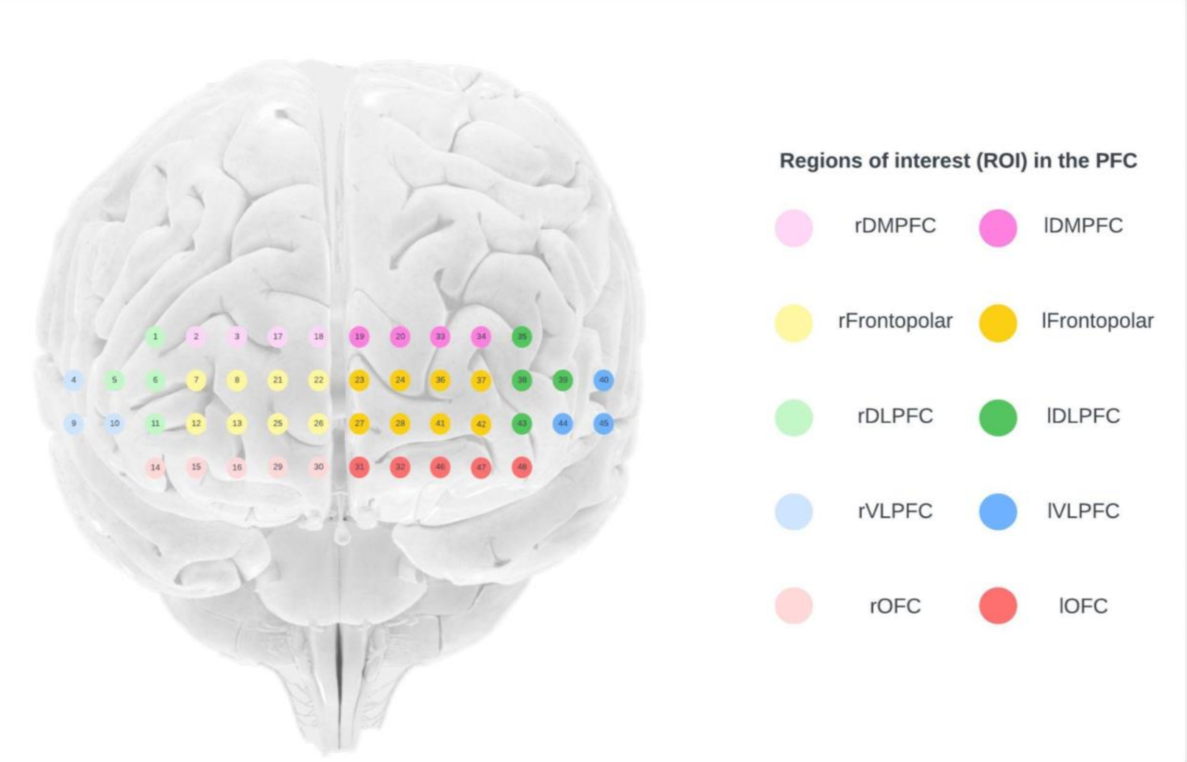


Figure 4.8 Spatial distribution of ROIs with the OBELAB NIRSIT channel configuration.

BDM scores analysis. Statistical analysis was conducted in Python. The mean BDM score for each biophilic design pattern was calculated for all groups. Linear mixed effects models were developed utilizing statsmodels' (https://www.statsmodels.org/dev/about.html) mixedLM procedure. The models were utilized to control for potential confounders, including age, gender, design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature. A random intercept for participants was included in all models to account for individual differences and repeated measures.

References

1. Klepeis, N. E. *et al.* The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J Expo Sci Environ Epidemiol* **11**, 231–252 (2001).
2. Barkow, J. H., Cosmides, L. & Tooby, J. *The Adapted Mind: Evolutionary Psychology and the Generation of Culture*. (Oxford University Press, 1992).
3. Kellert, S. R. & Wilson, E. O. *The Biophilia Hypothesis*. (Island Press, 1993).
4. Barbiero, G. & Berto, R. Biophilia as Evolutionary Adaptation: An Onto- and Phylogenetic Framework for Biophilic Design. *Front Psychol* **12**, 700709 (2021).
5. Kaplan, R. & Kaplan, S. *The Experience of Nature: A Psychological Perspective*. (Cambridge University Press, Cambridge ;, 1989).
6. Kaplan, S. The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology* **15**, 169–182 (1995).
7. Mezzacappa, E. Executive Function. in *Reference Module in Neuroscience and Biobehavioral Psychology* (Elsevier, 2017). doi:10.1016/B978-0-12-809324-5.06001-6.
8. Berman, M. G., Jonides, J. & Kaplan, S. The Cognitive Benefits of Interacting With Nature. *Psychol Sci* **19**, 1207–1212 (2008).
9. Gould van Praag, C. D. *et al.* Mind-wandering and alterations to default mode network connectivity when listening to naturalistic versus artificial sounds. *Sci Rep* **7**, 45273 (2017).
10. Song, C., Ikei, H., Kagawa, T. & Miyazaki, Y. Effect of Viewing Real Forest Landscapes on Brain Activity. *Sustainability* **12**, 6601 (2020).
11. Jo, H. *et al.* Physiological and Psychological Effects of Forest and Urban Sounds Using High-Resolution Sound Sources. *International Journal of Environmental Research and Public Health* **16**, 2649 (2019).
12. Atchley, R. A., Strayer, D. L. & Atchley, P. Creativity in the Wild: Improving Creative Reasoning through Immersion in Natural Settings. *PLOS ONE* **7**, e51474 (2012).
13. Ulrich, R. S. *et al.* Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology* **11**, 201–230 (1991).
14. Ulrich, R. S. Aesthetic and Affective Response to Natural Environment. in *Behavior and the Natural Environment* (eds. Altman, I. & Wohlwill, J. F.) 85–125 (Springer US, Boston, MA, 1983). doi:10.1007/978-1-4613-3539-9_4.
15. Ulrich, R. S. Natural Versus Urban Scenes: Some Psychophysiological Effects. *Environment and Behavior* **13**, 523–556 (1981).
16. Ulrich, R. View Through a Window May Influence Recovery from Surgery. *Science (New York, N.Y.)* **224**, 420–1 (1984).
17. Yin, J. *et al.* Effects of biophilic interventions in office on stress reaction and cognitive function: A randomized crossover study in virtual reality. *Indoor Air* **29**, 1028–1039 (2019).
18. Aristizabal, S. *et al.* Biophilic office design: Exploring the impact of a multisensory approach on human well-being. *Journal of Environmental Psychology* **77**, 101682 (2021).
19. Igarashi, M. *et al.* Effects of stimulation by three-dimensional natural images on prefrontal cortex and autonomic nerve activity: a comparison with stimulation using two-dimensional images. *Cogn Process* **15**, 551–556 (2014).

20. Park, B.-J. *et al.* Physiological effects of Shinrin-yoku (taking in the atmosphere of the forest)--using salivary cortisol and cerebral activity as indicators. *J Physiol Anthropol* **26**, 123–128 (2007).
21. Song, C., Ikei, H. & Miyazaki, Y. Effects of forest-derived visual, auditory, and combined stimuli. *Urban Forestry & Urban Greening* **64**, 127253 (2021).
22. Yin, J. *et al.* Effects of biophilic indoor environment on stress and anxiety recovery: A between-subjects experiment in virtual reality. *Environment International* **136**, 105427 (2020).
23. Yin, J., Zhu, S., MacNaughton, P., Allen, J. G. & Spengler, J. D. Physiological and cognitive performance of exposure to biophilic indoor environment. *Building and Environment* **132**, 255–262 (2018).
24. Yin, J., Zhu, S., MacNaughton, P., Allen, J. G. & Spengler, J. D. Physiological and cognitive performance of exposure to biophilic indoor environment. *Building and Environment* **132**, 255–262 (2018).
25. Berman, M. G. *et al.* Interacting with nature improves cognition and affect for individuals with depression. *Journal of Affective Disorders* **140**, 300–305 (2012).
26. Klotz, L. *et al.* Beyond rationality in engineering design for sustainability. *Nat Sustain* **1**, 225–233 (2018).
27. Gero, J. & Milovanovic, J. A design thinker's mind: insights on the neurocognitive processes of ideation. in *Research Handbook on Design Thinking* 7–24 (Edward Elgar Publishing, 2023).
28. Vieira, S. L. da S. *et al.* Comparing the Design Neurocognition of Mechanical Engineers and Architects: A Study of the Effect of Designer's Domain. *Proceedings of the Design Society: International Conference on Engineering Design* **1**, 1853–1862 (2019).
29. Shealy, T., Grohs, J. R., Hu, M., Maczka, D. K. & Panneton, R. Investigating Design Cognition during Brainstorming Tasks with Freshmen and Senior Engineering Students using Functional Near Infrared Spectroscopy. in (2017).
30. Labuschagne, I., Grace, C., Rendell, P., Terrett, G. & Heinrichs, M. An introductory guide to conducting the Trier Social Stress Test. *Neuroscience & Biobehavioral Reviews* **107**, 686–695 (2019).
31. Neubauer, A. C. & Fink, A. Intelligence and neural efficiency. *Neuroscience & Biobehavioral Reviews* **33**, 1004–1023 (2009).
32. Langer, N. *et al.* Functional brain network efficiency predicts intelligence. *Human Brain Mapping* **33**, 1393–1406 (2012).
33. Di Domenico, S. I., Rodrigo, A. H., Ayaz, H., Fournier, M. A. & Ruocco, A. C. Decision-making conflict and the neural efficiency hypothesis of intelligence: A functional near-infrared spectroscopy investigation. *NeuroImage* **109**, 307–317 (2015).
34. Boucsein, W. *et al.* Publication recommendations for electrodermal measurements. *Psychophysiology* **49**, 1017–1034 (2012).
35. Task Force of the European Society of Cardiology the North American Society of Pacing Electrophysiology. Heart Rate Variability - Standards of Measurement, Physiological Interpretation, and Clinical Use. **93**, 1043–1065 (1996).
36. Kleiger, R. E., Stein, P. K. & Bigger Jr., J. T. Heart Rate Variability: Measurement and Clinical Utility. *Annals of Noninvasive Electrocardiology* **10**, 88–101 (2005).
37. Ernst, G. Heart-Rate Variability—More than Heart Beats? *Frontiers in Public Health* **5**, (2017).

38. Rajendra Acharya, U., Paul Joseph, K., Kannathal, N., Lim, C. M. & Suri, J. S. Heart rate variability: a review. *Medical and Biological Engineering and Computing* **44**, 1031–1051 (2006).
39. Bullmore, E. & Sporns, O. The economy of brain network organization. *Nat Rev Neurosci* **13**, 336–349 (2012).
40. Rubinov, M. & Sporns, O. Complex network measures of brain connectivity: Uses and interpretations. *NeuroImage* **52**, 1059–1069 (2010).
41. Gero, J. Generalizing Design Cognition Research. in (Sydney, Australia, 2010). doi:10.13140/2.1.3756.5128.
42. Milovanovic, J., Hu, M., Shealy, T. & Gero, J. Evolution of Brain Network Connectivity in the Prefrontal Cortex During Concept Generation Using Brainstorming for a Design Task. in (American Society of Mechanical Engineers Digital Collection, 2020). doi:10.1115/DETC2020-22563.
43. Shealy, T. & Gero, J. The Neurocognition of Three Engineering Concept Generation Techniques. *Proceedings of the Design Society: International Conference on Engineering Design* **1**, 1833–1842 (2019).
44. Browning, W., Ryan, C. & Clancy, J. *14 Patterns of Biophilic Design*. http://www.terrapinbrightgreen.com/reports/14-patterns-of-biophilic-design/ (2014).
45. Marte, E. *et al.* Testing Reliability of Biophilic Design Matrix Within Urban Residential Playrooms. *Frontiers in Psychology* **11**, (2020).
46. McGee, B., Park, N.-K., Portillo, M., Bosch, S. & Swisher, M. Diy Biophilia: Development of the Biophilic Interior Design Matrix as a Design Tool. *Journal of Interior Design* **44**, 201–221 (2019).
47. McGee, B. & Marshall-Baker, A. Loving Nature From the Inside Out: A Biophilia Matrix Identification Strategy for Designers. *HERD : Health Environments Research & Design Journal* **8**, 115–130 (2015).
48. McGee, B., Jin, X., Park, N.-K., Ball, S. & Carr, A. Designers' perceptions of biophilia and testing of the biophilic interior design matrix in China. *Archnet-IJAR: International Journal of Architectural Research* **16**, 517–535 (2022).
49. Ojala, A. *et al.* Psychological and physiological effects of a wooden office room on human well-being: Results from a randomized controlled trial. *Journal of Environmental Psychology* **89**, 102059 (2023).
50. Andringa, T. C. & Lanser, J. J. L. How Pleasant Sounds Promote and Annoying Sounds Impede Health: A Cognitive Approach. *International Journal of Environmental Research and Public Health* **10**, 1439–1461 (2013).
51. Russell, J. A. Core affect and the psychological construction of emotion. *Psychological Review* **110**, 145–172 (2003).
52. Medvedev, O., Shepherd, D. & Hautus, M. J. The restorative potential of soundscapes: A physiological investigation. *Applied Acoustics* **96**, 20–26 (2015).
53. Koch, C. E., Leinweber, B., Drengberg, B. C., Blaum, C. & Oster, H. Interaction between circadian rhythms and stress. *Neurobiol Stress* **6**, 57–67 (2016).
54. Russell, G. & Lightman, S. The human stress response. *Nat Rev Endocrinol* **15**, 525–534 (2019).
55. Kohn, N. *et al.* Neural network of cognitive emotion regulation — An ALE meta-analysis and MACM analysis. *Neuroimage* **87**, 345–355 (2014).

56. Siddiqui, S. V., Chatterjee, U., Kumar, D., Siddiqui, A. & Goyal, N. Neuropsychology of prefrontal cortex. *Indian J Psychiatry* **50**, 202–208 (2008).
57. Rolls, E. T. The functions of the orbitofrontal cortex. *Brain and Cognition* **55**, 11–29 (2004).
58. Schacter, D. L. & Church, B. A. Auditory priming: Implicit and explicit memory for words and voices. *Journal of Experimental Psychology: Learning, Memory, and Cognition* **18**, 915–930 (1992).
59. Kakoun, N. A., Boy, F., Groves, C. & Xavier, P. Priming Civil Engineers Into Human-Centered Designing (and Its Unexpected Consequences). in (2021).
60. Klaniecki, K., Leventon, J. & Abson, D. J. Human–nature connectedness as a 'treatment' for pro-environmental behavior: making the case for spatial considerations. *Sustain Sci* **13**, 1375–1388 (2018).
61. Parker, J. & Simpson, G. D. A Theoretical Framework for Bolstering Human-Nature Connections and Urban Resilience via Green Infrastructure. *Land* **9**, 252 (2020).
62. Leung, G., Hazan, H. & Chan, C. S. Exposure to nature in immersive virtual reality increases connectedness to nature among people with low nature affinity. *Journal of Environmental Psychology* 101863 (2022) doi:10.1016/j.jenvp.2022.101863.
63. Hartig, T., Kaiser, F. G. & Strumse, E. Psychological restoration in nature as a source of motivation for ecological behaviour. *Environmental Conservation* **34**, 291–299 (2007).
64. Mackay, C. M. L. & Schmitt, M. T. Do people who feel connected to nature do more to protect it? A meta-analysis. *Journal of Environmental Psychology* **65**, 101323 (2019).
65. Annerstedt, M. *et al.* Inducing physiological stress recovery with sounds of nature in a virtual reality forest — Results from a pilot study. *Physiology & Behavior* **118**, 240–250 (2013).
66. Liszio, S., Graf, L. & Masuch, M. The relaxing effect of virtual nature: Immersive technology provides relief in acute stress situations. *Annual Review of CyberTherapy and Telemedicine* **16**, 87–93 (2018).
67. Thoma, M. V., Mewes, R. & Nater, U. M. Preliminary evidence: the stress-reducing effect of listening to water sounds depends on somatic complaints. *Medicine (Baltimore)* **97**, e9851 (2018).
68. Wang, X., Shi, Y., Zhang, B. & Chiang, Y. The Influence of Forest Resting Environments on Stress Using Virtual Reality. *International Journal of Environmental Research and Public Health* **16**, 3263 (2019).
69. Goodman, W. K., Janson, J. & Wolf, J. M. Meta-analytical assessment of the effects of protocol variations on cortisol responses to the Trier Social Stress Test. *Psychoneuroendocrinology* **80**, 26–35 (2017).
70. Gaekwad, J. S., Sal Moslehian, A. & Roös, P. B. A meta-analysis of physiological stress responses to natural environments: Biophilia and Stress Recovery Theory perspectives. *Journal of Environmental Psychology* **90**, 102085 (2023).
71. Parsons, R., Tassinary, L. G., Ulrich, R. S., Hebl, M. R. & Grossman-Alexander, M. THE VIEW FROM THE ROAD: IMPLICATIONS FOR STRESS RECOVERY AND IMMUNIZATION. *Journal of Environmental Psychology* **18**, 113–140 (1998).
72. Ergan, S., Radwan, A., Zou, Z., Tseng, H. & Han, X. Quantifying Human Experience in Architectural Spaces with Integrated Virtual Reality and Body Sensor Networks. *Journal of Computing in Civil Engineering* **33**, 04018062 (2019).

73. Li, D. & Sullivan, W. C. Impact of views to school landscapes on recovery from stress and mental fatigue. *Landscape and Urban Planning* **148**, 149–158 (2016).
74. Braithwaite, J. J., Watson, D. G., Jones, R. & Rowe, M. *A Guide for Analysing Electrodermal Activity (EDA) & Skin Conductance Responses (SCRs) for Psychological Experiments*. (2015).
75. Thayer, J. F., Åhs, F., Fredrikson, M., Sollers, J. J. & Wager, T. D. A meta-analysis of heart rate variability and neuroimaging studies: Implications for heart rate variability as a marker of stress and health. *Neuroscience & Biobehavioral Reviews* **36**, 747–756 (2012).
76. Kim, H.-G., Cheon, E.-J., Bai, D.-S., Lee, Y. H. & Koo, B.-H. Stress and Heart Rate Variability: A Meta-Analysis and Review of the Literature. *Psychiatry Investig* **15**, 235–245 (2018).
77. Beversdorf, D. Q., Hughes, J. D., Steinberg, B. A., Lewis, L. D. & Heilman, K. M. Noradrenergic modulation of cognitive flexibility in problem solving: *NeuroReport* **10**, 2763–2767 (1999).
78. Arnsten, A. F. T. Stress signalling pathways that impair prefrontal cortex structure and function. *Nat Rev Neurosci* **10**, 410–422 (2009).
79. Arnsten, A. F. T. Catecholamine modulation of prefrontal cortical cognitive function. *Trends Cogn Sci* **2**, 436–447 (1998).
80. Laird, A. R. *et al.* Behavioral interpretations of intrinsic connectivity networks. *J Cogn Neurosci* **23**, 4022–4037 (2011).
81. Hu, M. & Shealy, T. Application of Functional Near-Infrared Spectroscopy to Measure Engineering Decision-Making and Design Cognition: Literature Review and Synthesis of Methods. *Journal of Computing in Civil Engineering* **33**, 04019034 (2019).
82. Kocsis, L., Herman, P. & Eke, A. The modified Beer–Lambert law revisited. *Phys. Med. Biol.* **51**, N91 (2006).
83. Hoshi, Y., Kobayashi, N. & Tamura, M. Interpretation of near-infrared spectroscopy signals: a study with a newly developed perfused rat brain model. *Journal of Applied Physiology* **90**, 1657–1662 (2001).
84. Shealy, T. Do Sustainable Buildings Inspire More Sustainable Buildings? *Procedia Engineering* **145**, 412–419 (2016).
85. Mayer, F., Frantz, C., Bruehlman-Senecal, E. & Dolliver, K. Why Is Nature Beneficial?The Role of Connectedness to Nature. *Environment and Behavior - ENVIRON BEHAV* **41**, 607–643 (2009).
86. Richardson, M. & Butler, C. W. Nature connectedness and biophilic design. *Building Research & Information* **50**, 36–42 (2022).
87. Whitburn, J., Linklater, W. & Abrahamse, W. Meta-analysis of human connection to nature and proenvironmental behavior. *Conservation Biology* **34**, 180–193 (2020).
88. Bargh, J. A., Chen, M. & Burrows, L. Automaticity of social behavior: Direct effects of trait construct and stereotype activation on action. *Journal of Personality and Social Psychology* **71**, 230–244 (1996).
89. Hu, M. & Shealy, T. Priming the public to construct preferences for sustainable design: A discrete choice model for green infrastructure. *Journal of Environmental Psychology* **88**, 102005 (2023).
90. She, J. & MacDonald, E. Priming Designers to Communicate Sustainability. *Journal of Mechanical Design* **136**, (2013).

91. Kellert, S. R. Dimensions, Elements, and Attributes of Biophilic Design. in *Biophilic Design: The Theory, Science and Practice of Bringing Buildings to Life* (John Wiley & Sons, 2011).
92. Benedek, M. & Kaernbach, C. A continuous measure of phasic electrodermal activity. *Journal of Neuroscience Methods* **190**, 80–91 (2010).
93. Peltola, M. Role of editing of R-R intervals in the analysis of heart rate variability. *Frontiers in Physiology* **3**, (2012).
94. Ojala, A. *et al.* Short virtual nature breaks in the office environment can restore stress: An experimental study. *Journal of Environmental Psychology* **84**, 101909 (2022).
95. Santosa, H., Zhai, X., Fishburn, F. & Huppert, T. The NIRS Brain AnalyzIR Toolbox. *Algorithms* **11**, 73 (2018).
96. Fishburn, F. A., Ludlum, R. S., Vaidya, C. J. & Medvedev, A. V. Temporal Derivative Distribution Repair (TDDR): A motion correction method for fNIRS. *NeuroImage* **184**, 171–179 (2019).
97. Pinti, P., Scholkmann, F., Hamilton, A., Burgess, P. & Tachtsidis, I. Current Status and Issues Regarding Pre-processing of fNIRS Neuroimaging Data: An Investigation of Diverse Signal Filtering Methods Within a General Linear Model Framework. *Front Hum Neurosci* **12**, 505 (2019).
98. Yücel, M. A. *et al.* Mayer waves reduce the accuracy of estimated hemodynamic response functions in functional near-infrared spectroscopy. *Biomed. Opt. Express, BOE* **7**, 3078–3088 (2016).
99. Hagberg, A. A., Schult, D. A. & Swart, P. J. Exploring Network Structure, Dynamics, and Function using NetworkX. in *Proceedings of the 7th Python in Science Conference* (eds. Varoquaux, G., Vaught, T. & Millman, J.) 11–15 (Pasadena, CA USA, 2008).

Chapter 5 – Conclusion

This dissertation presented a study that investigated the effects of multisensory biophilic restorative experiences on how engineers feel, think, and design. Its main goal was to addresses two knowledge gaps identified in the literature. First, although the effects of visual exposure to biophilic experience have been well documented, less exploration has been done on the effects of biophilic auditory experiences. Furthermore, although some studies (Aristizabal et al., 2021; C. Song et al., 2019, 2021) have pointed out to multisensory interventions being a better representation of nature immersion and having the potential for the most impact, little is known about the nuances of differential sensory engagement. The second identified knowledge gap concerns the impacts of biophilic restorative experiences on cognitive performance. Most studies have utilized standardized cognitive tests to assess effects on cognitive performance, creating a lack of evidence for the applicability of the potentially beneficial cognitive effects on real-world and specific job tasks. To address the identified knowledge gaps, the following research question was asked: *what are the effects of biophilic restorative experiences on how engineers **feel**, **think**, and **design**?*

Questioning the effects on how engineers ***feel*** involved the exploration of physiological and psychological responses to biophilic experiences. Capturing effects on how engineers ***think*** involved the exploration of neurocognitive responses to the intervention. Asking how the intervention could affect how engineers ***design*** involved the assessment of changes in design cognition and decision-making.

A randomized controlled trial with a total sample size of 154 participants was conducted in order to answer the research question. Participants were randomly split into five different groups: control (no stimulus), active control (traffic sounds), auditory (biophilic auditory experience), visual (biophilic visual experience), and multisensory (combined biophilic auditory and visual experience). Data collection was split into two phases, taking place between February 2023 and March 2024. More than 165 dependent variables were tracked, all compiled into a data set with approximately 23,000 data points. Addressing the ***feel*** component of the research question and *H1*, results from both phases of the study showed that although all groups reported similar levels of relaxation after being exposed to the different conditions, the auditory group presented higher physiological arousal during and after the exposure period. Addressing the ***think*** component of the research question and *H2*, analysis of neurocognitive data showed that the biophilic conditions did assist the restoration of resources, while also affecting the functional connectivity between different prefrontal cortical ROIs. Lastly, addressing the ***design*** domain of the research question and hypotheses 3 (*H3*) and 4 (*H4*), assessments of the design concepts produced by participants showed that the neurocognitive effects were not enough to provoke a change in design originality, failing to support *H3*. No differences were found for exploration of the design space between groups. However, assessment of the incorporation of biophilic design showed that the visual group designed playgrounds that incorporated significantly more visual connection with nature, presence of water, and risk/peril elements than other groups. This finding supports *H4* and the idea that biophilic restorative experiences can affect design cognition.

5.1 Summary of Findings

In Chapter 2, a comprehensive assessment of the restorative effects of a biophilic auditory experience on the body and the brain is presented. The data presented was collected during the first phase of the study, which included the initial three groups: control (no stimulus), active control (traffic sounds), intervention (birdsong and water sounds). Twelve different metrics for physiological responses were tracked. Results showed that the 8-minute biophilic auditory experience led to significantly higher physiological arousal for the intervention group, both during the exposure period (i.e. restoration break) and during the subsequent design task. Compared to the other groups, the intervention group had significantly higher mean frequency of SCRs, mean SCL, and mean LF/HF ratio, as well as significantly lower RMSSD during the restoration break. During the design task, the intervention group had significantly higher mean SCL. Changes in the neurocognition were assessed by tracking recruitment of Oxy-Hb to ten different ROIs within the PFC. During the Design Task, the mean Oxy-Hb in the rDLPFC for the active control group was significantly lower than both the control and the intervention groups. This finding suggested that both the control and the intervention groups had more neurocognitive resources available to be spent in the design task compared to the group listened to traffic sounds during the restoration break.

In Chapter 3, results for the assessment of the design products are shared and a deeper dive into the neurocognitive effects is performed. We observed significantly higher brain functional connectivity, in terms of network density, for participants who listened to nature sounds during the restoration break. In addition, participants in the intervention group showed a larger distribution of central nodes during the design task, suggesting the engagement of a larger network. When assessing potential temporal changes in prefrontal cortical network engagement throughout the design task period by evenly splitting the period into 10 segments, we found that the intervention group had significantly higher network density during the 5th and 8th deciles. These findings supported the hypothesis that biophilic restorative experiences could lead to increased functional connectivity in the PFC. Effects to neurocognition were not reflected on design cognition. No significant differences were found between groups for exploration of the design space. Assessment of the design products for the incorporation of biophilic design showed that connectedness to nature acted as the main influencing factor. However, although contradictory, significant effects were found for the intervention and the active control groups, with participants in the intervention group incorporating significantly less *Material Connection with Nature,* and participants in the active control group incorporating significantly more *Visual Connection with Nature* and *Non-Rhythmic Sensory Stimuli* in their design concepts.

Chapter 4 introduced data from the second phase of the study. Now including groups that received biophilic visual and multisensory (auditory + visual) experiences (and excluding the active control group), this paper presents data that covers all domains of the dissertation’s main research question, with a total sample of 122 participants. Results showed that during the restoration break, the auditory condition drove the most significant physiological changes, inducing high arousal. Neurocognitive data showed that both the visual and the multisensory group presented significantly less centrality in ROIs part of the fronto-parietal, the cingulo-opercular, and the default-mode networks, suggesting potential support to the Neural Efficiency Hypothesis. Lastly, assessment of the design outcomes showed that the visual group incorporated significantly more of 3 out of 14 patterns of biophilic design, suggesting a potential priming effect of the biophilic visual experience on participants in the visual group.

5.2 Practical and Theoretical Implications

Evidence presented in the three proposed journal papers provide a significant contribution to the body of knowledge on the general effects of biophilic restorative experiences. One of main contributions is the amount and the granularity of neurocognitive data collected. The neuroimaging device utilized in this study (i.e. OBELAB NIRSIT) allowed us to acquire data with greater spatial resolution than most previous studies (Jo et al., 2019; C. Song et al., 2021; I. Song et al., 2023). Analysis of mean Oxy-Hb recruitment to different ROIs within the PFC, as well as functional connectivity analysis utilizing graph theory (Wijk et al., 2010), resulted in new insights that not only support the Attention Restoration Theory (ART) (Berman et al., 2008; R. Kaplan & Kaplan, 1989; S. Kaplan, 1995), but also introduce a potential connection between the neurocognitive effects of biophilic experiences and the Neural Efficiency Hypothesis (Langer et al., 2012; Neubauer & Fink, 2009). Our findings also support previous research (Atchley et al., 2012; Gould van Praag et al., 2017) that links exposure to biophilic experiences to a switch from top-down to bottom-up regulatory processes, modulated by engagement of the default-mode network (DMN). Results from functional connectivity analysis showed that listening to birdsong and water sounds led to increased functional connectivity within the DMN.

Another theoretical implication of the findings concerns the potential for more exploration of the effects of biophilic experience on design cognition. The first-of-its-kind assessment of the effects of biophilic experiences on designers' adoption of biophilic design practices presented here created a new, wide open field for investigation. While previously researchers had explored the effects of biophilic experiences on feelings of connectedness to nature (Leung et al., 2022; Richardson & Butler, 2022; Whitburn et al., 2020) and the correlations between connectedness to nature and self-reported pro-environmental behavior (Mackay & Schmitt, 2019; Zelenski et al., 2015), no one had explored how these changes could influence actual behavior. Our findings showed that a unique instance of short-term exposure (8 minutes) to a room with plants (Visual Connection with Nature), nature-inspired art (Biomorphic Forms and Shapes), and many windows (Dynamic and Diffuse Light) was capable of influencing engineering students to design playgrounds that could also foster some sort connection with nature for the kids who would frequent it. This powerful insight indicates that the path to a human reconnection with nature could start with reconnecting designers and nature. Exposing those responsible for envisioning, planning, and shaping the future of our society to biophilic experiences could result in a transformation of the relationship between humans, nature, and the built environment.

The findings presented in this dissertation are extremely practical given the applicability and accessibility of the interventions tested to the public. While many randomized controlled trials performed in laboratories utilized specifically crafted interventions, delivered through specialized equipment, the interventions tested in the study here presented are easily accessible to the public. The biophilic auditory experience tested comes from an application downloadable to both iOS and Android users (Delos Living LLC, 2020). Also, the auditory experience was delivered by relatively cheap ($35) over-the-ear headphones. The biophilic visual experience was composed of 4 plants (one small-size, two medium-sized, and one large-sized), 2 wall-hanged art pieces from a local artist, and windows. Given that, the biophilic conditions are easily replicable, benefiting the general public.

5.3 Recommendation for Future Research

Future research should address the limitations mentioned in the proposed journal papers. For instance, future experiments should include an assessment of the auditory experience in terms of pleasantness, arousal, familiarity, eventfulness, and dominance (Axelsson et al., 2010). Also, the addition of music as one of the auditory experiences, specifically as another "pleasant" experience, could expand the possibility of discussion on the role of biophilia in the restorative potential of auditory experiences, adding on to the works of Thoma et al. (2013) and Medvedev et al. (2015). For the findings to be truly generalizable, more data needs to be collected with professionals in design-related careers. Also, investigation is needed on the effects of biophilic restorative experiences on different types of design task. For example, an engineering task in which participants could follow a conventional or an innovative bioinspired/biomimetic approach. Could biophilic experiences prime engineers to adopt green, instead of grey, infrastructure? Future work should also investigate the effects of longer exposure periods, as well as longitudinal effects. Lastly, with the development of new technologies that enable the creation of immersive experiences, more research should be done on truly multisensory experiences that engage 3 or more senses.

5.4 Main Takeaways

1. Measuring "stress" takes more than self-reported stress levels and biomarkers.
2. The effects of biophilic restorative experiences on the brain are more complex than previously thought.
3. Assessment of design originality based on semantics is limited by language barriers.
4. Biophilic visual experiences have the potential to prime designers into adopting biophilic design.
5. Symbolic biophilic experiences that engage more senses do not necessarily result in greater restorative effects.

5.5 References

Aristizabal, S., Byun, K., Porter, P., Clements, N., Campanella, C., Li, L., Mullan, A., Ly, S., Senerat, A., Nenadic, I. Z., Browning, W. D., Loftness, V., & Bauer, B. (2021). Biophilic office design: Exploring the impact of a multisensory approach on human well-being. *Journal of Environmental Psychology*, *77*, 101682. https://doi.org/10.1016/j.jenvp.2021.101682

Atchley, R. A., Strayer, D. L., & Atchley, P. (2012). Creativity in the Wild: Improving Creative Reasoning through Immersion in Natural Settings. *PLOS ONE*, *7*(12), e51474. https://doi.org/10.1371/journal.pone.0051474

Axelsson, Ö., Nilsson, M. E., & Berglund, B. (2010). A principal components model of soundscape perception. *The Journal of the Acoustical Society of America*, *128*(5), 2836–2846. https://doi.org/10.1121/1.3493436

Berman, M. G., Jonides, J., & Kaplan, S. (2008). The Cognitive Benefits of Interacting With Nature. *Psychological Science*, *19*(12), 1207–1212. https://doi.org/10.1111/j.1467-9280.2008.02225.x

Delos Living LLC. (2020). *MindBreaks—Relax & Recharge* (1.0.12) [Computer software]. Delos Living LLC. https://apps.apple.com/us/app/mindbreaks-relax-recharge/id1498782851

Gould van Praag, C. D., Garfinkel, S. N., Sparasci, O., Mees, A., Philippides, A. O., Ware, M., Ottaviani, C., & Critchley, H. D. (2017). Mind-wandering and alterations to default mode network connectivity when listening to naturalistic versus artificial sounds. *Scientific Reports*, *7*(1), Article 1. https://doi.org/10.1038/srep45273

Jo, H., Song, C., Ikei, H., Enomoto, S., Kobayashi, H., & Miyazaki, Y. (2019). Physiological and Psychological Effects of Forest and Urban Sounds Using High-Resolution Sound Sources. *International Journal of Environmental Research and Public Health*, *16*(15), Article 15. https://doi.org/10.3390/ijerph16152649

Kaplan, R., & Kaplan, S. (1989). *The experience of nature: A psychological perspective*. Cambridge University Press.

Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology*, *15*(3), 169–182. https://doi.org/10.1016/0272-4944(95)90001-2

Langer, N., Pedroni, A., Gianotti, L. R. R., Hänggi, J., Knoch, D., & Jäncke, L. (2012). Functional brain network efficiency predicts intelligence. *Human Brain Mapping*, *33*(6), 1393–1406. https://doi.org/10.1002/hbm.21297

Leung, G., Hazan, H., & Chan, C. S. (2022). Exposure to nature in immersive virtual reality increases connectedness to nature among people with low nature affinity. *Journal of Environmental Psychology*, 101863. https://doi.org/10.1016/j.jenvp.2022.101863

Mackay, C. M. L., & Schmitt, M. T. (2019). Do people who feel connected to nature do more to protect it? A meta-analysis. *Journal of Environmental Psychology*, *65*, 101323. https://doi.org/10.1016/j.jenvp.2019.101323

Medvedev, O., Shepherd, D., & Hautus, M. J. (2015). The restorative potential of soundscapes: A physiological investigation. *Applied Acoustics*, *96*, 20–26. https://doi.org/10.1016/j.apacoust.2015.03.004

Neubauer, A. C., & Fink, A. (2009). Intelligence and neural efficiency. *Neuroscience & Biobehavioral Reviews, 33*(7), 1004–1023. https://doi.org/10.1016/j.neubiorev.2009.04.001

Richardson, M., & Butler, C. W. (2022). Nature connectedness and biophilic design. *Building Research & Information, 50*(1–2), 36–42. https://doi.org/10.1080/09613218.2021.2006594

Song, C., Ikei, H., & Miyazaki, Y. (2019). Physiological effects of forest-related visual, olfactory, and combined stimuli on humans: An additive combined effect. *Urban Forestry & Urban Greening, 44*, 126437. https://doi.org/10.1016/j.ufug.2019.126437

Song, C., Ikei, H., & Miyazaki, Y. (2021). Effects of forest-derived visual, auditory, and combined stimuli. *Urban Forestry & Urban Greening, 64*, 127253. https://doi.org/10.1016/j.ufug.2021.127253

Song, I., Baek, K., Kim, C., & Song, C. (2023). Effects of nature sounds on the attention and physiological and psychological relaxation. *Urban Forestry & Urban Greening, 86*, 127987. https://doi.org/10.1016/j.ufug.2023.127987

Thoma, M. V., Marca, R. L., Brönnimann, R., Finkel, L., Ehlert, U., & Nater, U. M. (2013). The Effect of Music on the Human Stress Response. *PLOS ONE, 8*(8), e70156. https://doi.org/10.1371/journal.pone.0070156

Whitburn, J., Linklater, W., & Abrahamse, W. (2020). Meta-analysis of human connection to nature and proenvironmental behavior. *Conservation Biology, 34*(1), 180–193. https://doi.org/10.1111/cobi.13381

Wijk, B. C. M. van, Stam, C. J., & Daffertshofer, A. (2010). Comparing Brain Networks of Different Size and Connectivity Density Using Graph Theory. *PLOS ONE, 5*(10), e13701. https://doi.org/10.1371/journal.pone.0013701

Zelenski, J. M., Dopko, R. L., & Capaldi, C. A. (2015). Cooperation is in our nature: Nature exposure may promote cooperative and environmentally sustainable behavior. *Journal of Environmental Psychology, 42*, 24–31. https://doi.org/10.1016/j.jenvp.2015.01.005

Chapter 6 – Reflection

The journey towards the completion of this PhD dissertation has been full of lessons and truly transformational. I feel very fortunate to have had the opportunity to enjoy the freedom for my individual intellectual and creative pursuits for the last four years, which culminated in the production of this work. A little sticky note on my desk with the Greek term “scholé” written on it always reminded me that I should enjoy the process and understand that the learning and studying and the pursuit of higher things associated with the PhD should not be so laborious as much as it enjoyable. Reflecting back on my journey, I would like to share some of the lessons I have learned along the way that might be helpful to anyone engaging in similar academic pursuits.

Under-promise and over-deliver

Ambition is good, but be careful not to bite off more than you can chew. After my proposal defense, a couple of my committee members (as well as my advisor) showed some concern with the grandiosity of the study I was proposing. The study would require more than 150 subjects, meaning more than 150 hours of data collection. Furthermore, I would need to recruit all of those subjects, find a volunteer to help me run every single session, and then analyze all the data collected (approximately 24,000 data points). My advisor insisted that 60% of what I was proposing would have been enough for a PhD. I did not listen. Then I had to live with the fear and stress of not being able to deliver what I promised. On top of all the concerns associated with the research itself. Fortunately, against all odds, I was able to accomplish all I had proposed, earning myself the "Simba Award" for "laughing in the face of danger". But in hindsight, I see that under-promising and over-delivering would have reduced the strain associated with this process.

Do not rush the process.

Another factor that added some strain in my journey was the fact that I set a goal of finishing my PhD in two years. In the beginning, I believed that this journey was just something I needed to get through as quick as possible so that I could reach whatever would come next, when I would be able to truly enjoy my life. The truth is, I gave up on enjoying more of the PhD process by trying to rush it. The deeper I got into it, the more enjoyable it became. The more I realized how fortunate I was to be working on something I was passionate about. The more I enjoyed what I was doing in the now instead of losing myself dreaming about the future. In the end, everything seemed to happen at the right time, but I truly believe that to get the most out of the PhD, the process should not be rushed.

Routine beats motivation.

As I got into my last semester needing to collect data with 60 more subjects and write the whole dissertation to be able to graduate, I realized that even the fact that my family had already bought tickets to come from Brazil to watch me walk in the graduation ceremony was not enough push for me to get it done on time. After a couple of weeks trying to write when I felt motivated, I realized that motivation was not enough. I needed to establish a routine and consistently write (or at least try to) until it became a habit. I blocked four bouts of writing on my calendar every day, each with a goal for the number of words to be written. The motivation of beating that goal every day was much stronger than any other. It helped me build momentum, to the point that by the end of the process, I could easily write more than 1,000 per day. I believe that building a writing routine was the key for getting this dissertation done.

Give yourself freedom to explore, but have a clear vision of the ultimate goal.

As someone who is very curious and has a hard time saying no, throughout the PhD journey I got involved in many side projects, including a 6-month internship that had me go to Dubai. Although at times, at least superficially, it seemed like I straying away too much from my research work or my career goals, I always made sure this alternative experience could somehow link back to ultimate goal. I understand it is very tempting to get involved with activities and experiences that let you forget about your research for a moment, but I believe that even in those cases there should be some intentionality of extracting some sort of lesson that is applied to your own work.

Appendix A – Pilot study

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 (Saegert and Winkel, 1990; Kellert, Heerwagen and Mador, 2011). Biophilic restorative experiences involve positive interactions with nature-based stimuli, either through direct (Song, Ikei and Miyazaki, 2016), indirect (Soga, Gaston and Yamaura, 2017), 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 (Baird et al., 2012), is also observable by the rest of executive network functions in the brain (Williams et al., 2018; 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.

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 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 (Dumas, Organisciak and Doherty, 2020).

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 cognition and decision-making. 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.

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.

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.

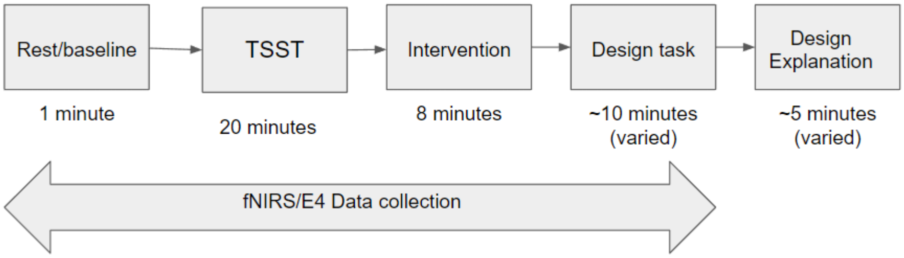


Figure 1: Experiment phases

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).

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

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 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.

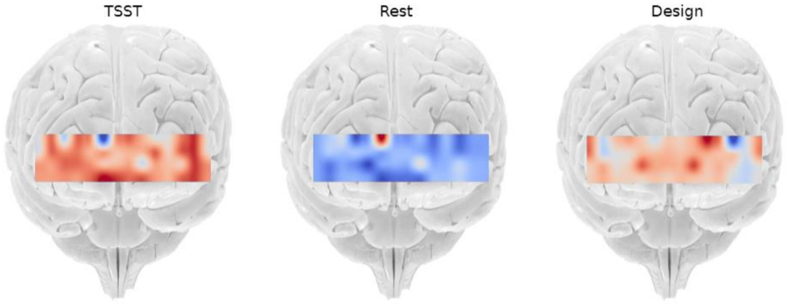


Figure 2: Brain activation during each experiment phase for the Control group. Red indicates greater oxy-Hb recruitment, while blue indicates a decrease in oxy-Hb.

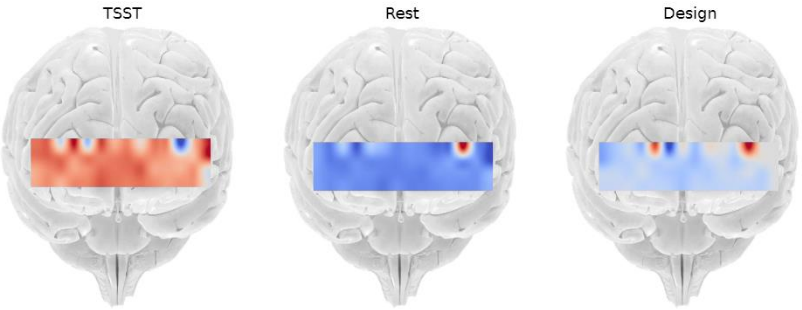


Figure 3: Brain activation during each experiment phase for the Intervention group. Red indicates greater oxy-Hb recruitment, while blue indicates a decrease in oxy-Hb.

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.

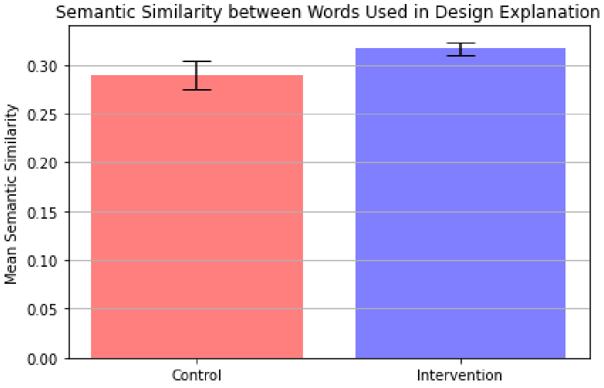


Figure 4: The control group used words that were overall less semantically similar when compared to the intervention group.

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.

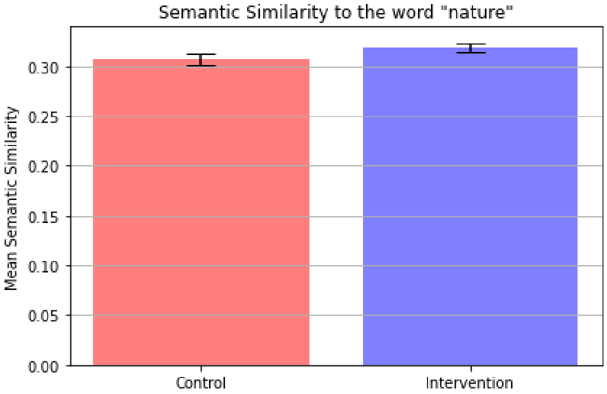


Figure 5: The intervention groups used words that were more semantically similar to the word "nature" when compared to the control group.

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).

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 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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References

Aristizabal, S., Byun, K., Porter, P., Clements, N., Campanella, C., Li, L., Mullan, A., Ly, S., Senerat, A., Nenadic, I.Z., Browning, W.D., Loftness, V., Bauer, B., 2021. Biophilic office design: Exploring the impact of a multisensory approach on human well-being. Journal of Environmental Psychology 77, 101682. https://doi.org/10.1016/j.jenvp.2021.101682

Atchley, R.A., Strayer, D.L., Atchley, P., 2012. Creativity in the Wild: Improving Creative Reasoning through Immersion in Natural Settings. PLOS ONE 7, e51474. https://doi.org/10.1371/journal.pone.0051474

Berman, M.G., Jonides, J., Kaplan, S., 2008. The Cognitive Benefits of Interacting With Nature. Psychological Science 19, 1207–1212. https://doi.org/10.1111/j.1467-9280.2008.02225.x

Bratman, G.N., Hamilton, J.P., Daily, G.C., 2012. The impacts of nature experience on human cognitive function and mental health. Annals of the New York Academy of Sciences 1249, 118–136. https://doi.org/10.1111/j.1749-6632.2011.06400.x

Delos Living LLC, 2020. MindBreaks - Relax & Recharge.

Deng, L., Luo, H., Ma, J., Huang, Z., Sun, L.-X., Jiang, M.-Y., Zhu, C.-Y., Li, X., 2020. Effects of integration between visual stimuli and auditory stimuli on restorative potential and aesthetic preference in urban green spaces. Urban Forestry & Urban Greening 53, 126702. https://doi.org/10.1016/j.ufug.2020.126702

Ernst, G., 2017. Heart-Rate Variability—More than Heart Beats? Frontiers in Public Health 5.

Fishburn, F.A., Ludlum, R.S., Vaidya, C.J., Medvedev, A.V., 2019. Temporal Derivative Distribution Repair (TDDR): A motion correction method for fNIRS. NeuroImage 184, 171–179. https://doi.org/10.1016/j.neuroimage.2018.09.025

Goodman, W.K., Janson, J., Wolf, J.M., 2017. Meta-analytical assessment of the effects of protocol variations on cortisol responses to the Trier Social Stress Test. Psychoneuroendocrinology 80, 26–35. https://doi.org/10.1016/j.psyneuen.2017.02.030

Gray, T., Birrell, C., 2014. Are Biophilic-Designed Site Office Buildings Linked to Health Benefits and High Performing Occupants? International Journal of Environmental Research and Public Health 11, 12204–12222. https://doi.org/10.3390/ijerph111212204

Honnibal, M., Montani, I., Van Landeghem, S., Boyd, A., 2020. spaCy: Industrial-strength Natural Language Processing in Python [WWW Document]. URL 10.5281/zenodo.1212303

Hu, M., Shealy, T., 2019a. Application of Functional Near-Infrared Spectroscopy to Measure Engineering Decision-Making and Design Cognition: Literature Review and Synthesis of Methods. Journal of Computing in Civil Engineering 33, 04019034. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000848

Hu, M., Shealy, T., 2019b. Application of Functional Near-Infrared Spectroscopy to Measure Engineering Decision-Making and Design Cognition: Literature Review and Synthesis of Methods. Journal of Computing in Civil Engineering 33, 04019034. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000848

Igarashi, M., Yamamoto, T., Lee, J., Song, C., Ikei, H., Miyazaki, Y., 2014. Effects of stimulation by three-dimensional natural images on prefrontal cortex and autonomic nerve activity: a comparison with stimulation using two-dimensional images. Cognitive Processing 15, 551–556. https://doi.org/10.1007/s10339-014-0627-z

Jo, H., Song, C., Ikei, H., Enomoto, S., Kobayashi, H., Miyazaki, Y., 2019. Physiological and Psychological Effects of Forest and Urban Sounds Using High-Resolution Sound Sources. International Journal of Environmental Research and Public Health 16, 2649. https://doi.org/10.3390/ijerph16152649

Kaplan, S., 1995. The restorative benefits of nature: Toward an integrative framework. Journal of Environmental Psychology 15, 169–182. https://doi.org/10.1016/0272-4944(95)90001-2

Kaplan, S., Kaplan, R., 1989. Cognition and Environment : Functioning in an Uncertain World. Ulrichs Books, Ann Arbor, Mich.

Kenett, Y.N., 2018. Going the Extra Creative Mile: The Role of Semantic Distance in Creativity – Theory, Research, and Measurement, in: Vartanian, O., Jung, R.E. (Eds.), The Cambridge Handbook of the Neuroscience of Creativity, Cambridge Handbooks in Psychology. Cambridge University Press, Cambridge, pp. 233–248. https://doi.org/10.1017/9781316556238.014

Kim, J., Cha, S.H., Koo, C., Tang, S., 2018. The effects of indoor plants and artificial windows in an underground environment. Building and Environment 138, 53–62. https://doi.org/10.1016/j.buildenv.2018.04.029

Krzywicka, P., Byrka, K., 2017. Restorative Qualities of and Preference for Natural and Urban Soundscapes. Frontiers in Psychology 8.

Labuschagne, I., Grace, C., Rendell, P., Terrett, G., Heinrichs, M., 2019. An introductory guide to conducting the Trier Social Stress Test. Neuroscience & Biobehavioral Reviews 107, 686–695. https://doi.org/10.1016/j.neubiorev.2019.09.032

Lee, J., Li, Q., Tyrväinen, L., Tsunetsugu, Y., Park, B.-J., Kagawa, T., Miyazaki, Y., 2012. Nature Therapy and Preventive Medicine, Public Health - Social and Behavioral Health. IntechOpen. https://doi.org/10.5772/37701

Leung, G., Hazan, H., Chan, C.S., 2022. Exposure to nature in immersive virtual reality increases connectedness to nature among people with low nature affinity. Journal of Environmental Psychology 101863. https://doi.org/10.1016/j.jenvp.2022.101863

Lloyd-Cox, J., Chen, Q., Beaty, R.E., 2022. The time course of creativity: Multivariate classification of default and executive network contributions to creative cognition over time. Cortex 156, 90–105. https://doi.org/10.1016/j.cortex.2022.08.008

McGee, B., Marshall-Baker, A., 2015. Loving Nature From the Inside Out: A Biophilia Matrix Identification Strategy for Designers. HERD : Health Environments Research & Design Journal 8, 115–130. https://doi.org/10.1177/1937586715578644

Milovanovic, J., Hu, M., Shealy, T., Gero, J., 2021. Characterization of concept generation for engineering design through temporal brain network analysis. Design Studies 76, 101044. https://doi.org/10.1016/j.destud.2021.101044

Park, B.-J., Tsunetsugu, Y., Kasetani, T., Hirano, H., Kagawa, T., Sato, M., Miyazaki, Y., 2007. Physiological effects of Shinrin-yoku (taking in the atmosphere of the forest)--using salivary cortisol and cerebral activity as indicators. Journal of Physiological Anthropology 26, 123–128. https://doi.org/10.2114/jpa2.26.123

Parsons, R., Tassinary, L.G., Ulrich, R.S., Hebl, M.R., Grossman-Alexander, M., 1998. THE VIEW FROM THE ROAD: IMPLICATIONS FOR STRESS RECOVERY AND IMMUNIZATION. Journal of Environmental Psychology 18, 113–140. https://doi.org/10.1006/jevp.1998.0086

Plambech, T., Konijnendijk van den Bosch, C.C., 2015. The impact of nature on creativity – A study among Danish creative professionals. Urban Forestry & Urban Greening 14, 255–263. https://doi.org/10.1016/j.ufug.2015.02.006

Rajendra Acharya, U., Paul Joseph, K., Kannathal, N., Lim, C.M., Suri, J.S., 2006. Heart rate variability: a review. Medical and Biological Engineering and Computing 44, 1031–1051. https://doi.org/10.1007/s11517-006-0119-0

Rashid, M., Zimring, C., 2008. A Review of the Empirical Literature on the Relationships Between Indoor Environment and Stress in Health Care and Office Settings: Problems and Prospects of Sharing Evidence. Environment and Behavior 40, 151–190. https://doi.org/10.1177/0013916507311550

Ratcliffe, E., Gatersleben, B., Sowden, P.T., 2013. Bird sounds and their contributions to perceived attention restoration and stress recovery. Journal of Environmental Psychology 36, 221–228. https://doi.org/10.1016/j.jenvp.2013.08.004

Richardson, M., Butler, C.W., 2022. Nature connectedness and biophilic design. Building Research & Information 50, 36–42. https://doi.org/10.1080/09613218.2021.2006594

Schubert, C., Lambertz, M., Nelesen, R.A., Bardwell, W., Choi, J.-B., Dimsdale, J.E., 2009. Effects of stress on heart rate complexity—A comparison between short-term and chronic stress. Biological Psychology 80, 325–332. https://doi.org/10.1016/j.biopsycho.2008.11.005

Sharam, L.A., Mayer, K.M., Baumann, O., 2023. Design by nature: The influence of windows on cognitive performance and affect. Journal of Environmental Psychology 85, 101923. https://doi.org/10.1016/j.jenvp.2022.101923

She, J., MacDonald, E., 2013. Priming Designers to Communicate Sustainability. Journal of Mechanical Design 136. https://doi.org/10.1115/1.4025488

Shealy, T., 2016. Do Sustainable Buildings Inspire More Sustainable Buildings? Procedia Engineering, ICSDEC 2016 – Integrating Data Science, Construction and Sustainability 145, 412–419. https://doi.org/10.1016/j.proeng.2016.04.008

Shealy, T., Gero, J., Ignacio Junior, P., 2022. How the use of concept maps changes students' minds and brains How the use of concept maps changes students' minds and brains. Presented at the American Society for Engineering Education.

Song, C., Ikei, H., Miyazaki, Y., 2021. Effects of forest-derived visual, auditory, and combined stimuli. Urban Forestry & Urban Greening 64, 127253. https://doi.org/10.1016/j.ufug.2021.127253

Song, C., Ikei, H., Miyazaki, Y., 2016. Physiological Effects of Nature Therapy: A Review of the Research in Japan. International Journal of Environmental Research and Public Health 13, 781. https://doi.org/10.3390/ijerph13080781

Task Force of the European Society of Cardiology the North American Society of Pacing Electrophysiology, 1996. Heart Rate Variability - Standards of Measurement, Physiological Interpretation, and Clinical Use 93, 1043–1065.

Thoma, M.V., Mewes, R., Nater, U.M., 2018. Preliminary evidence: the stress-reducing effect of listening to water sounds depends on somatic complaints. Medicine (Baltimore) 97, e9851. https://doi.org/10.1097/MD.0000000000009851

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

van den Berg, M.M.H.E., Maas, J., Muller, R., Braun, A., Kaandorp, W., van Lien, R., van Poppel, M.N.M., van Mechelen, W., van den Berg, A.E., 2015. Autonomic Nervous System Responses to Viewing Green and Built Settings: Differentiating Between Sympathetic and Parasympathetic Activity. International Journal of Environmental Research and Public Health 12, 15860–15874. https://doi.org/10.3390/ijerph121215026

Wang, X., Shi, Y., Zhang, B., Chiang, Y., 2019. The Influence of Forest Resting Environments on Stress Using Virtual Reality. International Journal of Environmental Research and Public Health 16, 3263. https://doi.org/10.3390/ijerph16183263

Yin, J., Arfaei, N., MacNaughton, P., Catalano, P.J., Allen, J.G., Spengler, J.D., 2019. Effects of biophilic interventions in office on stress reaction and cognitive function: A randomized crossover study in virtual reality. Indoor Air 29, 1028–1039. https://doi.org/10.1111/ina.12593

Yin, J., Yuan, J., Arfaei, N., Catalano, P.J., Allen, J.G., Spengler, J.D., 2020. Effects of biophilic indoor environment on stress and anxiety recovery: A between-subjects experiment in virtual reality. Environment International 136, 105427. https://doi.org/10.1016/j.envint.2019.105427

Yin, J., Zhu, S., MacNaughton, P., Allen, J.G., Spengler, J.D., 2018. Physiological and cognitive performance of exposure to biophilic indoor environment. Building and Environment 132, 255–262. https://doi.org/10.1016/j.buildenv.2018.01.006

Appendix B – Supporting data for Chapter 3

Table 1.

Descriptive statistics of all semantic distance measures. Outliers within groups were removed from analysis using the IQR method.

Measure	Condition	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
SS	AW, DE	A	32	0.3049	0.0221	0.2726	0.3495	0.0875	0.3037	0.7388
		C	31	0.3005	0.0235	0.2564	0.3457	0.5243		
		I	32	0.3030	0.0218	0.2596	0.3417	0.5351		
	N, DE	A	31	0.2996	0.0180	0.2618	0.3303	0.2767	0.0348	0.9658
		C	32	0.3002	0.0193	0.2560	0.3423	0.9781		
		I	32	0.2989	0.0180	0.2542	0.3426	0.7429		
	N, DE (ON)	A	32	0.2915	0.0261	0.2463	0.3460	0.6659	0.2520	0.7778
		C	30	0.2902	0.0233	0.2321	0.3474	0.8540		
		I	31	0.2874	0.0187	0.2498	0.3251	0.5094		
DSI	DE + DP	A	32	0.8153	0.0069	0.7983	0.8286	0.8652	0.1552	0.8564
		C	32	0.8161	0.0050	0.8040	0.8273	0.9965		
		I	31	0.8158	0.0057	0.8029	0.8253	0.7085		
	DE	A	32	0.8139	0.0090	0.7949	0.8232	0.2203	0.1568	0.9246
		C	32	0.8153	0.0057	0.8029	0.8237	0.3553		
		I	30	0.8152	0.0063	0.8015	0.8260	0.6617		
	DP	A	32	0.8050	0.0096	0.7884	0.8208	0.1318	1.2238	0.5423
		C	31	0.8077	0.0097	0.7871	0.8266	0.6682		
		I	31	0.8064	0.0095	0.7873	0.8212	0.0313		

Note. Measure: SS – Semantic Similarity; DSI – Divergent Semantic Integration. Condition: AW – mean semantic similarity between all words used; N – mean semantic similarity between all words used and the word "nature"; DE – explanation of the design product; DP – explanation of the design process; ON – only nouns. Group: A – Active Control; C – Control; I – Intervention. S-W *p* – Shapiro-Wilk *p*-value.

Table 2.

Time designing (minutes). Outliers within groups were removed from analysis using the IQR method.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
Time	A	31	11.80	5.75	3.88	26.15	0.03	1.24	0.54
	C	30	12.36	6.17	3.28	28.49	0.06		
	I	29	10.13	4.10	3.11	21.45	0.03		

Note. Group: A – Active Control; C – Control; I – Intervention. S-W *p* – Shapiro-Wilk *p*-value.

Table 3.

Descriptive statistics for the measure of incorporation of biophilia (modified version of the BDM). Raters 1 and 2 were volunteering graduate students non-trained in biophilic design. Raters 3 and 4 were a volunteering graduate student and a volunteering post-doctoral researcher, respectively, both trained in biophilic design.

Measure	Rater	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
BDM (Total)	Designer	A	32	8.69	8.35	0	32	< 0.05	0.155	0.926
		C	32	8.97	7.73	0	29	< 0.05		
		I	32	8.28	5.71	0	21	0.298		
	Rater 1	A	30	22.43	7.65	13	39	< 0.05	0.858	0.651
		C	30	23.93	8.12	12	38	< 0.05		
		I	30	21.80	8.13	10	41	0.08		
	Rater 2	A	30	15.53	8.97	6	37	< 0.05	1.582	0.453
		C	32	14.19	8.14	6	35	< 0.05		

		I	31	15.74	7.62	7	34	< 0.05		
	Rater 3	A	32	8.50	7.82	0	27	< 0.05	6.877	**0.032***
		C	32	6.09	7.48	0	23	< 0.05		
		I	32	4.38	6.47	0	23	< 0.05		
	Rater 4	A	32	12.34	8.31	0	32	< 0.05	1.958	0.376
		C	32	14.91	11.18	3	41	< 0.05		
		I	32	14.78	7.69	3	39	< 0.05		
Visual Connection with Nature	Designer	A	32	0.84	1.05	0	3	< 0.05	1.331	0.514
		C	32	0.78	1.10	0	3	< 0.05		
		I	32	0.94	0.88	0	3	< 0.05		
	Rater 1	A	30	1.60	0.97	0	3	< 0.05	2.456	0.293
		C	30	1.67	1.09	0	3	< 0.05		
		I	30	1.27	1.08	0	3	< 0.05		
	Rater 2	A	30	1.13	1.25	0	3	< 0.05	2.840	0.242
		C	32	0.63	1.01	0	3	< 0.05		
		I	31	0.87	1.28	0	3	< 0.05		
	Rater 3	A	32	0.50	0.80	0	3	< 0.05	2.527	0.283
		C	32	0.19	0.40	0	1	< 0.05		
		I	32	0.38	0.71	0	2	< 0.05		
	Rater 4	A	32	1.19	1.12	0	3	< 0.05	0.352	0.838
		C	32	1.06	1.11	0	3	< 0.05		
		I	32	0.97	0.82	0	3	< 0.05		
Non-Visual Connection with Nature	Designer	A	32	0.28	0.77	0	3	< 0.05	1.327	0.515
		C	32	0.38	0.91	0	3	< 0.05		
		I	32	0.56	1.11	0	3	< 0.05		
	Rater 1	A	30	1.57	0.97	0	3	< 0.05	1.546	0.462
		C	30	1.83	0.83	1	3	< 0.05		
		I	30	1.63	0.76	1	3	< 0.05		
	Rater 2	A	30	0.40	0.97	0	3	< 0.05	2.384	0.304
		C	32	0.72	1.28	0	3	< 0.05		

		I	31	0.94	1.39	0	3	< 0.05		
	Rater 3	A	32	0.53	0.92	0	3	< 0.05	0.686	0.710
		C	32	0.66	1.21	0	3	< 0.05		
		I	32	0.38	0.79	0	3	< 0.05		
	Rater 4	A	32	1.156	0.987	0	3	< 0.05	0.090	0.956
		C	32	1.00	1.24	0	3	< 0.05		
		I	32	0.94	0.98	0	3	< 0.05		
Non-Rhythmic Sensory Stimuli	Designer	A	32	0.41	0.95	0	3	< 0.05	1.281	0.527
		C	32	0.25	0.76	0	3	< 0.05		
		I	32	0.19	0.64	0	3	< 0.05		
	Rater 1	A	30	1.60	0.93	0	3	< 0.05	0.448	0.799
		C	30	1.77	0.90	1	3	< 0.05		
		I	30	1.67	0.76	1	3	< 0.05		
	Rater 2	A	30	1.37	1.43	0	3	< 0.05	2.269	0.322
		C	32	0.97	1.36	0	3	< 0.05		
		I	31	0.90	1.33	0	3	< 0.05		
	Rater 3	A	32	0.81	1.12	0	3	< 0.05	1.336	0.513
		C	32	0.47	0.76	0	2	< 0.05		
		I	32	0.59	1.01	0	3	< 0.05		
	Rater 4	A	32	0.86	0.94	0	3	< 0.05	0.976	0.614
		C	32	0.78	1.01	0	3	< 0.05		
		I	32	0.94	0.88	0	3	< 0.05		
Thermal & Airflow Variability	Designer	A	32	0.84	0.95	0	3	< 0.05	0.338	0.844
		C	32	0.78	1.04	0	3	< 0.05		
		I	32	0.75	0.98	0	3	< 0.05		
	Rater 1	A	30	1.87	0.94	0	3	< 0.05	0.207	0.902
		C	30	1.97	0.76	1	3	< 0.05		
		I	30	1.93	0.78	0	3	< 0.05		
	Rater 2	A	30	1.47	1.33	0	3	< 0.05	1.838	0.399
		C	32	1.03	1.18	0	3	< 0.05		

		I	31	1.26	1.12	0	3	< 0.05		
	Rater 3	A	32	0.81	0.93	0	3	< 0.05	4.706	0.095
		C	32	0.50	0.76	0	2	< 0.05		
		I	32	0.38	0.71	0	2	< 0.05		
	Rater 4	A	32	1.00	0.98	0	3	< 0.05	2.253	0.324
		C	32	1.13	1.10	0	3	< 0.05		
		I	32	1.31	0.86	0	3	< 0.05		
Presence of Water	Designer	A	32	0.56	1.05	0	3	< 0.05	0.140	0.933
		C	32	0.56	1.13	0	3	< 0.05		
		I	32	0.56	1.05	0	3	< 0.05		
	Rater 1	A	30	0.63	1.22	0	3	< 0.05	1.548	0.461
		C	30	1.03	1.43	0	3	< 0.05		
		I	30	0.97	1.35	0	3	< 0.05		
	Rater 2	A	30	0.37	0.93	0	3	< 0.05	1.051	0.591
		C	32	0.66	1.26	0	3	< 0.05		
		I	31	0.77	1.33	0	3	< 0.05		
	Rater 3	A	32	0.47	1.02	0	3	< 0.05	0.854	0.652
		C	32	0.75	1.32	0	3	< 0.05		
		I	32	0.47	1.05	0	3	< 0.05		
	Rater 4	A	32	0.47	0.983	0	3	< 0.05	1.885	0.390
		C	32	0.91	1.35	0	3	< 0.05		
		I	32	0.56	1.11	0	3	< 0.05		
Dynamic & Diffuse Light	Designer	A	32	0.91	1.20	0	3	< 0.05	3.170	0.205
		C	32	0.78	0.91	0	3	< 0.05		
		I	32	0.47	0.84	0	3	< 0.05		
	Rater 1	A	30	2.47	0.51	2	3	< 0.05	3.382	0.184
		C	30	2.33	0.55	1	3	< 0.05		
		I	30	2.23	0.43	2	3	< 0.05		
	Rater 2	A	30	3.00	0.00	3	3	1.00	4.043	0.132
		C	32	3.00	0.00	3	3	1.00		

		I	31	2.90	0.40	1	3	< 0.05		
	Rater 3	A	32	0.63	0.75	0	2	< 0.05	3.124	0.210
		C	32	0.44	0.62	0	2	< 0.05		
		I	32	0.31	0.54	0	2	< 0.05		
	Rater 4	A	32	0.97	0.97	0	3	< 0.05	1.839	0.399
		C	32	1.16	1.02	0	3	< 0.05		
		I	32	1.25	0.84	0	3	< 0.05		
Connection with Natural Systems	Designer	A	32	0.63	1.04	0	3	< 0.05	1.129	0.569
		C	32	0.44	0.84	0	3	< 0.05		
		I	32	0.34	0.70	0	3	< 0.05		
	Rater 1	A	30	2.13	0.51	1	3	< 0.05	14.539	**0.0007***
		C	30	2.30	0.60	1	3	< 0.05		
		I	30	1.67	0.71	1	3	< 0.05		
	Rater 2	A	30	3.00	0.00	3	3	1.00	2.000	0.368
		C	32	3.00	0.00	3	3	1.00		
		I	31	2.97	0.18	2	3	< 0.05		
	Rater 3	A	32	0.41	0.56	0	2	< 0.05	2.794	0.247
		C	32	0.38	0.66	0	2	< 0.05		
		I	32	0.19	0.40	0	1	< 0.05		
	Rater 4	A	32	1.41	0.71	0	3	< 0.05	1.672	0.433
		C	32	1.47	0.84	0	3	< 0.05		
		I	32	1.22	0.49	1	3	< 0.05		
Biomorphic Forms & Patterns	Designer	A	32	0.44	0.88	0	3	< 0.05	1.738	0.419
		C	32	0.63	0.87	0	3	< 0.05		
		I	32	0.63	1.01	0	3	< 0.05		
	Rater 1	A	30	1.63	0.56	0	2	< 0.05	0.695	0.706
		C	30	1.60	0.77	0	3	< 0.05		
		I	30	1.53	0.68	0	3	< 0.05		
	Rater 2	A	30	0.70	0.75	0	3	< 0.05	0.667	0.717
		C	32	0.78	0.61	0	3	< 0.05		

		I	31	0.71	0.64	0	3	< 0.05		
	Rater 3	A	32	0.63	0.87	0	3	< 0.05	4.730	0.094
		C	32	0.44	0.76	0	3	< 0.05		
		I	32	0.19	0.40	0	1	< 0.05		
	Rater 4	A	32	0.56	0.71	0	2	< 0.05	4.051	0.132
		C	32	0.94	0.88	0	3	< 0.05		
		I	32	0.97	0.97	0	3	< 0.05		
Material Connection with Nature	Designer	A	32	0.78	0.97	0	3	< 0.05	1.238	0.539
		C	32	0.70	1.11	0	3	< 0.05		
		I	32	0.53	0.84	0	3	< 0.05		
	Rater 1	A	30	1.53	0.73	0	3	< 0.05	6.98	**0.030***
		C	30	1.50	0.94	0	3	< 0.05		
		I	30	1.00	0.98	0	3	< 0.05		
	Rater 2	A	30	0.27	0.52	0	2	< 0.05	7.943	**0.019***
		C	32	0.66	0.94	0	3	< 0.05		
		I	31	0.68	0.60	0	2	< 0.05		
	Rater 3	A	32	0.47	0.72	0	3	< 0.05	7.186	**0.028***
		C	32	0.31	0.54	0	2	< 0.05		
		I	32	0.09	0.30		1	< 0.05		
	Rater 4	A	32	0.69	0.78	0	3	< 0.05	4.871	0.088
		C	32	1.09	0.82	0	3	< 0.05		
		I	32	0.88	0.66	0	2	< 0.05		
Complexity & Order	Designer	A	32	0.50	0.95	0	3	< 0.05	3.868	0.145
		C	32	0.50	0.80	0	3	< 0.05		
		I	32	0.19	0.54	0	2	< 0.05		
	Rater 1	A	30	1.23	0.77	0	3	< 0.05	2.085	0.353
		C	30	1.47	0.73	0	3	< 0.05		
		I	30	1.20	0.85	0	3	< 0.05		
	Rater 2	A	30	1.30	1.39	0	3	< 0.05	3.584	0.167
		C	32	0.75	1.22	0	3	< 0.05		

		I	31	0.87	1.34	0	3	< 0.05		
	Rater 3	A	32	0.44	0.72	0	2	< 0.05	4.032	0.133
		C	32	0.19	0.59	0	3	< 0.05		
		I	32	0.22	0.55	0	2	< 0.05		
	Rater 4	A	32	0.63	0.79	0	3	< 0.05	3.812	0.149
		C	32	0.63	1.01	0	3	< 0.05		
		I	32	0.94	0.91	0	3	< 0.05		
Prospect	Designer	A	32	0.63	1.07	0	3	< 0.05	0.891	0.640
		C	32	0.84	1.17	0	3	< 0.05		
		I	32	0.88	1.18	0	3	< 0.05		
	Rater 1	A	30	1.93	0.58	1	3	< 0.05	0.840	0.657
		C	30	1.73	0.74	0	3	< 0.05		
		I	30	1.83	0.87	0	3	< 0.05		
	Rater 2	A	30	0.43	0.86	0	3	< 0.05	3.079	0.215
		C	32	0.38	0.66	0	3	< 0.05		
		I	31	0.77	1.06	0	3	< 0.05		
	Rater 3	A	32	1.13	1.01	0	3	< 0.05	9.388	**0.009***
		C	32	0.66	1.04	0	3	< 0.05		
		I	32	0.44	0.76	0	3	< 0.05		
	Rater 4	A	32	1.19	0.86	0	3	< 0.05	4.486	0.106
		C	32	1.44	0.95	0	3	< 0.05		
		I	32	1.69	0.82	1	3	< 0.05		
Refuge	Designer	A	32	0.75	0.98	0	3	< 0.05	1.992	0.369
		C	32	1.03	1.03	0	3	< 0.05		
		I	32	1.09	1.15	0	3	< 0.05		
	Rater 1	A	30	1.23	1.19	0	3	< 0.05	1.159	0.560
		C	30	0.97	1.33	0	3	< 0.05		
		I	30	1.20	1.40	0	3	< 0.05		
	Rater 2	A	30	1.50	1.48	0	3	< 0.05	0.534	0.766
		C	32	1.13	1.21	0	3	< 0.05		

		I	31	1.39	1.38	0	3	< 0.05		
	Rater 3	A	32	0.88	0.94	0	3	< 0.05	5.875	0.053
		C	32	0.56	0.84	0	3	< 0.05		
		I	32	0.34	0.60	0	2	< 0.05		
	Rater 4	A	32	0.78	0.79	0	3	< 0.05	4.347	0.114
		C	32	1.25	1.14	0	3	< 0.05		
		I	32	1.19	0.82	0	3	< 0.05		
Mystery	Designer	A	32	0.72	0.92	0	3	< 0.05	0.286	0.867
		C	32	0.81	1.06	0	3	< 0.05		
		I	32	0.72	1.11	0	3	< 0.05		
	Rater 1	A	30	1.20	0.76	0	3	< 0.05	3.097	0.213
		C	30	1.57	0.97	0	3	< 0.05		
		I	30	1.57	0.86	0	3	< 0.05		
	Rater 2	A	30	0.47	0.90	0	3	< 0.05	3.057	0.217
		C	32	0.28	0.73	0	3	< 0.05		
		I	31	0.61	0.95	0	3	< 0.05		
	Rater 3	A	32	0.53	0.95	0	3	< 0.05	1.178	0.555
		C	32	0.34	0.65	0	2	< 0.05		
		I	32	0.25	0.57	0	2	< 0.05		
	Rater 4	A	32	0.88	0.66	0	2	< 0.05	0.421	0.810
		C	32	0.91	0.93	0	3	< 0.05		
		I	32	1.00	0.80	0	3	< 0.05		
Risk/Peril	Designer	A	32	0.41	0.71	0	2	< 0.05	0.124	0.940
		C	32	0.47	0.92	0	3	< 0.05		
		I	32	0.44	0.91	0	3	< 0.05		
	Rater 1	A	30	1.80	0.66	1	3	< 0.05	7.280	**0.026***
		C	30	2.20	0.66	0	3	< 0.05		
		I	30	2.10	0.55	1	3	< 0.05		
	Rater 2	A	30	0.13	0.57	0	3	< 0.05	0.275	0.872
		C	32	0.22	0.75	0	3	< 0.05		

		I	31	0.10	0.40	0	2	< 0.05		
	Rater 3	A	32	0.28	0.58	0	2	< 0.05	0.540	0.764
		C	32	0.22	0.49	0	2	< 0.05		
		I	32	0.16	0.37	0	1	< 0.05		
	Rater 4	A	32	0.81	0.86	0	3	< 0.05	2.245	0.325
		C	32	1.16	0.99	0	3	< 0.05		
		I	32	0.94	0.84	0	3	< 0.05		

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that for the "Connection with Natural Systems" pattern, when scored by Rater 1, the Intervention group's score was significantly lower than both the Control (p = 0.001, Cohen's d = 0.965) and the Active Control (p = 0.010, Cohen's d = 0.755) groups, with large and medium to large effect sizes.

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that, when scored by Rater 1, the score for the "Material Connection with Nature" pattern did not differ significantly between groups. The test returned the *p*-values 0.097 (Intervention vs Control), 0.061 (Intervention vs Active Control), and 0.878 (Control vs Active Control).

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that, when scored by Rater 1, the score for the "Risk/Peril" pattern did not differ significantly between groups. The test returned the *p*-values 0.527 (Intervention vs Control), 0.123 (Intervention vs Active Control), and 0.070 (Control vs Active Control).

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that for the "Material Connection with Nature" pattern, when scored by Rater 2, the Intervention group's score was significantly higher than the Active Control group's score (p = 0.018), with a medium to large effect size (Cohen's d = 0.731). No significant difference was found between the Control and Active Control groups (p = 0.099), nor between the Control and Intervention groups (p = 0.916).

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that, when scored by Rater 3, the total score for the BID-M did not differ significantly between groups. The test returned the *p*-values 0.426 (Intervention vs Control), 0.075 (Intervention vs Active Control), and 0.426 (Control vs Active Control).

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that for the "Material Connection with Nature" pattern, when scored by Rater 3, the Intervention group's score was significantly lower than the Active Control group's score (p = 0.025), with a medium effect size (Cohen's d = 0.683). No significant difference was found between the Control and Active Control groups (p = 0.327), nor between the Control and Intervention groups (p = 0.095).

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that for the "Prospect" pattern, when scored by Rater 3, the Active Control group's score was significantly higher than the Intervention group's score (*p* = 0.009), with a medium to large effect size (Cohen's *d* = 0.770). No significant difference was found between the Control and Active Control groups (*p* = 0.143), nor between the Control and Intervention groups (*p* = 0.339).

Table 4.

Linear mixed effects model results. Adjusted for design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature. The model indicates scores in the post-experiment NR-6 had a significant effect on the dependent variable. Participants that reported greater connectedness to nature after the experiment score lower for the Visual Connection with Nature pattern. Even after controlling for post-experiment NR-6, participants in the active control group still had significantly higher scores for this biophilic design pattern.

Pattern	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Visual Connection with Nature	C (intercept)	0.700	0.406	1.725	0.084	(-0.095, 1.495)
	A	0.400	0.166	2.419	**0.016***	(0.076, 0.725)
	I	0.104	0.162	0.640	0.522	(-0.214, 0.422)
	NR-6 (post)	-0.168	0.075	-2.230	**0.026***	(-0.315, -0.020)

Table 5.

Linear mixed effects model results. Adjusted for design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature. The model indicates that design experience had a significant effect on the variable. Participants who had previous experience working with design incorporated more non-visual connection with nature in their design concepts.

Pattern	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Non-Visual Connection	C (intercept)	1.316	0.459	2.867	0.004	(0.416, 2.215)

with Nature	A	0.264	0.215	1.231	0.218	(-0.156, 0.685)
	I	-0.218	0.214	-1.021	0.307	(-0.638, 0.201)
	Design Experience	0.393	0.180	2.185	**0.029***	(0.040, 0.746)

Table 6.

Linear mixed effects model results. Adjusted for design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature. The model indicates that pre- and post-experiment feelings of connectedness to nature had a significant effect on the variable. Participants with higher scores in the pre-experiment NR-6 had higher scores for the Non-Rhythmic Sensory Stimuli pattern. On the other hand, participants with higher scores in the post-experiment NR-6 had lower scores for the same pattern. After controlling for these two confounders, the active control group still had significantly higher scores for this pattern.

Pattern	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Non-Rhythmic Sensory Stimuli	C (intercept)	0.518	0.383	1.351	0.177	(-0.233, 1.269)
	A	0.420	0.192	2.187	**0.029***	(0.044, 0.796)
	I	0.288	0.194	1.480	0.139	(-0.093, 0.669)
	NR-6 (pre)	0.319	0.035	9.208	**< 0.001***	(0.251, 0.387)
	NR-6 (post)	-0.353	0.131	-2.689	**0.007***	(-0.610, -0.096)

Table 7.

Linear mixed effects model results. Adjusted for design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature. The model indicates scores in the post-experiment NR-6 had a significant effect on the dependent variable. Scores in the post-experiment NR-6 had a negative main effect on the Thermal and Airflow Variability pattern.

Pattern	Group	Model Estimate (β)	Std. Err.	Z	*p*-value	95% CI
Thermal and Airflow Variability	C (intercept)	1.140	0.499	2.282	0.023	(0.161, 2.118)
	A	0.199	0.190	1.048	0.295	(-0.173, 0.571)
	I	-0.008	0.190	-0.042	0.966	(-0.380, 0.364)
	NR-6 (post)	-0.229	0.020	-11.206	**< 0.001***	(-0.269, -0.189)

Table 8.

Linear mixed effects model results. Adjusted for design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature. The model indicates scores in the post-experiment NR-6 had a significant effect on the dependent variable. Scores in the post-experiment NR-6 had a negative main effect on the Presence of Water pattern.

Pattern	Group	Model Estimate (β)	Std. Err.	Z	*p*-value	95% CI
Presence of Water	C (intercept)	0.936	0.623	1.503	0.133	(-0.285, 2.157)
	A	0.267	0.245	1.090	0.276	(-0.213, 0.748)
	I	-0.451	0.248	-1.822	0.068	(-0.937, 0.034)
	NR-6 (post)	-0.217	0.095	-2.276	**0.023***	(-0.404, -0.030)

Table 9.

Linear mixed effects model results. Adjusted for design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature. The model indicates that pre- and post-experiment feelings of connecteness to nature had a significant effect on the variable. Participants with higher scores in the pre-experiment NR-6 had higher scores for the Dynamic and Diffuse Light pattern. On the other hand, participants with higher scores in the post-experiment NR-6 had lower scores for the same pattern.

Pattern	Group	Model Estimate (β)	Std. Err.	Z	*p*-value	95% CI
Dynamic and Diffuse Light	C (intercept)	0.977	0.329	2.971	0.003	(0.333, 1.622)
	A	0.147	0.156	0.939	0.348	(-0.159, 0.453)
	I	-0.079	0.158	-0.497	0.619	(-0.389, 0.231)
	NR-6 (pre)	0.172	0.022	7.660	**< 0.001***	(0.128, 0.216)
	NR-6 (post)	-0.259	0.099	-2.619	**0.009***	(-0.453, -0.065)

Table 10.

Linear mixed effects model results. Adjusted for design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature. The model indicates the none of the confounders had a significant effect on the dependent variable.

Pattern	Group	Model Estimate (β)	Std. Err.	Z	*p*-value	95% CI
Connection with Natural Systems	C (intercept)	1.290	0.160	8.057	0.000	(0.976, 1.604)
	A	0.101	0.127	0.790	0.429	(-0.149, 0.350)
	I	-0.250	0.128	-1.952	0.051	(-0.501, 0.001)

Table 11.

Linear mixed effects model results. Adjusted for design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature. The model indicates the none of the confounders had a significant effect on the dependent variable.

Pattern	Group	Model Estimate (β)	Std. Err.	Z	*p*-value	95% CI

Biomorphic Forms & Patterns	C (intercept)	0.673	0.162	4.168	0.000	(0.357, 0.990)
	A	0.018	0.139	0.129	0.897	(-0.255, 0.291)
	I	-0.131	0.140	-0.940	0.347	(-0.405, 0.142)

Table 12.

Linear mixed effects model results. Adjusted for design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature. The model indicates that design experience had a significant effect on the variable. Participants who had previous experience working with design incorporated more material connection with nature in their design concepts. Even after controlling for confounders, the intervention still had a significant effect on the dependent variable. Participants who listened to the nature sounds had significantly lower scores for incorporating material connection with nature.

Pattern	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Material Connection with Nature	C (intercept)	1.081	0.155	6.986	0.000	(0.777, 1.384)
	A	-0.084	0.112	-0.749	0.454	(-0.305, 0.136)
	I	-0.277	0.110	-2.524	**0.012***	(-0.493, -0.062)
	Design Experience	0.201	0.095	2.121	**0.034***	(0.015, 0.387)

Table 13.

Linear mixed effects model results. Adjusted for design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature. The model indicates the none of the confounders had a significant effect on the dependent variable.

Pattern	Group	Model Estimate (β)	Std. Err.	Z	*p*-value	95% CI
Complexity & Order	C (intercept)	0.336	0.185	1.821	0.069	(-0.026, 0.698)
	A	0.174	0.143	1.215	0.224	(-0.106, 0.454)
	I	0.001	0.146	0.005	0.996	(-0.286, 0.287)

Table 14.

Linear mixed effects model results. Adjusted for design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature. The model indicates that previous knowledge about biophilic design had a significant effect on the variable. Particpants who were familiar with biophilic design (4 out of 96) incorporated more of the Prospect pattern in their design concepts.

Pattern	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Prospect	C (intercept)	1.235	0.330	3.747	0.000	(0.589, 1.882)
	A	-0.088	0.165	-0.534	0.593	(-0.410, 0.235)
	I	-0.136	0.166	-0.819	0.413	(-0.462, 0.190)
	Biophilic Design Knowledge	0.721	0.343	2.099	**0.036***	(0.048, 1.393)

Table 15.

Linear mixed effects model results. Adjusted for design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature. The model indicates that pre- and post-experiment feelings of connecteness to nature had a significant effect on the variable. Participants with higher scores in the pre-experiment NR-6 had higher scores for the Refuge pattern. On the other hand, participants with higher scores in the post-experiment NR-6 had lower scores for the same pattern.

Pattern	Group	Model Estimate (β)	Std. Err.	Z	*p*-value	95% CI
Refuge	C (intercept)	1.015	0.362	2.806	0.005	(0.306, 1.724)
	A	0.139	0.152	0.910	0.363	(-0.160, 0.438)
	I	-0.275	0.157	-1.757	0.079	(-0.582, 0.032)
	NR-6 (pre)	0.149	0.044	3.359	**0.001***	(0.062, 0.235)
	NR-6 (post)	-0.231	0.079	-2.941	**0.003***	(-0.386, -0.077)

Table 16.

Linear mixed effects model results. Adjusted for design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature. The model indicates scores in the post-experiment NR-6 had a significant effect on the dependent variable. Scores in the post-experiment NR-6 had a negative main effect on the Mystery pattern.

Pattern	Group	Model Estimate (β)	Std. Err.	Z	*p*-value	95% CI
Mystery	C (intercept)	1.209	0.413	2.925	0.003	(0.399, 2.019)
	A	0.017	0.156	0.106	0.915	(-0.290, 0.323)
	I	-0.159	0.158	-1.003	0.316	(-0.469, 0.151)
	NR-6 (post)	-0.229	0.010	-23404	**< 0.001***	(-0.248, -0.209)

Table 17.

Linear mixed effects model results. Adjusted for design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature. The model indicates scores in the pre-experiment NR-6 had a significant effect on the dependent variable. Scores in the post-experiment NR-6 had a positive main effect on the incorporation of the Risk/Peril pattern.

Pattern	Group	Model Estimate (β)	Std. Err.	Z	*p*-value	95% CI
Risk/Peril	C (intercept)	0.483	0.333	1.453	0.146	(-0.169, 1.136)
	A	0.103	0.149	0.691	0.490	(-0.189, 0.394)
	I	-0.142	0.152	-0.937	0.349	(-0.121, 0.376)
	NR-6 (pre)	0.142	0.032	4.479	< **0.001***	(0.080, 0.204)

Table 18.

Network density. The network density score goes from 0 to 1. The higher the number of edges (i.e. correlations between channels), the higher the density. Outliers within groups were removed from analysis using the IQR method.

Measure	Phase	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
Brain Netork Density	TSST	A	30	0.0516	0.0415	0.0027	0.1551	0.0067	2.1590	0.3398
		C	29	0.0520	0.0362	0.0027	0.1410	0.0746		
		I	32	0.0694	0.0521	0.0080	0.1995	0.0088		
	Rest	A	29	0.0727	0.0400	0.0195	0.1543	0.0460	7.6713	**0.0216***
		C	30	0.0960	0.0520	0.0098	0.2278	0.0754		
		I	30	0.1220	0.0746	0.0106	0.2828	0.1672		
	Task	A	31	0.0833	0.0686	0.0009	0.2518	0.0050	0.4365	0.8039
		C	30	0.0909	0.0734	0.0133	0.2766	0.0003		
		I	30	0.0835	0.0698	0.0106	0.2553	0.0020		

Note. Group: A – Active Control; C – Control; I – Intervention. S-W *p* – Shapiro-Wilk *p*-value.

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the restoration break, the mean network density for the Intervention group was significantly higher than the Active Control group (*p* = 0.0079), with a large effect size (Cohen’s *d* = 0.8196). However, although also having a higher score, the Intervention group did not significantly differ from the Control group (*p* = 0.1234).

Table 19.

Summary of regions with highest degree centrality and their associated cognitive functions.

Phase	Group	Channel	Degree Centrality	ROI	Associated function
TSST	A	22	0.016	rFrontopolar	
	C	22, 26	0.085	rFrontopolar	
	I	22	0.106	rFrontopolar	
Rest	A	8, 26	0.213	rFrontopolar	
	C	41	0.277	lFrontopolar	
	I	24	0.277	lFrontopolar	
Task	A	22	0.191	rFrontopolar	
	C	26	0.149	rFrontopolar	
	I	22, 23, 26, 41	0.106	rFrontopolar & lFrontopolar	

Note. Group: A – Active Control; C – Control; I – Intervention.

During the design task, the intervention group had 4 central nodes. This can show how the intervention group was able to have a wider activation?

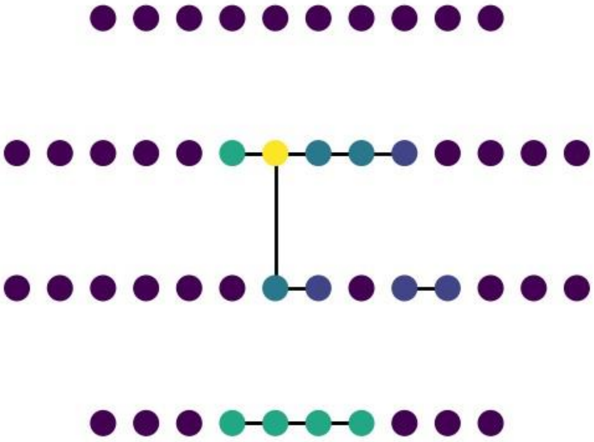


Fig. 1. Functional connectivity in the PFC during the TSST for the active control group.

For the active control group, during the TSST, the channels with the highest degree centrality were channels 22 (0.106), 21 (0.064), 29 (0.064), 30 (0.064), and 31 (0.064).

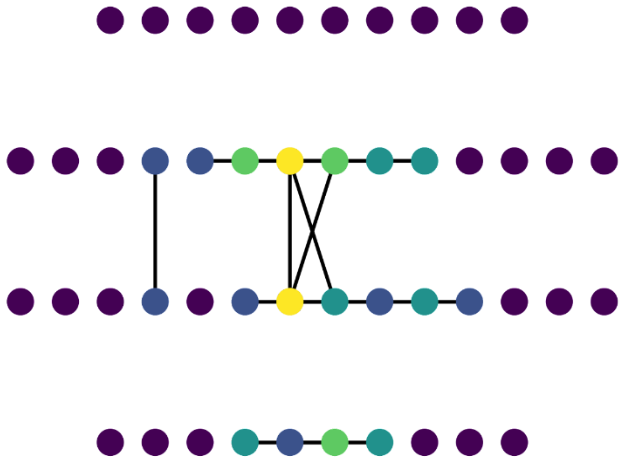


Fig. 2. Functional connectivity in the PFC during the TSST for the control group.

For the control group, during the TSST, the channels with the highest degree centrality were channels 22 (0.085), 26 (0.085), 21 (0.064), 23 (0.064), and 31 (0.064).

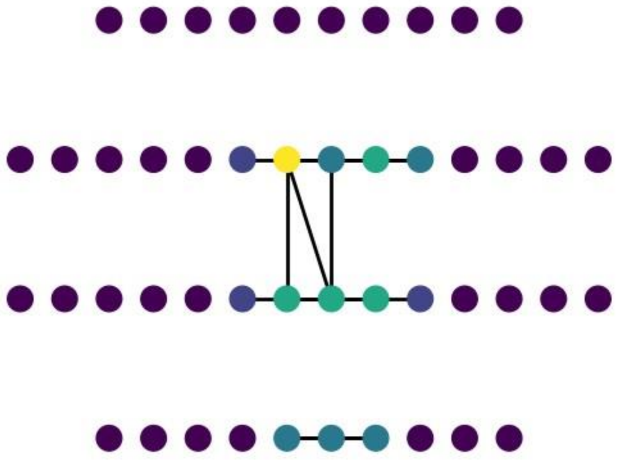


Fig. 3. Functional connectivity in the PFC during the TSST for the intervention group.

For the intervention group, during the TSST, the channels with the highest degree centrality were channels 22 (0.106), 24 (0.064), 26 (0.064), 27 (0.064), and 28 (0.064).

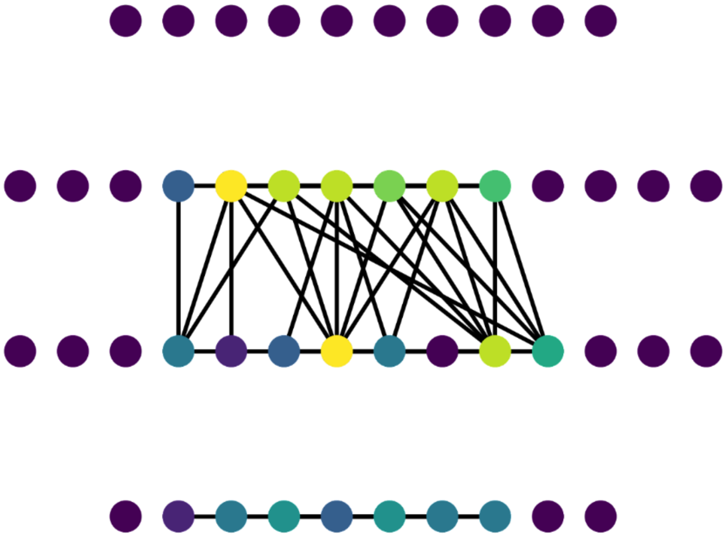


Fig. 4. Functional connectivity in the PFC during the restoration break for the active control group.

For the active control group, during the restoration break, the channels with the highest degree centrality were channels 8 (0.213), 26 (0.213), 21 (0.191), 22 (0.191), and 24 (0.191).

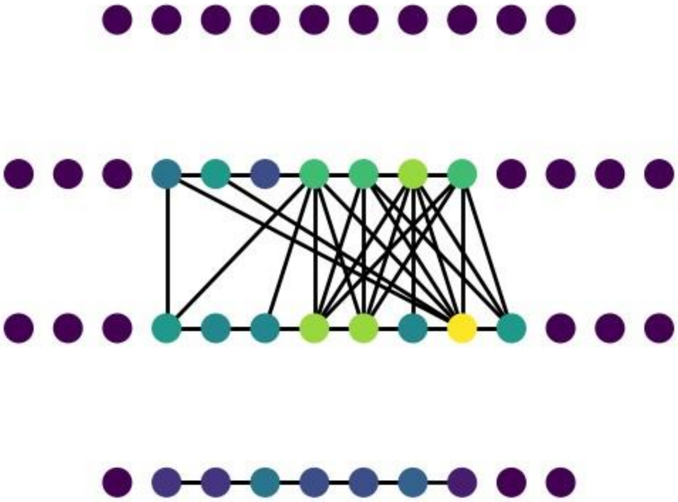


Fig. 5. Functional connectivity in the PFC during the restoration break for the control group.

For the control group, during the restoration break, the channels with the highest degree centrality were channels 41 (0.277), 24 (0.234), 26 (0.234), 27 (0.234), and 22 (0.191).

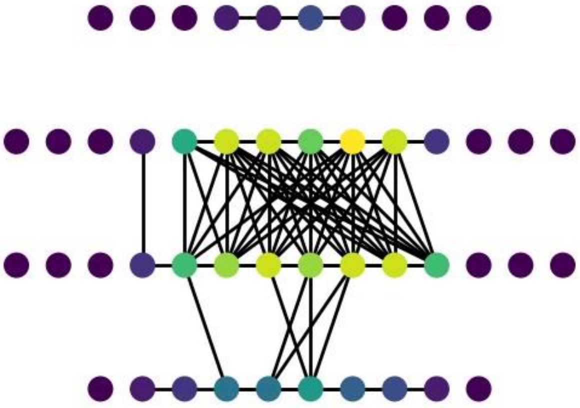


Fig. 6. Functional connectivity in the PFC during the restoration break for the intervention group.

For the intervention group, during the restoration break, the channels with the highest degree centrality were channels 24 (0.277), 21 (0.255), 22 (0.255), 26 (0.255), and 28 (0.255).

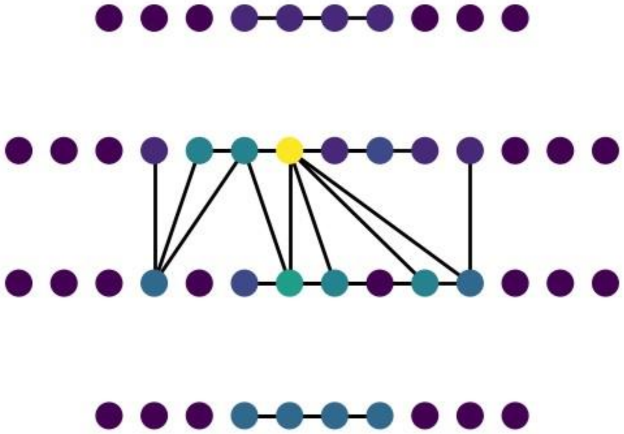


Fig. 7. Functional connectivity in the PFC during the design task for the active control group.

For the active control group, during the design task, the channels with the highest degree centrality were channels 22 (0.191), 26 (0.106), 8 (0.085), 21 (0.085), and 27 (0.085).

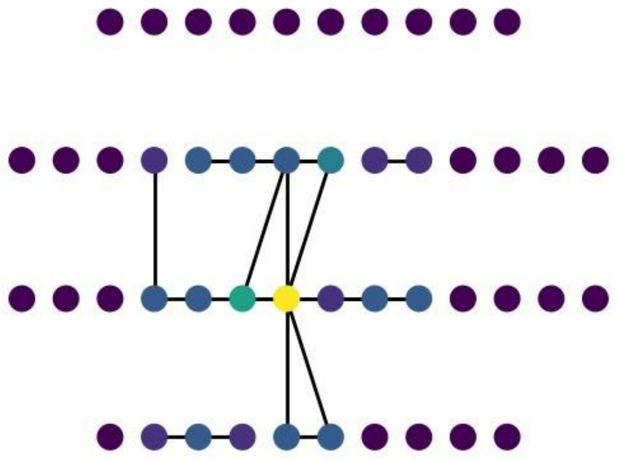


Fig. 8. Functional connectivity in the PFC during the design task for the control group.

For the control group, during the design task, the channels with the highest degree centrality were channels 26 (0.149), 25 (0.085), 23 (0.064), 8 (0.043), and 12 (0.043).

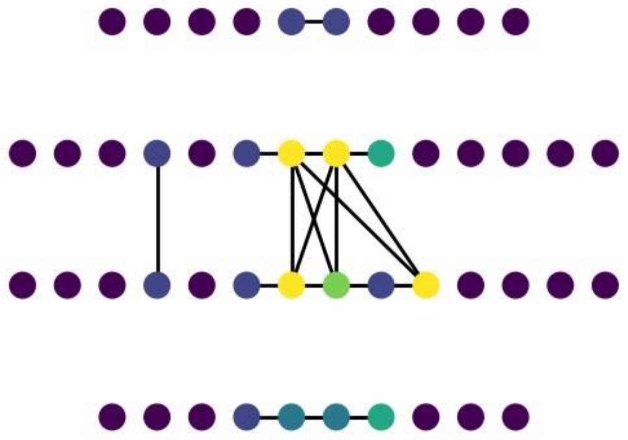
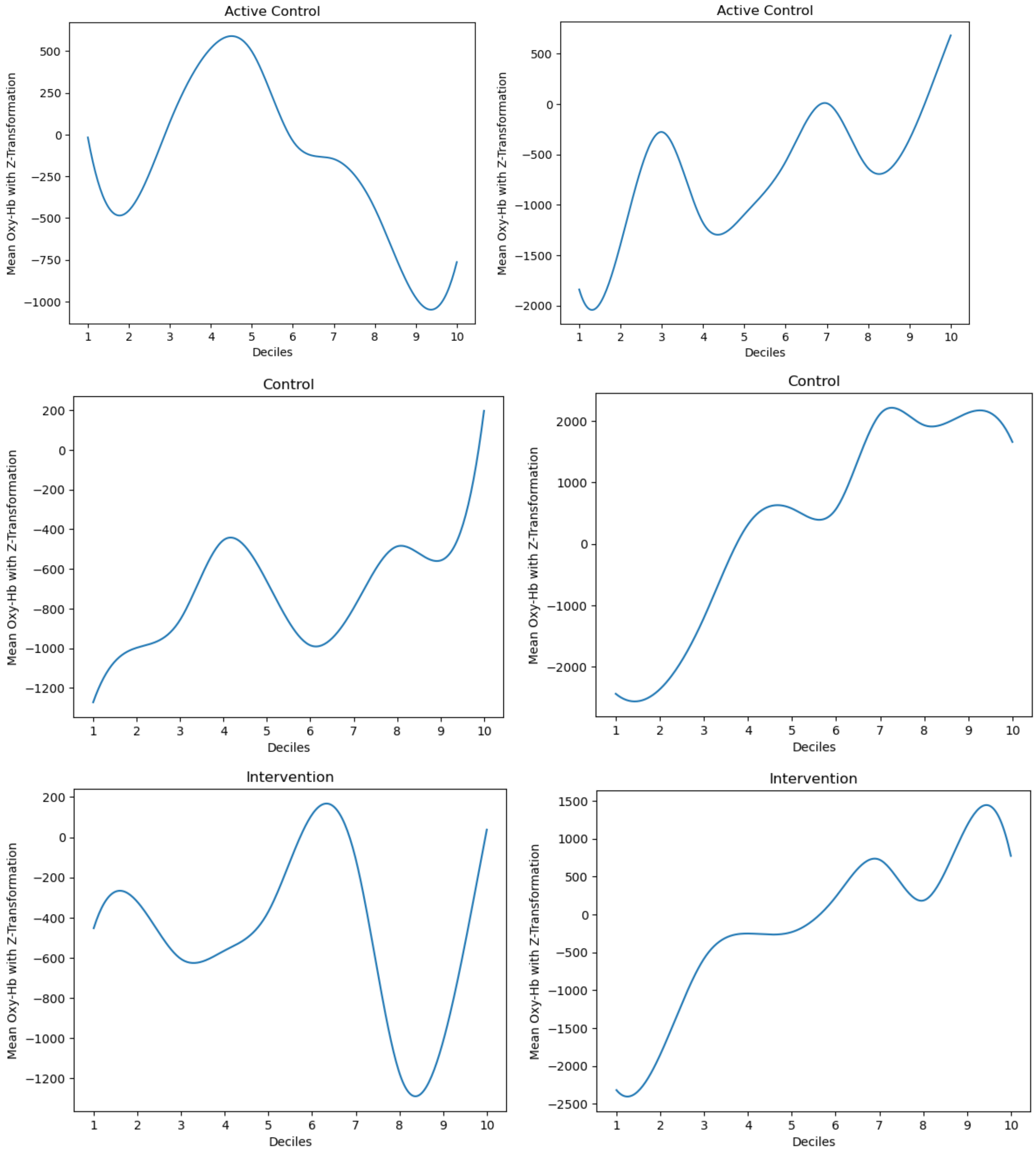


Fig. 9. Functional connectivity in the PFC during the design task for the intervention group.

For the intervention group, during the design task, the channels with the highest degree centrality were channels 22 (0.106), 23 (0.106), 26 (0.106), 41 (0.106), and 27 (0.085).

Temporal dynamics of Oxy-Hb recruitment


Active Control

Active Control

Control

Control

Intervention

Intervention

Fig. 10. Temporal dynamics of Oxy-Hb recruitment across the PFC during the restoration break (left) and the design task (right).

Table 20.

Summary of regions with highest degree centrality during the design task, as well as their associated cognitive functions.

Decile	Active Control; Subregions of PFC with central channels (Channel and node degree centrality value)	Control; Subregions of PFC with central channels (Channel and node degree centrality value)	Intervention; Subregions of PFC with central channels (Channel and node degree centrality value)
1	(channel 22; 0.1064)	(channels 26 and 31; 0.1277)	(channels 26 and 27; 0.0851)
2	(channel 24; 0.1702)	(channels 22 and 25; 0.2128)	(channels 6, 7, and 12; 0.0426)
3	(channel 22; 0.1489)	(channel 22; 0.2128)	(channel 22; 0.1702)
4	(channel 22; 0.2340)	(channel 22; 0.2340)	(channel 26; 0.1702)
5	(channels 22 and 26; 0.0851)	(channel 23; 0.1277)	(channels 26 and 32; 0.0851)
6	(channel 22; 0.1915)	(channels 22 and 41; 0.0851)	(channel 26; 0.1915)
7	(channel 24; 0.1489)	(channel 26, 0.1489)	(channel 26; 0.0851)
8	(channels 21 and 27; 0.1064)	(channels 21, 23, and 26; 0.0638)	(channels 22, 23, 26, 27, and 31; 0.0638)
9	(channels 21 and 32; 0.0851)	(channel 26, 0.1277)	(channel 27; 0.1277)
10	(channel 27; 0.0426)	(channels 25 and 26; 0.0638)	(channels 26, 27, 28, 30, 31, and 41; 0.0213)

Note. Group: A – Active Control; C – Control; I – Intervention.

Table 21.

Network density for each group during the Design Task. The network density score goes from 0 to 1. The higher the number of edges (i.e. correlations between channels), the higher the density. Outliers within groups were removed from analysis using the IQR method.

Measure	Decile	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
Brain Netork Density	1	A	31	0.1150	0.0659	0.0124	0.1472	0.1957	0.9298	0.3984
		C	31	0.1375	0.0679	0.0222	0.3209	0.4604		
		I	30	0.1310	0.0665	0.0071	0.2819	0.7488		
	2	A	31	0.1254	0.0733	0.0337	0.3138	0.0215	3.1361	0.2084
		C	30	0.1257	0.0540	0.0115	0.2119	0.4411		
		I	31	0.1693	0.1081	0.0231	0.4468	0.0067		
	3	A	31	0.1249	0.0862	0.0204	0.3200	0.0097	0.2585	0.8788
		C	32	0.1301	0.0757	0.0204	0.3236	0.1164		
		I	29	0.1204	0.0619	0.0195	0.2695	0.6696		
	4	A	29	0.1126	0.0533	0.0363	0.2243	0.1692	2.9113	0.2333
		C	32	0.1381	0.0848	0.0124	0.3404	0.2462		
		I	31	0.1586	0.0950	0.0160	0.3546	0.0090		
	5	A	27	0.0834	0.0378	0.0301	0.2030	0.0028	6.4546	**0.0397***
		C	29	0.0983	0.0510	0.0142	0.1809	0.0774		
		I	29	0.1267	0.0654	0.0319	0.2544	0.2116		
	6	A	31	0.1237	0.0914	0.0168	0.3892	0.0017	1.7314	0.4208
		C	31	0.1198	0.0609	0.0133	0.2491	0.0524		
		I	29	0.1420	0.0854	0.0363	0.3608	0.0125		
	7	A	28	0.0929	0.0436	0.0177	0.2163	0.2588	4.7360	0.0937

	C	30	0.1171	0.0715	0.0124	0.2784	0.2435		
	I	30	0.1466	0.0900	0.0222	0.3369	0.0270		
8	A	30	0.1054	0.0590	0.0301	0.2722	0.0099	7.3308	**0.0256***
	C	31	0.1060	0.0586	0.0053	0.2323	0.5394		
	I	31	0.1569	0.0867	0.0363	0.3537	0.1111		
9	A	30	0.0963	0.0563	0.0160	0.2252	0.0718	2.9613	0.2275
	C	31	0.1185	0.0720	0.0124	0.3209	0.1500		
	I	32	0.1421	0.0989	0.0231	0.3715	0.0008		
10	A	30	0.0831	0.0431	0.0080	0.1764	0.0538	1.7861	0.4094
	C	31	0.1028	0.0600	0.0204	0.2331	0.0684		
	I	30	0.1050	0.0629	0.0160	0.2748	0.0232		

Note. Group: A – Active Control; C – Control; I – Intervention. S-W *p* – Shapiro-Wilk *p*-value.

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the 5th decile, the mean network density for the Intervention group was significantly higher than the Active Control group ($p = 0.0121$), with a large effect size (Cohen's $d = 0.8032$). However, although also having a higher score, the Intervention group did not significantly differ from the Control group ($p = 0.1398$).

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the 8th decile, the mean network density for the Intervention group was significantly higher than both the Active Control group ($p = 0.0267$, Cohen's $d = 0.6919$) and the Control group ($p = 0.0267$, Cohen's $d = 0.6868$), with medium to large effect sizes.

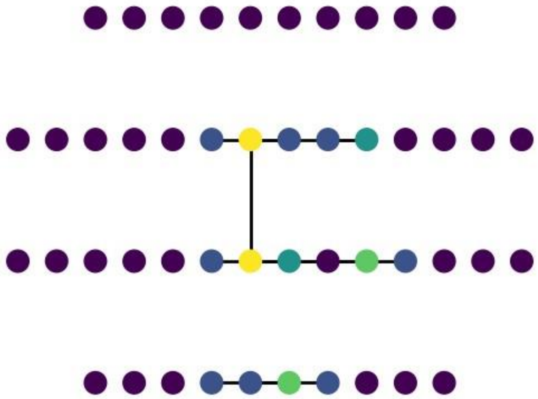


Fig. 11. Functional connectivity in the PFC during the 5th decile of the design task for the active control group.

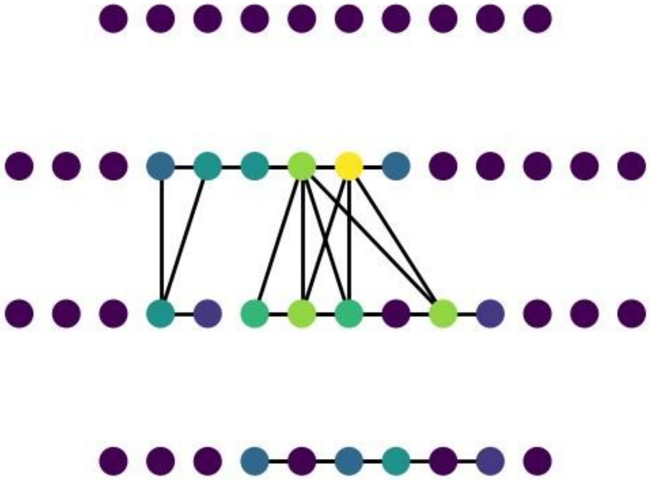


Fig. 12. Functional connectivity in the PFC during the 5th decile of the design task for the control group.

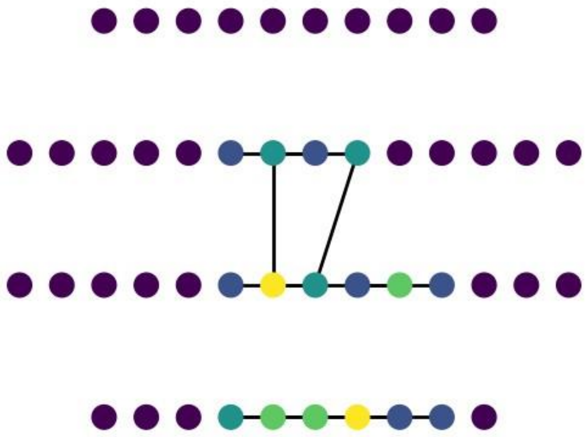


Fig. 13. Functional connectivity in the PFC during the 5th decile of the design task for the intervention group.

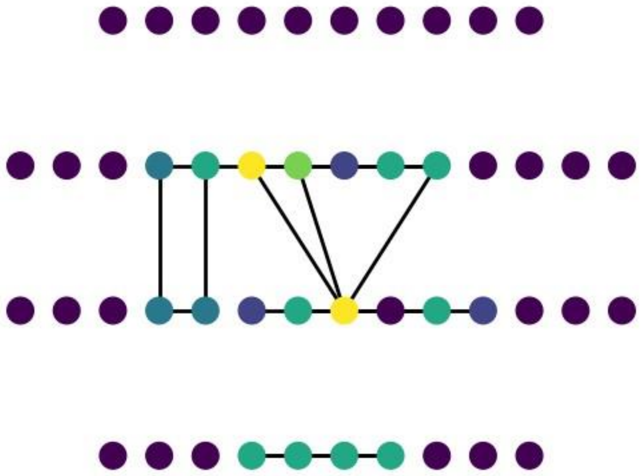


Fig. 14. Functional connectivity in the PFC during the 8th decile of the design task for the active control group.

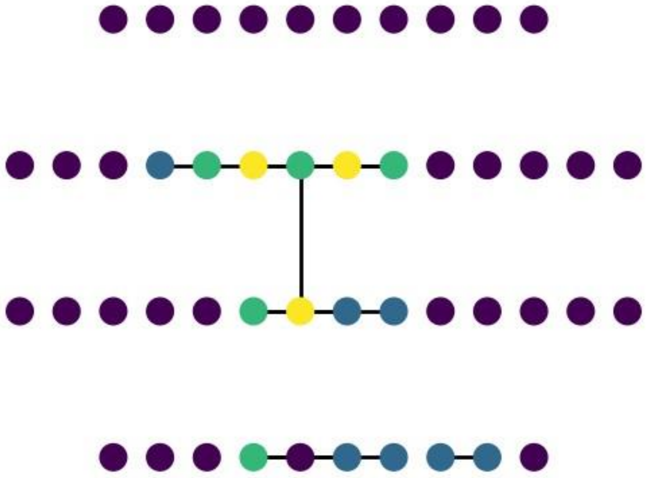


Fig. 15. Functional connectivity in the PFC during the 8th decile of the design task for the control group.

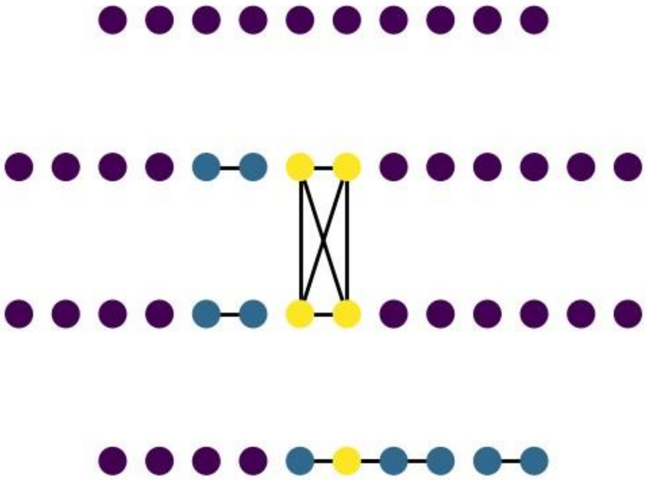


Fig. 16. Functional connectivity in the PFC during the 8th decile of the design task for the intervention group.

Table 22.

Linear mixed effects model results. A random intercept for participants was included to account for individual differences and repeated measures.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
SS AW DE	C (intercept)	0.301	0.001	210.971	0.000	(0.298, 0.303)
	A	0.004	0.005	0.894	0.371	(-0.005, 0.014)
	I	0.003	0.005	0.507	0.612	(-0.007, 0.012)

Note. Measure: SS AW DE: Semantic Similarity between all word used in the design explanation; Group: A – Active Control; C – Control; I – Intervention; Std. Err. – Standard Error; CI – Confidence Interval

Table 23.

Linear mixed effects model results. Adjusted for age, gender, native language, and caffeine consumption within two hours of the experiment. The model indicates that caffeine consumption and being a non-native English speaker had a significant influence on the dependent variable (semantic similarity between all word used in the design explanation).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
SS AW DE	C (intercept)	0.309	0.002	203.887	0.000	(0.306, 0.312)
	A	0.003	0.006	0.492	0.623	(-0.008, 0.014)
	I	0.006	0.006	0.996	0.319	(-0.005, 0.021)
	NN English	0.011	0.005	2.120	**0.034***	(0.001, 0.021)
	Caffeine	-0.013	0.006	-2.180	**0.029***	(-0.024, -0.001)

Table 24.

Linear mixed effects model results. A random intercept for participants was included to account for individual differences and repeated measures.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
SS AW DE ONJ	C (intercept)	0.272	0.001	213.661	0.000	(0.269, 0.274)
	A	0.001	0.003	0.346	0.730	(-0.004, 0.006)
	I	0.003	0.005	0.619	0.536	(-0.006, 0.012)

Note. Measure: SS AW DE ONJ: Semantic Similarity between all word used in the design explanation (counting only nouns and adjectives); Group: A – Active Control; C – Control; I – Intervention; Std. Err. – Standard Error; CI – Confidence Interval

Table 25.

Linear mixed effects model results. Adjusted for age, gender, native language, and caffeine consumption within two hours of the experiment. The model indicates that age and being a non-native English speaker had a significant influence on the dependent variable (semantic similarity between all word used in the design explanation).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
SS AW DE	C (intercept)	0.279	0.007	39.049	0.000	(0.265, 0.293)
	A	-0.000	0.006	-0.001	0.999	(-0.011, 0.011)
	I	0.006	0.006	0.972	0.331	(-0.006, 0.017)
	NN English	0.013	0.005	2.598	**0.009***	(0.003, 0.023)
	Age	-0.000	0.000	-3.152	**0.002***	(-0.000, -0.000)

Table 26.

Linear mixed effects model results. A random intercept for participants was included to account for individual differences and repeated measures.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
SS N DE	C (intercept)	0.300	0.001	222.802	0.000	(0.298, 0.303)
	A	-0.001	0.004	-0.132	0.895	(-0.009, 0.008)
	I	-0.001	0.004	-0.321	0.749	(-0.009, 0.006)

Note. Measure: SS N DE: Semantic Similarity to the word “nature” in the design explanation; Group: A – Active Control; C – Control; I – Intervention; Std. Err. – Standard Error; CI – Confidence Interval

Table 27.

Linear mixed effects model results. Adjusted for age, gender, native language, and caffeine consumption within two hours of the experiment. The model indicates that being a non-native English speaker had a significant influence on the dependent variable (semantic similarity to the word "nature" in the design explanation).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
SS AW DE	C (intercept)	0.284	0.013	21.943	0.000	(0.259, 0.310)
	A	-0.001	0.005	-0.134	0.893	(-0.009, 0.008)
	I	0.002	0.005	0.480	0.631	(-0.007, 0.011)
	NN English	0.011	0.005	2.273	**0.023***	(0.001, 0.020)

Table 28.

Linear mixed effects model results. A random intercept for participants was included to account for individual differences and repeated measures.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
SS N DE ON	C (intercept)	0.290	0.001	413.679	0.000	(0.289, 0.292)
	A	0.001	0.005	0.287	0.774	(-0.008, 0.010)
	I	-0.003	0.004	-0.731	0.465	(-0.010, 0.005)

Note. Measure: SS N DE ON: Semantic Similarity to the word "nature" in the design explanation (considering only nouns); Group: A – Active Control; C – Control; I – Intervention; Std. Err. – Standard Error; CI – Confidence Interval

Table 29.

Linear mixed effects model results. Adjusted for age, gender, native language, and caffeine consumption within two hours of the experiment. The model indicates that age and being a non-native English speaker had a significant influence on the dependent variable (semantic similarity to the word "nature" in the design explanation).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
SS AW DE ON	C (intercept)	0.269	0.002	128.911	0.000	(0.265, 0.273)
	A	0.000	0.006	0.050	0.960	(-0.011, 0.011)
	I	0.000	0.006	0.031	0.975	(-0.011, 0.011)
	NN English	0.015	0.005	2.703	**0.007***	(0.004, 0.025)
	Age	0.001	0.000	3.435	**0.001***	(0.000, 0.001)

Table 30.

Linear mixed effects model results. A random intercept for participants was included to account for individual differences and repeated measures.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
DSI	C (intercept)	0.816	0.001	784.939	0.000	(0.814, 0.818)
	A	-0.001	0.001	-0.551	0.582	(-0.004, 0.002)
	I	-0.000	0.001	-0.202	0.840	(-0.003, 0.003)

Note. Measure: DSI: Divergent Semantic Integration score for the combination of design explanation and design process; Group: A – Active Control; C – Control; I – Intervention; Std. Err. – Standard Error; CI – Confidence Interval

Table 31.

Linear mixed effects model results. Adjusted for age, gender, native language, and caffeine consumption within two hours of the experiment. The model indicates that age and being a non-native English speaker had a significant influence on the dependent variable (semantic similarity to the word "nature" in the design explanation).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
DSI	C (intercept)	0.814	0.004	197.744	0.000	(0.805, 0.822)
	A	-0.001	0.001	-0.423	0.672	(-0.003, 0.002)
	I	-0.001	0.001	-0.608	0.543	(-0.004, 0.002)
	NN English	-0.004	0.001	-2.739	**0.006***	(-0.007, -0.001)
	Male*	0.004	0.001	2.520	**0.012***	(0.001, 0.007)

Table 32.

Linear mixed effects model results. A random intercept for participants was included to account for individual differences and repeated measures.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Design time	C (intercept)	12.356	0.173	71.494	0.000	(12.018, 12.695)
	A	-0.553	1.054	-0.525	0.599	(-2.619, 1.512)
	I	-2.227	0.841	-2.649	**0.008***	(-3.875, -0.579)

Note. Group: A – Active Control; C – Control; I – Intervention; Std. Err. – Standard Error; CI – Confidence Interval

Table 33.

Linear mixed effects model results. Adjusted for age, gender, native language, and caffeine consumption within two hours of the experiment. The model indicates that age had a significant influence on the dependent variable (time designing).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Design time	C (intercept)	21.207	2.151	9.861	0.000	(16.992, 25.423)
	A	-0.900	1.361	-0.661	0.509	(-3.568, 1.768)
	I	-2.608	1.389	-1.877	0.060	(-5.330, 0.115)
	Age	-0.424	0.063	-6.704	**0.000***	(-0.548, -0.300)

Table 34.

Linear mixed effects model results. A random intercept for participants was included to account for individual differences and repeated measures.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Network Density (TSST)	C (intercept)	0.052	0.002	21.792	0.000	(0.047, 0.057)
	A	-0.000	0.008	-0.051	0.960	(-0.016, 0.015)
	I	0.017	0.005	3.381	**0.001***	(0.007, 0.027)

Note. Group: A – Active Control; C – Control; I – Intervention; Std. Err. – Standard Error; CI – Confidence Interval

Table 35.

Linear mixed effects model results. Adjusted for age, gender, and caffeine consumption within two hours of the experiment. The model indicates that none of the potential confounders had a significant influence on the dependent variable (network density during the TSST).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Network Density (TSST)	C (intercept)	0.057	0.032	1.788	0.074	(-0.005, 0.120)
	A	0.001	0.012	0.069	0.945	(-0.022, 0.024)
	I	0.018	0.012	1.585	0.113	(-0.004, 0.041)

Table 36.

Linear mixed effects model results. A random intercept for participants was included to account for individual differences and repeated measures.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Network Density (Rest)	C (intercept)	0.096	0.006	16.968	0.000	(0.085, 0.107)
	A	-0.023	0.014	-1.631	0.103	(-0.051, 0.005)
	I	0.026	0.014	1.867	0.062	(-0.001, 0.053)

Note. Group: A – Active Control; C – Control; I – Intervention; Std. Err. – Standard Error; CI – Confidence Interval

Table 37.

Linear mixed effects model results. Adjusted for age, gender, and caffeine consumption within two hours of the experiment. The model indicates that none of the potential confounders had a significant influence on the dependent variable (network density during the TSST), but the intervention (biophilic auditory experience) did.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Network Density (Rest)	C (intercept)	0.070	0.041	1.698	0.090	(-0.011, 0.151)
	A	-0.022	0.015	-1.399	0.162	(-0.052, 0.009)
	I	0.033	0.015	2.145	**0.032***	(0.003, 0.063)

Table 38.

Linear mixed effects model results. A random intercept for participants was included to account for individual differences and repeated measures.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Network Density (Task)	C (intercept)	0.091	0.013	7.052	0.000	(0.066, 0.116)
	A	-0.008	0.018	-0.422	0.673	(-0.043, 0.028)
	I	-0.007	0.018	-0.404	0.686	(-0.043, 0.028)

Note. Group: A – Active Control; C – Control; I – Intervention; Std. Err. – Standard Error; CI – Confidence Interval

Table 39.

Linear mixed effects model results. Adjusted for age, gender, and caffeine consumption within two hours of the experiment. The model indicates that none of the potential confounders had a significant influence on the dependent variable (network density during the TSST), but the intervention (biophilic auditory experience) did.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Network Density (Task)	C (intercept)	0.031	0.050	0.616	0.538	(-0.067, 0.129)
	A	-0.008	0.019	-0.437	0.662	(-0.045, 0.028)
	I	-0.004	0.019	-0.237	0.813	(-0.041, 0.032)

Table 40.

Linear mixed effects model results. A random intercept for participants was included to account for individual differences and repeated measures.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Network Density Task (5th decile)	C (intercept)	0.098	0.004	26.342	0.000	(0.091, 0.106)
	A	-0.015	0.010	-1.524	0.128	(-0.034, 0.004)
	I	0.028	0.006	4.926	**0.000***	(0.017, 0.040)

Note. Group: A – Active Control; C – Control; I – Intervention; Std. Err. – Standard Error; CI – Confidence Interval

Table 41.

Linear mixed effects model results. Adjusted for age, gender, and caffeine consumption within two hours of the experiment. The model indicates that age had a significant influence on the dependent variable (network density during the 5th decile of the design task), but so did the intervention (biophilic auditory experience).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Network Density Task (5th decile)	C (intercept)	0.027	0.008	3.407	0.001	(0.011, 0.042)
	A	-0.013	0.014	-0.900	0.368	(-0.040, 0.015)
	I	0.031	0.014	2.256	**0.024***	(0.004, 0.058)
	Age	0.003	0.000	9.761	**0.000***	(0.003, 0.004)

Table 42.

Linear mixed effects model results. A random intercept for participants was included to account for individual differences and repeated measures.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Network Density Task (8th decile)	C (intercept)	0.106	0.003	33.651	0.000	(0.100, 0.112)
	A	-0.001	0.010	-0.067	0.947	(-0.020, 0.019)
	I	0.051	0.011	4.601	**0.000***	(0.029, 0.072)

Note. Group: A – Active Control; C – Control; I – Intervention; Std. Err. – Standard Error; CI – Confidence Interval

Table 43.

Linear mixed effects model results. Adjusted for age, gender, and caffeine consumption within two hours of the experiment. The model indicates that age had a significant influence on the dependent variable (network density during the 5th decile of the design task), but so did the intervention (biophilic auditory experience).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Network Density Task (8th decile)	C (intercept)	0.052	0.017	2.980	0.003	(0.018, 0.086)
	A	0.002	0.017	0.118	0.906	(-0.031, 0.034)
	I	0.051	0.017	3.055	**0.002***	(0.018, 0.083)
	Age	0.003	0.001	3.001	**0.003***	(0.001, 0.005)

Appendix C – Supporting data for Chapter 4

Table 1.

Baseline stress level.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
Baseline Stress	C	32	1.50	0.72	0	3	< 0.01	9.612	0.022
	A	32	1.53	1.22	0	4	< 0.01		
	V	29	1.00	1.20	0	4	< 0.01		
	M	29	1.79	0.98	0	4	0.02		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.

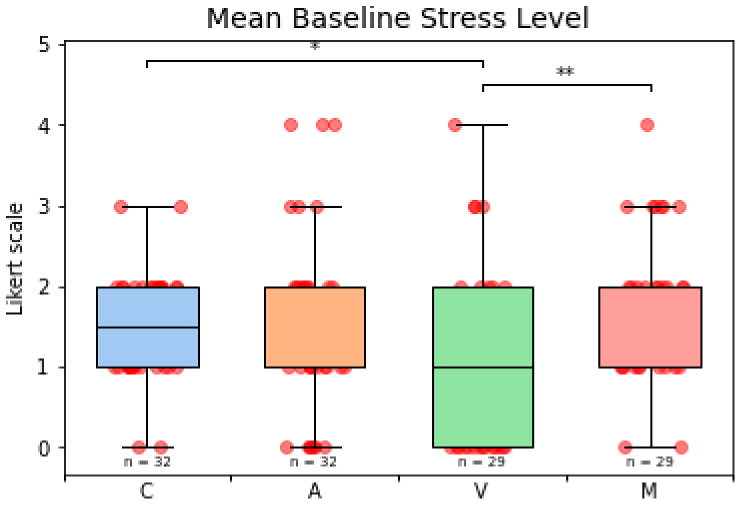


Table 2.

Stress post-TSST.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
Stress post-TSST	C	32	3.81	0.82	2	5	< 0.01	2.336	0.506
	A	32	3.72	0.85	1	5	< 0.01		
	V	29	3.45	1.12	1	5	< 0.01		

	M	29	3.51	0.83	1	5	< 0.01		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.

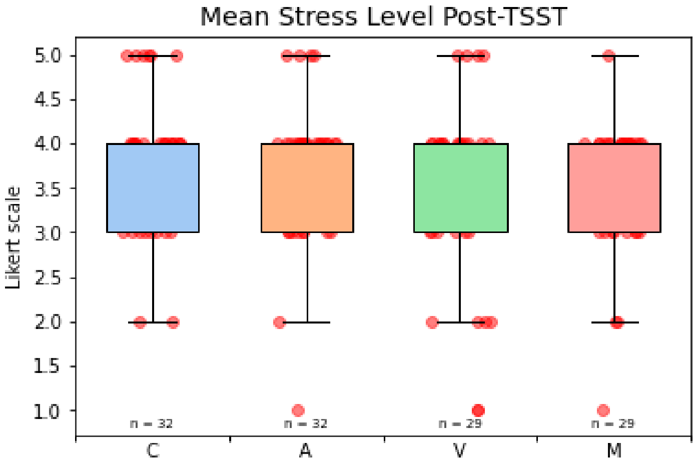


Table 3.

Relaxation level post restoration break.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
Relaxation Level	C	32	3.63	1.24	1	5	< 0.01	1.197	0.754
	I	32	3.63	1.01	1	5	< 0.01		
	V	29	3.65	1.23	1	5	< 0.01		
	M	29	3.48	1.06	1	5	< 0.01		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.

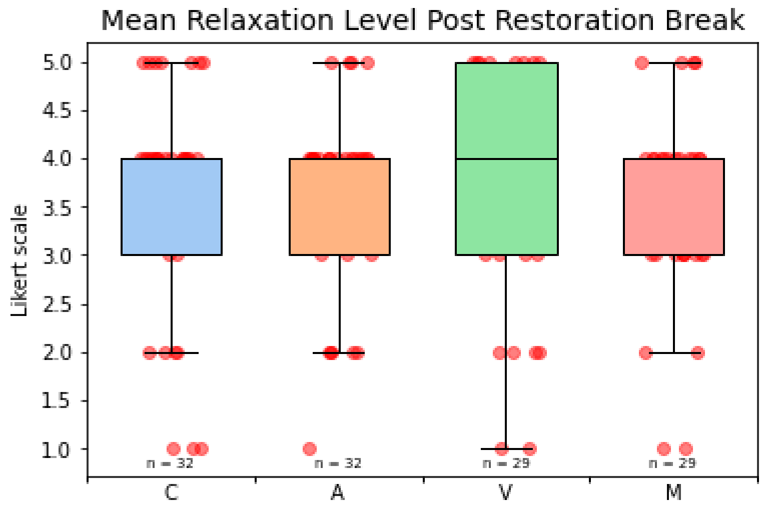


Table 4.

Mental demand associated with the design task.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
Mental Demand	C	32	2.09	0.96	0	4	< 0.01	2.219	0.528
	I	32	2.16	0.95	0	4	< 0.01		
	V	29	1.83	0.97	0	3	< 0.01		
	M	29	1.83	0.89	0	3	< 0.01		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.

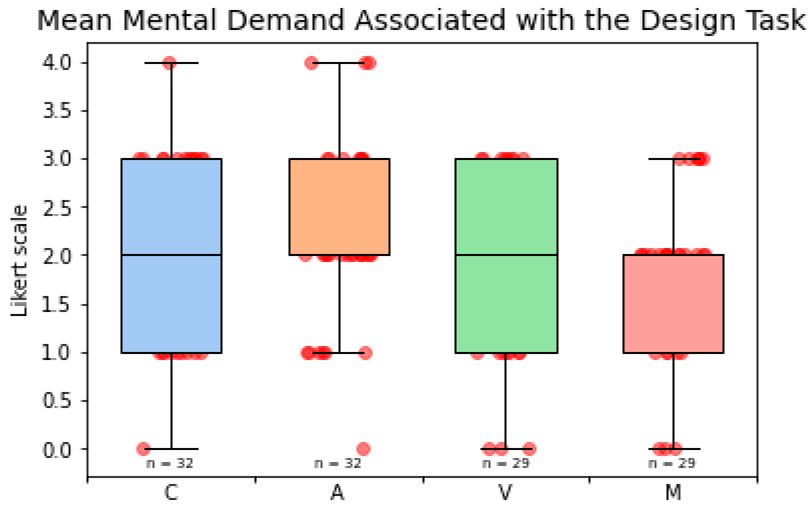


Table 5.

Linear mixed effects model results. Adjusted for age, gender, time of day, and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Relaxation Level	C (intercept)	2.868	0.513	5.589	0.000	(1.862, 3.874)
	A	0.068	0.285	0.238	0.812	(-0.491, 0.627)
	M	-0.154	0.290	-0.533	0.594	(-0.723, 0.414)
	V	-0.029	0.290	-0.101	0.920	(-0.597, 0.539)
	Transman	-2.616	1.154	-2.267	**0.023***	(-4.878, -0.355)

Table 6.

Linear mixed effects model results. Adjusted for age, gender, time of day, and design experience. The model indicates that age had a significant main effect on the dependent variable (mental demand associated with the design task). Given most participants mentioned trying to go back in their memories to think of what they used to like in playgrounds as a kid, perhaps retrieving older memories made the task more mentally demanding to older participants.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Mental Demand	C (intercept)	0.675	0.492	1.371	0.170	(-0.290, 1.640)
	A	0.142	0.187	0.761	0.447	(-0.224, 0.508)
	M	-0.235	0.213	-1.105	0.269	(-0.652, 0.182)
	V	-0.075	0.224	-1.227	0.220	(-0.713, 0.164)
	Age	0.060	0.024	2.475	**0.013***	(0.012, 0.108)

Table 7.

Linear mixed effects model results. Adjusted for age, gender, time of day, baseline connectedness to nature, and relaxation level post restoration break. The model indicates that age and baseline connectedness to nature had a significant main effect on the dependent variable (connectedness to nature post-experiment).

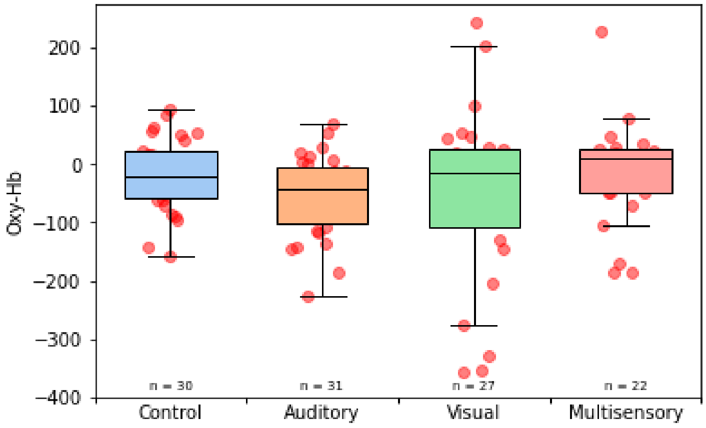
Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
NR-6 post	C (intercept)	-0.282	0.365	-0.773	0.440	(-0.998, 0.433)
	A	-0.058	0.121	-0.478	0.633	(-0.296, 0.180)
	M	0.045	0.124	0.359	0.720	(-0.199, 0.288)
	V	0.081	0.123	0.655	0.513	(-0.161, 0.322)
	Age	0.027	0.013	2.118	**0.034***	(0.002, 0.052)
	NR-6 (pre)	0.866	0.067	12.996	< **0.01***	(0.736, 0.997)

Table 8.

Mean Oxy-Hb concentration in the rVLPFC during the restoration break.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
rVLPFC (rest)	C	30	-18.54	62.68	-157.94	95.71	0.920	4.292	0.232
	I	31	-53.16	69.27	-225.44	70.10	0.651		
	V	27	-46.76	151.29	-357.92	244.99	0.029		
	M	22	-16.27	92.49	-186.30	226.50	0.054		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.



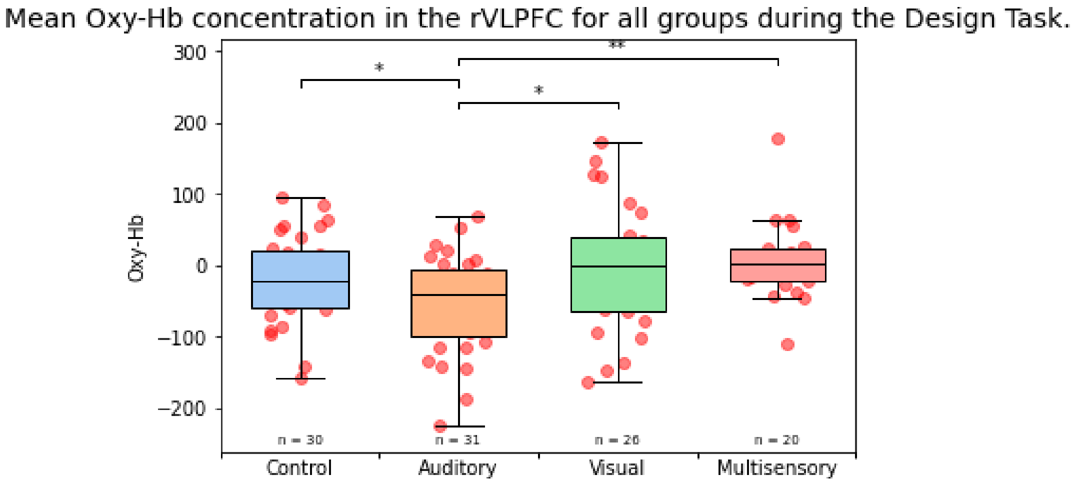
Mean Oxy-Hb concentration in the rVLPFC for all groups during the Restoration Break.

Table 9.

Mean Oxy-Hb concentration in the rVLPFC during the design task.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
rVLPFC (task)	C	30	-18.54	62.68	-157.94	95.71	0.920	1.020	0.387
	I	31	-53.16	69.27	-225.44	70.10	0.651		
	V	26	-4.04	90.19	-162.33	173.29	0.800		
	M	20	5.83	57.67	-109.85	178.07	0.054		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.



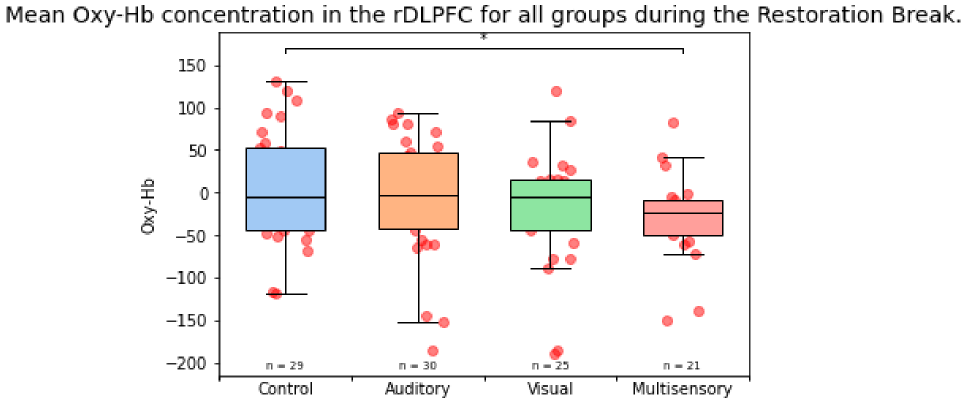
Mean Oxy-Hb concentration in the rVLPFC for all groups during the Design Task.

Table 10.

Mean Oxy-Hb concentration in the rDLPFC during the restoration break.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
rDLPFC (rest)	C	29	7.44	65.69	-117.81	130.06	0.640	1.478	0.225
	I	30	-7.56	70.26	-185.39	93.42	0.084		
	V	25	-19.62	9.53	-189.63	120.49	0.066		
	M	21	-29.28	52.14	-149.17	83.17	0.131		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.



Mean Oxy-Hb concentration in the rDLPFC for all groups during the Restoration Break.

Table 11.

Mean Oxy-Hb concentration in the rDLPFC during the design task.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
rDLPFC (task)	C	28	2.06	33.49	-71.20	74.93	0.168	0.795	0.499
	I	25	-0.10	52.25	-103.87	138.31	0.662		
	V	26	14.16	46.33	-63.74	114.41	0.679		
	M	25	14.14	40.99	-73.44	102.24	0.154		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.

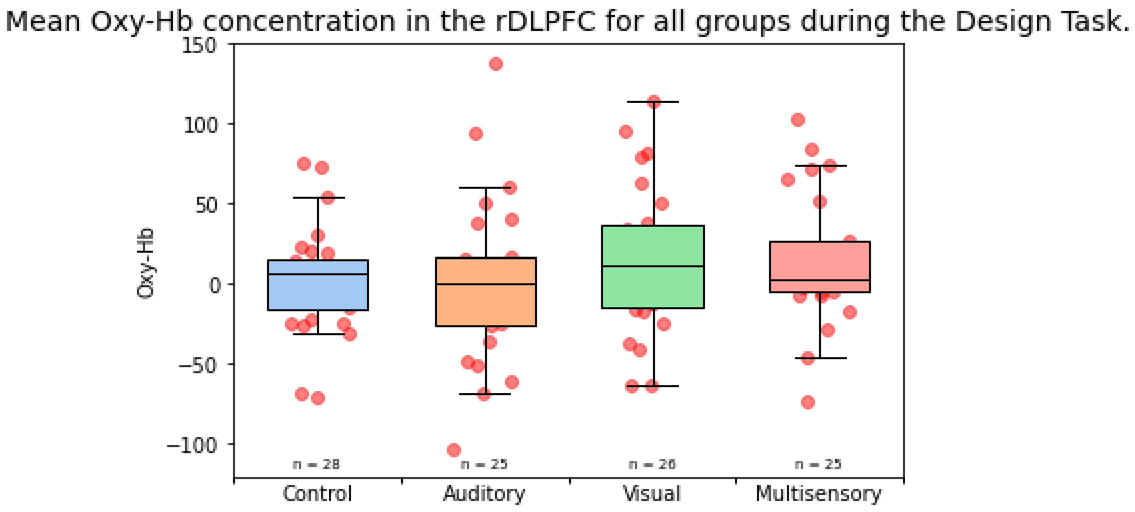


Table 12.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI

rVLPFC (rest)	C (intercept)	-135.679	102.628	-1.322	0.186	(-423.179, 151.881)
	A	-49.843	50.086	-0.995	0.320	(-148.819, 49.171)
	M	-35.358	52.152	-0.678	0.498	(-136.712, 66.372)
	V	-23.948	52.173	-0.450	0.652	(-125.593, 78.493)
	Age	3.154	1.430	2.206	**0.027***	(0.352, 5.957)

Table 13.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rVLPFC (task)	C (intercept)	176.173	126.344	1.394	0.163	(-71.457, 423.803)
	A	-50.271	55.541	-0.905	0.365	(-159.130, 58.588)
	M	-46.441	57.366	-0.810	0.418	(-158.876, 65.994)
	V	35.267	58.742	0.600	0.548	(-79.866, 150.399)

Table 14.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
lVLPFC (rest)	C (intercept)	-119.379	140.881	-0.847	0.397	(-395.500, 156.743)
	A	34.616	53.514	0.647	0.518	(-70.269, 139.502)

	M	10.860	54.744	0.198	0.843	(-96.435, 118.156)
	V	79.245	52.703	1.504	0.133	(-24.051, 182.54)
	Male	136.221	39.427	3.455	**0.001***	(58.945, 213.497)

Table 15.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
lVLPFC (task)	C (intercept)	-120.859	128.724	-0.939	0.348	(-373.154, 131.436)
	A	10.473	45.021	0.233	0.816	(-77.767, 98.714)
	M	-14.518	45.790	-0.317	0.751	(-104.265, 75.228)
	V	-11.957	46.988	-0.254	0.799	(-104.052, 80.138)

Table 16.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rDLPFC (rest)	C (intercept)	137.224	89.326	1.536	0.124	(-37.852, 312.300)
	A	-45.650	35.645	-1.281	0.200	(-115.512, 24.212)
	M	-57.287	37.238	-1.538	0.124	(-130.273, 15.699)
	V	-56.693	37.712	-1.503	0.133	(-130.607, 17.221)
	Stress (pre)	24.539	12.296	1.996	**0.046***	(0.440, 48.638)
	NR-6 (pre)	-35.780	12.085	-2.961	**0.003***	(-59.465, -12.095)

Table 17.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rDLPFC (task)	C (intercept)	22.659	43.747	0.518	0.604	(-63.083, 108.402)
	A	-7.149	23.921	-0.299	0.765	(-54.032, 39.735)
	M	14.786	24.700	0.599	0.549	(-33.625, 63.198)
	V	4.232	25.416	0.166	0.868	(-45.582, 54.046)

Table 18.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
lDLPFC (rest)	C (intercept)	-96.915	121.918	-0.795	0.427	(-335.870, 142.041)
	A	-6.004	43.084	-0.139	0.889	(-90.447, 78.440)
	M	-81.809	44.406	-1.842	0.065	(-168.844, 5.226)
	V	-62.554	44.727	-1.399	0.162	(-150.216, 25.108)
	NR-6 (pre)	26.922	9.353	2.879	**0.004***	(8.591, 45.253)

Table 19.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
lDLPFC (task)	C (intercept)	31.705	61.326	0.605	0.605	(-88.492, 151.902)
	A	-31.244	28.023	-1.115	0.265	(-86.167, 23.680)
	M	19.198	29.169	0.658	0.510	(-37.972, 76.367)
	V	-6.062	29.917	-0.203	0.839	(-64.698, 52.573)

Table 20.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rDMPFC (rest)	C (intercept)	75.726	42.781	1.770	0.077	(-8.124, 159.576)
	A	-2.079	37.341	-0.056	0.956	(-75.266, 71.107)
	M	-4.696	38.400	-0.122	0.903	(-79.958, 70.566)
	V	8.075	39.784	0.203	0.839	(-69.900, 86.050)

Table 21.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rDMPFC (task)	C (intercept)	-12.226	95.369	-0.128	0.898	(-199.145, 174.694)

	A	-4.611	33.617	-0.137	0.891	(-70.498, 61.277)
	M	10.310	34.334	0.300	0.764	(-56.984, 77.603)
	V	-24.308	35.412	-0.686	0.492	(-93.713, 45.098)

Table 22.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
lDMPFC (rest)	C (intercept)	-217.192	109.612	-1.981	0.048	(-432.028, -2.356)
	A	5.941	37.732	0.157	0.875	(-68.012, 79.894)
	M	72.307	38.867	1.860	0.063	(-3.870, 148.484)
	V	43.639	39.635	1.101	0.271	(-34.044, 121.322)
	NR-6 (pre)	39.262	11.123	3.530	**0.000***	(17.461, 61.063)

Table 23.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
lDMPFC (task)	C (intercept)	36.010	82.128	0.438	0.661	(-124.959, 196.979)
	A	6.676	28.559	0.234	0.815	(-49.298, 62.650)
	M	27.661	29.551	0.936	0.349	(-30.258, 85.580)
	V	-3.933	30.115	-0.131	0.896	(-62.957, 55.092)

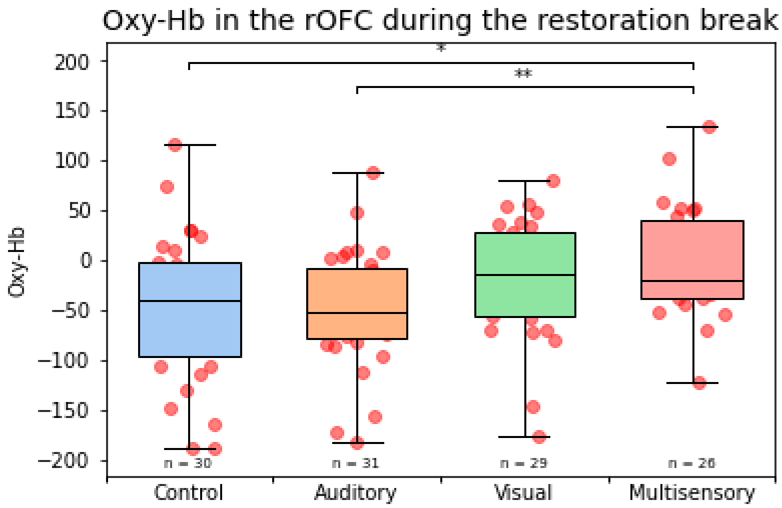


Table 24.

Mean Oxy-Hb concentration in the rDLPFC during the design task.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
rOFC (rest)	C	30	-46.95	73.58	-189.64	115.19	0.716	3.450	**0.019***
	I	31	-49.89	59.62	-183.90	88.51	0.505		
	V	29	-19.49	59.19	-177.08	80.18	0.281		
	M	26	-4.578	56.03	-123.19	133.48	0.170		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the restoration break, activity in the rOFC for the multisensory group was significantly higher than the auditory group (*p* = 0.029), with medium to large (Cohen's *d* = 0.781) effect size.

Table 25.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature. The model indicates that the visual and the multisensory group had significantly higher Oxy-Hb concentration in the rOFC during the rest period, even after controlling for confounders.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rOFC (rest)	C (intercept)	-172.333	60.804	-2.834	0.005	(-291.508, -53.159)
	A	28.948	22.009	1.315	0.188	(-14.189, 72.086)
	M	62.513	22.681	2.756	**0.006***	(18.060, 106.967)
	V	49.110	23.121	2.124	**0.034***	(3.794, 94.426)
	NR-6 (pre)	16.906	3.831	4.413	**0.000***	(9.397, 24.415)

Table 26.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rOFC (task)	C (intercept)	11.463	26.543	0.432	0.666	(-40.560, 63.487)
	A	-9.115	12.323	-0.740	0.459	(-33.268, 15.037)
	M	-7.374	12.939	-0.570	0.569	(-32.734, 17.986)
	V	-14.391	13.202	-1.090	0.276	(-40.267, 11.484)
	NR-6 (pre)	-12.389	3.162	-3.918	**0.000***	(-18.587, -6.192)

Table 27.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
lOFC (rest)	C (intercept)	-111.082	36.515	-3.042	0.002	(-182.649, -39.514)
	A	-8.556	20.389	-0.420	0.675	(-48.518, 31.406)
	M	9.700	21.219	0.457	0.648	(-31.890, 51.289)
	V	37.216	21.660	1.718	0.086	(-5.237, 79.670)

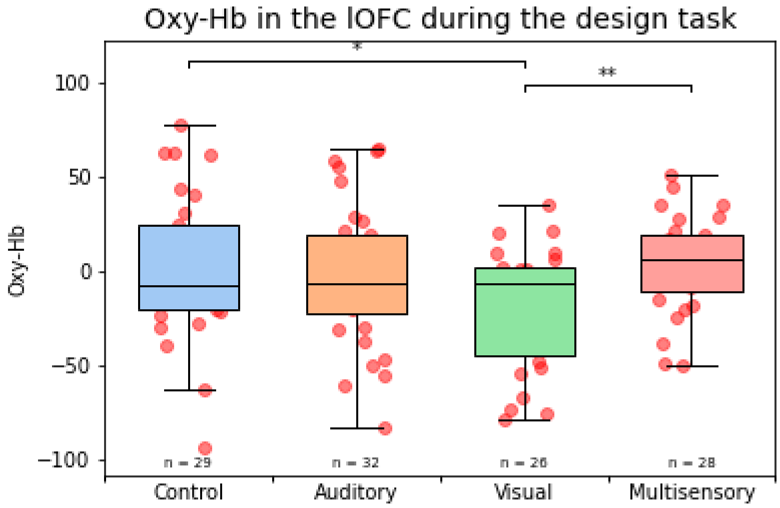


Table 28.

Mean Oxy-Hb concentration in the rDLPFC during the design task.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
lOFC (task)	C	29	2.40	38.83	-93.95	24.93	0.422	2.422	0.070
	I	32	-2.53	37.07	-82.44	64.61	0.658		
	V	26	-18.33	32.59	-79.02	35.54	0.057		
	M	28	4.34	25.76	-49.61	50.69	0.608		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.

Table 29.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
lOFC (task)	C (intercept)	-25.422	27.860	-0.913	0.361	(-80.026, 29.182)
	A	-0.575	11.230	-0.051	0.959	(-22.585, 21.434)
	M	6.049	11.504	0.526	0.599	(-16.499, 28.596)
	V	-24.342	12.157	-2.002	**0.045***	(-48.168, -0.515)

Table 30.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rFrontopolar (rest)	C (intercept)	-37.727	42.535	-0.887	0.375	(-121.093, 45.640)
	A	23.858	18.494	1.290	0.197	(-12.390, 60.106)
	M	23.610	19.325	1.222	0.222	(-14.266, 61.487)
	V	15.425	19.720	0.782	0.434	(-23.226, 54.076)

Table 31.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rFrontopolar (task)	C (intercept)	-14.446	24.771	-0.583	0.560	(-62.997, 34.105)
	A	4.521	9.504	0.476	0.634	(-14.107, 23.148)
	M	2.232	9.584	0.233	0.816	(-16.553, 21.017)
	V	-4.259	9.835	-0.433	0.665	(-23.535, 15.017)
	NR-6 (pre)	9.085	4.430	2.051	**0.040***	(0.403, 17.768)

Table 32.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
lFrontopolar (rest)	C (intercept)	-10.586	24.711	-0.428	0.668	(-59.020, 37.847)
	A	13.601	23.552	0.577	0.564	(-32.560, 59.762)
	M	42.858	24.468	1.752	0.080	(-5.098, 90.814)
	V	25.849	25.361	1.019	0.308	(-23.857, 75.556)

Table 33.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within 2 hours of the experiment, time of day, baseline stress level and baseline connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI

lFrontopolar (task)	C (intercept)	2.617	16.635	0.157	0.875	(-29.988, 35.222)
	A	-26.818	14.772	-1.816	0.069	(-55.770, 2.134)
	M	-11.909	15.363	-0.775	0.438	(-42.019, 18.202)
	V	-30.382	15.829	-1.919	0.055	(-61.406, 0.642)

Table 34.

Mean brain network density during the restoration break.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
Density (rest)	C	30	0.096	0.052	0.010	0.228	0.075	5.130	**0.002***
	A	30	0.122	0.075	0.011	0.283	0.167		
	M	27	0.082	0.053	0.010	0.207	0.090		
	V	27	0.064	0.046	0.004	0.192	0.064		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the restoration break, the mean network density for the auditory group was significantly higher than the visual group (*p* = 0.006), with a large effect size (Cohen's *d* = 0.928). No significant differences were found between other groups.

	C	I	M	V
C	1.000000	0.370211	0.380886	0.083883
I	0.370211	1.000000	0.098771	0.005638
M	0.380886	0.098771	1.000000	0.380886
V	0.083883	0.005638	0.380886	1.000000

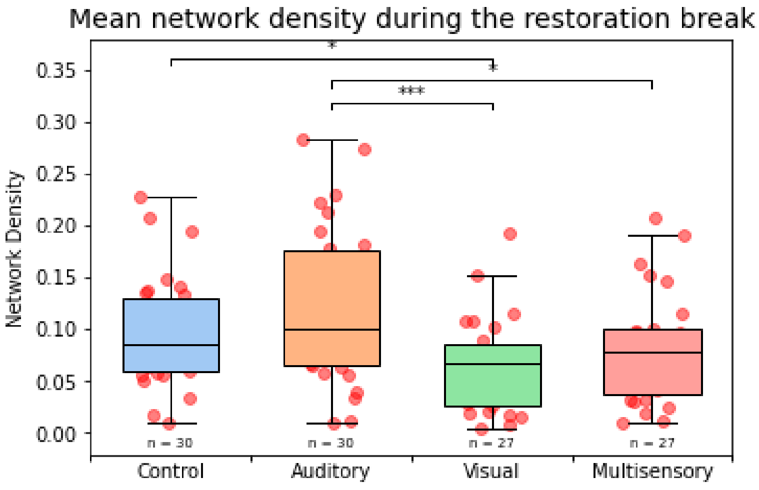
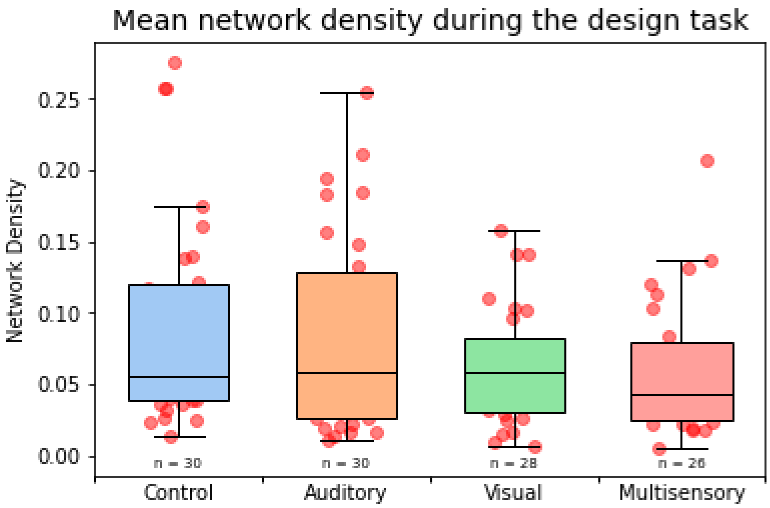


Table 35.

Mean brain network density during the design task.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
Density (task)	C	30	0.091	0.073	0.013	0.277	< 0.01	2.954	0.399
	A	30	0.084	0.070	0.011	0.255	< 0.01		
	M	26	0.060	0.048	0.004	0.207	< 0.01		
	V	28	0.063	0.041	0.006	0.159	0.095		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.



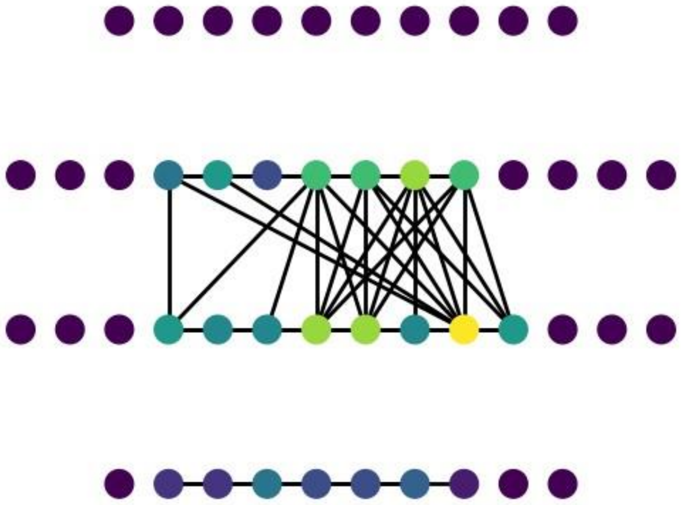


Fig. 1. Functional connectivity in the PFC during the restoration break for the control group.

For the control group, during the restoration break, the channels with the highest degree centrality were channels 41 (0.277), 24 (0.234), 26 (0.234), 27 (0.234), and 22 (0.191).

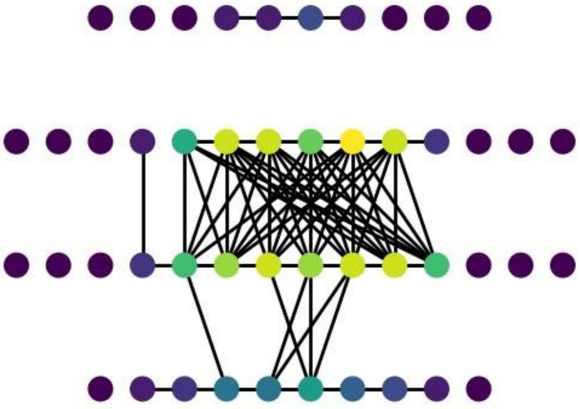


Fig. 2. Functional connectivity in the PFC during the restoration break for the intervention group.

For the intervention group, during the restoration break, the channels with the highest degree centrality were channels 24 (0.277), 21 (0.255), 22 (0.255), 26 (0.255), and 28 (0.255).

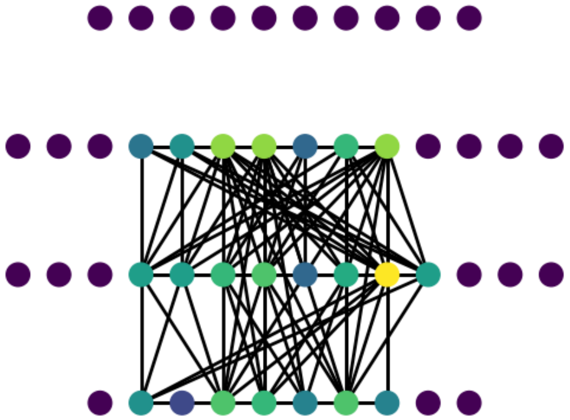


Fig. 3. Functional connectivity in the PFC during the restoration break for the visual group.

For the visual group, during the restoration break, the channels with the highest degree centrality were channels 41 (0.383), 21 (0.319), 22 (0.319), 36 (0.319), 26, 29, and 32 (0.277).

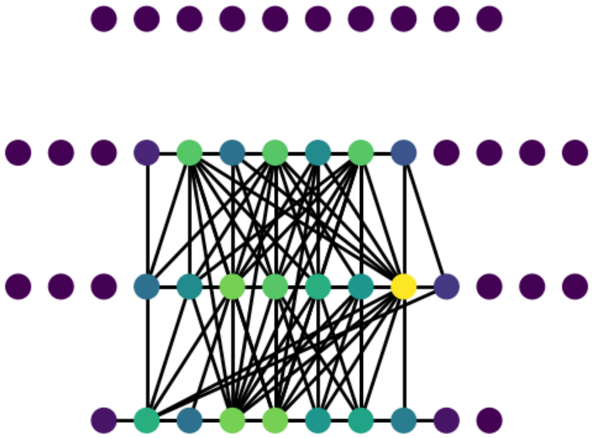


Fig. 4. Functional connectivity in the PFC during the restoration break for the multisensory group.

For the multisensory group, during the restoration break, the channels with the highest degree centrality were channels 41 (0.404), 25 (0.319), 29 (0.319), 30 (0.319), 8, 22, 24, and 26 (0.298).

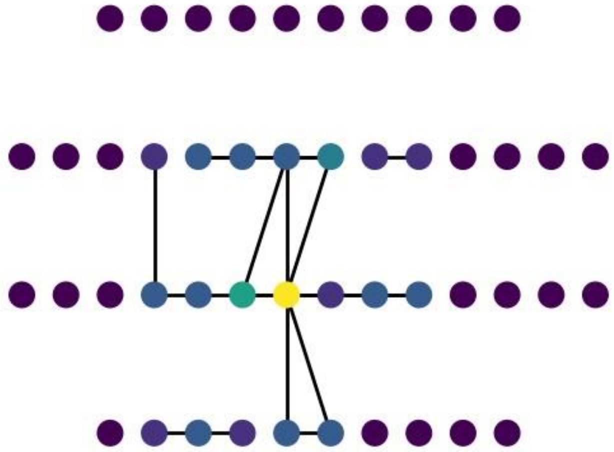


Fig. 5. Functional connectivity in the PFC during the design task for the control group.

For the control group, during the design task, the channels with the highest degree centrality were channels 26 (0.149), 25 (0.085), 23 (0.064), 8 (0.043), and 12 (0.043).

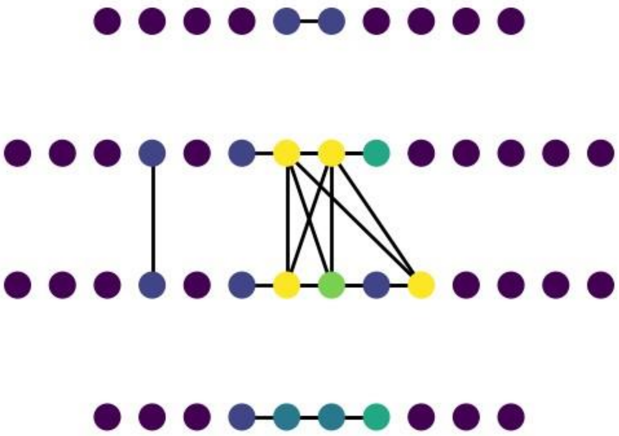


Fig. 6. Functional connectivity in the PFC during the design task for the intervention group.

For the intervention group, during the design task, the channels with the highest degree centrality were channels 22 (0.106), 23 (0.106), 26 (0.106), 41 (0.106), and 27 (0.085).

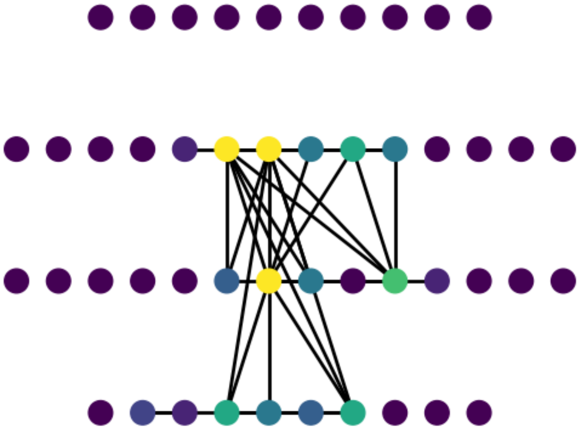


Fig. 7. Functional connectivity in the PFC during the design task for the visual group.

For the visual group, during the design task, the channels with the highest degree centrality were channels 21 (0.213), 22 (0.213), 26 (0.213), 41 (0.145), 24, 29, and 32 (0.128).

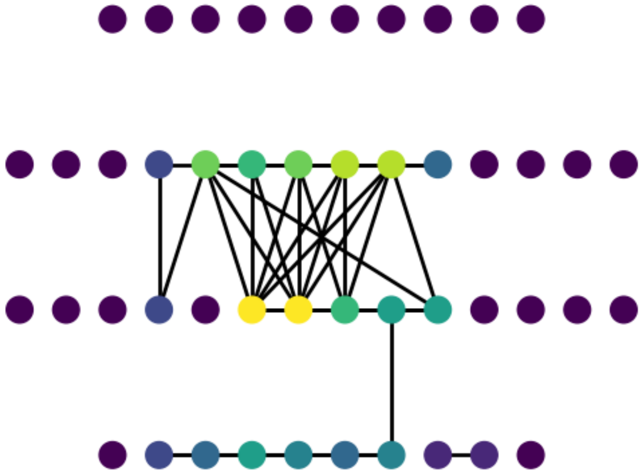


Fig. 8. Functional connectivity in the PFC during the design task for the multisensory group.

For the multisensory group, during the design task, the channels with the highest degree centrality were channels 25 (0.191), 26 (0.191), 23 (0.170), 24 (0.170), 8, and 22 (0.149).

Table 36.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within two hours of the experiment, baseline stress level and connectedness to nature. The model indicates that none of the potential confounders had a significant influence on the dependent variable (network density during the restoration break).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Network Density (rest)	C (intercept)	0.138	0.064	2.156	0.031	(0.012, 0.263)
	A	0.025	0.023	1.099	0.272	(-0.020, 0.070)
	M	-0.024	0.023	-1.037	0.300	(-0.070, 0.022)
	V	-0.026	0.024	-1.094	0.274	(-0.073, 0.021)

Table 37.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within two hours of the experiment, baseline stress level, and reported mental demand associated with the design task. The model indicates that gender had a significant influence on the dependent variable (network density during the design task), with male participants having significantly lower network density during the design task.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
Network Density (task)	C (intercept)	0.154	0.065	2.364	0.018	(0.026, 0.281)
	A	0.005	0.025	0.204	0.839	(-0.044, 0.054)
	M	-0.024	0.026	-0.923	0.356	(-0.076, 0.027)
	V	-0.044	0.027	-1.614	0.107	(-0.097, 0.009)
	Male	-0.030	0.010	-3.110	**0.002***	(-0.049, -0.011)

Table 38.

Network density for each group during the Design Task. The network density score goes from 0 to 1. The higher the number of edges (i.e. correlations between channels), the higher the density. Outliers within groups were removed from analysis using the IQR method.

Measure	Decile	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
Brain Netork Density	1	C	31	0.1375	0.0679	0.0222	0.3209	0.4604	3.0058	**0.0335***
		A	30	0.1310	0.0665	0.0071	0.2819	0.7488		
		V	26	0.0928	0.0580	0.0027	0.2473	0.1920		
		M	27	0.1088	0.0565	0.0310	0.2553	0.0693		
	2	C	30	0.1257	0.0540	0.0115	0.2119	0.4411	18.392	**0.0004***
		A	31	0.1693	0.1081	0.0231	0.4468	0.0067		
		V	27	0.1000	0.0587	0.0053	0.2243	0.2202		

	M	24	0.0791	0.0384	0.0275	0.1631	0.1832		
3	C	32	0.1301	0.0757	0.0204	0.3236	0.1164	0.1265	0.9885
	A	29	0.1204	0.0619	0.0195	0.2695	0.6696		
	V	27	0.1266	0.0856	0.0053	0.3404	0.1471		
	M	29	0.1256	0.0738	0.0319	0.2855	0.0028		
4	**C**	32	0.1381	0.0848	0.0124	0.3404	0.2462	6.0650	0.1085
	A	31	0.1586	0.0950	0.0160	0.3546	0.0090		
	V	28	0.1090	0.0712	0.0053	0.2731	0.0610		
	M	28	0.1089	0.0536	0.0372	0.2518	0.1747		
5	C	29	0.0983	0.0510	0.0142	0.1809	0.0774	3.4509	0.3272
	A	29	0.1267	0.0654	0.0319	0.2544	0.2116		
	V	29	0.1447	0.1023	0.0160	0.3324	0.0086		
	M	28	0.1057	0.0583	0.0257	0.2385	0.0366		
6	C	31	0.1198	0.0609	0.0133	0.2491	0.0524	0.8203	0.8446
	A	29	0.1420	0.0854	0.0363	0.3608	0.0125		
	V	29	0.1201	0.0719	0.0044	0.2828	0.3005		
	M	28	0.1277	0.0722	0.0222	0.3059	0.2386		
7	**C**	30	0.1171	0.0715	0.0124	0.2784	0.2435	2.7220	0.4365
	A	30	0.1466	0.0900	0.0222	0.3369	0.0270		
	V	28	0.1161	0.0667	0.0053	0.2385	0.3800		
	M	28	0.1065	0.0553	0.0222	0.2429	0.4215		
8	C	31	0.1060	0.0586	0.0053	0.2323	0.5394	6.8977	0.0752
	A	31	0.1569	0.0867	0.0363	0.3537	0.1111		
	V	27	0.1120	0.0613	0.0053	0.2651	0.4390		
	M	29	0.1448	0.0828	0.0479	0.3644	0.0144		
9	C	31	0.1185	0.0720	0.0124	0.3209	0.1500	3.5114	0.3193
	A	32	0.1421	0.0989	0.0231	0.3715	0.0008		
	V	27	0.0974	0.0600	0.0062	0.2252	0.0401		
	M	29	0.1072	0.0646	0.0257	0.2456	0.0245		
10	C	31	0.1028	0.0600	0.0204	0.2331	0.0684	1.5122	0.6795
	A	30	0.1050	0.0629	0.0160	0.2748	0.0232		

	V	29	0.0997	0.0723	0.0062	0.2713	0.0375
	M	28	0.1157	0.0623	0.0266	0.2615	0.1903

Note. Group: A – Active Control; C – Control; I – Intervention. S-W *p* – Shapiro-Wilk *p*-value.

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that no significant differences existed between groups during the 1st decile.

	C	I	V	M
C	1.000000	0.707068	0.064140	0.355778
I	0.707068	1.000000	0.134847	0.549745
V	0.064140	0.134847	1.000000	0.625702
M	0.355778	0.549745	0.625702	1.000000

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the 2nd decile, the mean network density for the auditory group was significantly higher than the visual ($p = 0.0174$) and the multisensory ($p = 0.0016$) groups, with medium to large (Cohen’s d = 0.782) and large (Cohen’s d = 1.060) effect sizes. Also, the mean network density for the control group was significantly higher than the multisensory group ($p = 0.0039$), with a large effect size (Cohen’s d = 0.977).

	C	I	V	M
C	1.000000	0.155994	0.181194	0.003926
I	0.155994	1.000000	0.017447	0.001643
V	0.181194	0.017447	1.000000	0.181194
M	0.003926	0.001643	0.181194	1.000000

Table 39.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within two hours of the experiment, baseline stress level, and reported mental demand associated with the design task. The model indicates that age had a significant influence on the dependent variable (network density during the design task).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
1st decile Density (task)	C (intercept)	0.107	0.042	2.523	0.012	(0.024, 0.190)
	A	-0.007	0.025	-0.260	0.795	(-0.056, 0.043)
	M	-0.031	0.026	-1.191	0.234	(-0.082, 0.020)
	V	-0.034	0.027	-1.270	0.204	(-0.086, 0.018)
	Age	0.004	0.001	4.082	**0.000***	(0.002, 0.006)

Table 40.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within two hours of the experiment, baseline stress level, and reported mental demand associated with the design task. The model indicates that age had a significant influence on the dependent variable (network density during the design task).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
2nd decile Density (task)	C (intercept)	0.032	0.011	2.812	0.005	(0.010, 0.054)
	A	0.020	0.028	0.733	0.464	(-0.034, 0.075)
	M	-0.025	0.029	-0.850	0.395	(-0.083, 0.033)
	V	-0.018	0.030	-0.588	0.556	(-0.077, 0.042)
	Age	0.007	0.002	2.869	**0.004***	(0.002, 0.011)

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Table 41.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within two hours of the experiment, time of the day (AM/PM), baseline stress level and connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rDMPFC (rest)	C (intercept)	0.117	0.039	3.005	0.003	(0.041, 0.194)
	A	0.004	0.022	0.202	0.840	(-0.39, 0.048)
	M	-0.032	0.023	-1.414	0.157	(-0.077, 0.012)
	V	-0.052	0.023	-2.232	**0.026***	(-0.097, -0.006)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
lDMPFC (rest)	C (intercept)	0.094	0.071	1.315	0.188	(-0.046, 0.234)
	A	0.030	0.027	1.130	0.259	(-0.022, 0.083)
	M	-0.039	0.028	-1.398	0.162	(-0.093, 0.016)
	V	-0.039	0.028	-1.367	0.172	(-0.094, 0.017)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rDLPFC (rest)	C (intercept)	0.114	0.017	6.763	0.000	(0.081, 0.147)
	A	0.016	0.023	0.700	0.484	(-0.029, 0.060)
	M	-0.019	0.024	-0.791	0.429	(-0.065, 0.028)
	V	-0.032	0.024	-1.300	0.194	(-0.080, 0.016)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI

lDLPFC (rest)	C (intercept)	0.118	0.051	2.326	0.020	(0.018, 0.217)
	A	0.001	0.021	0.031	0.975	(-0.040, 0.041)
	M	-0.012	0.021	-0.584	0.559	(-0.054, 0.029)
	V	-0.024	0.022	-1.114	0.265	(-0.067, 0.018)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rFrontopolar (rest)	C (intercept)	0.220	0.012	19.082	0.000	(0.197, 0.243)
	A	0.039	0.030	1.323	0.186	(-0.019, 0.097)
	M	-0.026	0.031	-0.846	0.398	(-0.087. 0.035)
	V	-0.025	0.032	-0.774	0.439	(-0.087, 0.038)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
lFrontopolar (rest)	C (intercept)	0.160	0.094	1.695	0.090	(-0.025, 0.344)
	A	0.040	0.032	1.225	0.221	(-0.024, 0.103)
	M	-0.035	0.033	-1.044	0.297	(-0.100, 0.031)
	V	-0.023	0.034	-0.688	0.491	(-0.089, 0.043)
	Caffeine	0.067	0.032	2.110	**0.035***	(0.005, 0.128)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI

rVLPFC (rest)	C (intercept)	0.042	0.050	0.841	0.400	(-0.055, 0.139)
	A	0.033	0.022	1.517	0.129	(-0.010, 0.076)
	M	-0.020	0.023	-0.882	0.378	(-0.065, 0.025)
	V	-0.027	0.023	-1.161	0.246	(-0.073, 0.019)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
lVLPFC (rest)	C (intercept)	0.070	0.047	1.472	0.141	(-0.023, 0.163)
	A	-0.007	0.016	-0.425	0.671	(-0.039, 0.025)
	M	-0.039	0.018	-2.203	**0.028***	(-0.074, -0.004)
	V	-0.046	0.018	-2.579	**0.010***	(-0.082, -0.011)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rOFC (rest)	C (intercept)	0.089	0.096	0.929	0.353	(-0.099, 0.277)
	A	0.052	0.032	1.623	0.105	(-0.011, 0.115)
	M	0.022	0.033	0.667	0.505	(-0.043, 0.088)
	V	0.006	0.035	0.171	0.865	(-0.062, 0.074)
	Caffeine	0.067	0.032	2.077	**0.038***	(0.004, 0.130)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
lOFC (rest)	C (intercept)	0.085	0.068	1.260	0.208	(-0.047, 0.218)
	A	0.021	0.031	0.683	0.495	(-0.039, 0.081)
	M	-0.021	0.032	-0.657	0.511	(-0.083, 0.041)
	V	-0.011	0.032	-0.330	0.742	(-0.074, 0.053)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rDMPFC (task)	C (intercept)	0.189	0.016	11.620	0.000	(0.157, 0.220)
	A	-0.029	0.019	-1.518	0.129	(-0.066, 0.008)
	M	-0.052	0.020	-2.640	**0.008***	(-0.090, -0.013)
	V	-0.059	0.020	-2.935	**0.003***	(-0.099, -0.020)
	NR-6 (pre)	-0.026	0.010	-2.615	**0.009***	(-0.045, -0.007)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
lDMPFC (task)	C (intercept)	0.120	0.052	2.328	0.020	(0.019, 0.222)
	A	-0.001	0.025	-0.057	0.955	(-0.050, 0.047)
	M	-0.051	0.026	-1.976	**0.048***	(-0.101, -0.000)
	V	-0.038	0.026	-1.458	0.145	(-0.090, 0.013)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rDLPFC (task)	C (intercept)	0.101	0.059	1.719	0.086	(-0.014, 0.216)
	A	0.007	0.020	0.342	0.732	(-0.032, 0.046)
	M	-0.022	0.021	-1.049	0.294	(-0.063, 0.019)
	V	-0.055	0.021	-2.589	**0.010***	(-0.096, -0.013)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
lDLPFC (task)	C (intercept)	0.123	0.031	3.988	0.000	(0.063, 0.184)
	A	0.002	0.027	0.071	0.943	(-0.051, 0.055)

	M	-0.039	0.028	-1.381	0.167	(-0.094, 0.016)
	V	-0.062	0.029	-2.120	**0.034***	(-0.119, -0.005)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rFrontopolar (task)	C (intercept)	0.274	0.059	4.633	0.000	(0.158, 0.390)
	A	-0.017	0.031	-0.545	0.586	(-0.078, 0.044)
	M	-0.032	0.033	-0.985	0.325	(-0.096, 0.032)
	V	-0.060	0.034	-1.759	0.079	(-0.127, 0.007)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
lFrontopolar (task)	C (intercept)	0.200	0.066	3.016	0.003	(0.070, 0.330)
	A	0.014	0.033	0.439	0.660	(0.050, 0.079)
	M	-0.012	0.035	-0.352	0.725	(-0.081, 0.056)
	V	-0.035	0.037	-0.956	0.339	(-0.107, 0.037)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rVLPFC (task)	C (intercept)	0.169	0.085	2.000	0.045	(0.003, 0.335)
	A	0.034	0.030	1.134	0.257	(-0.025, 0.093)
	M	-0.012	0.031	-0.387	0.698	(-0.073, 0.049)
	V	-0.049	0.032	-1.559	0.120	(-0.111, 0.013)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI

lVLPFC (task)	C (intercept)	0.121	0.053	2.290	0.022	(0.017, 0.224)
	A	-0.005	0.021	-0.215	0.829	(-0.046, 0.037)
	M	-0.030	0.022	-1.51	0.177	(-0.073, 0.014)
	V	-0.062	0.023	-2.703	**0.007***	(-0.106, -0.017)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
rOFC (task)	C (intercept)	0.130	0.046	2.813	0.005	(0.039, 0.221)
	A	-0.001	0.035	-0.031	0.975	(-0.070, 0.068)
	M	-0.012	0.037	-0.339	0.734	(-0.084, 0.059)
	V	-0.016	0.037	-0.436	0.663	(-0.090, 0.057)

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
lOFC (task)	C (intercept)	0.084	0.091	0.920	0.357	(-0.095, 0.262)
	A	0.063	0.034	1.848	0.065	(-0.004, 0.129)
	M	0.020	0.035	0.561	0.757	(-0.049, 0.089)
	V	-0.005	0.036	-0.131	0.895	(-0.076, 0.066)
	NR-6 (pre)	-0.009	0.003	-3.002	**0.003***	(-0.016, -0.003)

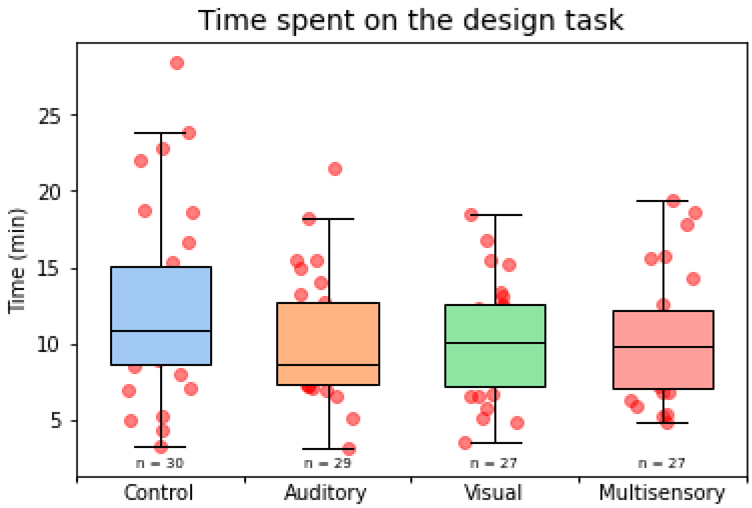

Table 42.

Time spent on the design task.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
Time on the design task	C	30	12.36	6.17	3.28	28.49	0.058	2.238	0.525
	A	29	10.13	4.10	3.11	21.45	0.027		
	M	27	10.53	4.45	4.81	19.34	0.091		
	V	27	10.20	3.79	3.54	18.51	0.893		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.

Table 43.

SCL during the TSST.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
SCL (TSST)	C	27	1.469	1.405	0.002	5.228	0.002	5.682	0.128
	A	29	2.700	2.696	-0.033	9.388	0.001		
	M	28	1.699	1.273	-0.012	3.953	0.063		
	V	27	1.199	1.168	-0.078	4.594	0.004		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.

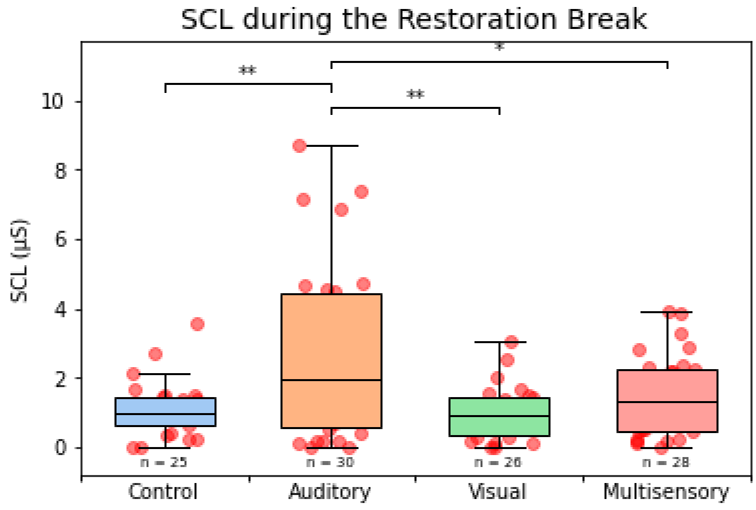

Table 44.

SCL during the restoration break.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
SCL (rest)	C	25	1.116	0.821	-0.024	3.580	0.034	9.609	**0.022***
	A	30	2.737	2.469	-0.003	8.707	0.008		
	M	28	1.477	1.186	0.000	3.947	0.030		
	V	26	0.993	0.775	-0.003	3.055	0.091		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the restoration break, the mean SCL for the auditory group was significantly higher than the visual ($p = 0.006$, Cohen's $d = 0.925$) and the control ($p = 0.014$, Cohen's $d = 0.850$) groups, with large effect sizes.

	C	I	M	V
C	1.000000	0.013901	0.416149	0.584449
I	0.013901	1.000000	0.070072	0.006496
M	0.416149	0.070072	1.000000	0.251833
V	0.584449	0.006496	0.251833	1.000000

Table 45.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within two hours of the experiment, time of the day (AM/PM), baseline stress level and connectedness to nature. The model indicates that none of the potential confounders had a significant influence on the dependent variable (mean tonic driver during the restoration break).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
SCL (rest)	C (intercept)	1.311	1.409	0.931	0.352	(-1.450, 4.072)
	A	1.702	0.663	2.569	**0.010***	(0.404, 3.001)
	M	-0.294	0.693	-0.425	0.671	(-1.652, 1.064)
	V	-0.250	0.709	-0.353	0.724	(-1.640, 1.139)
	Age	-0.054	0.021	-2.638	**0.008***	(-0.095, -0.014)

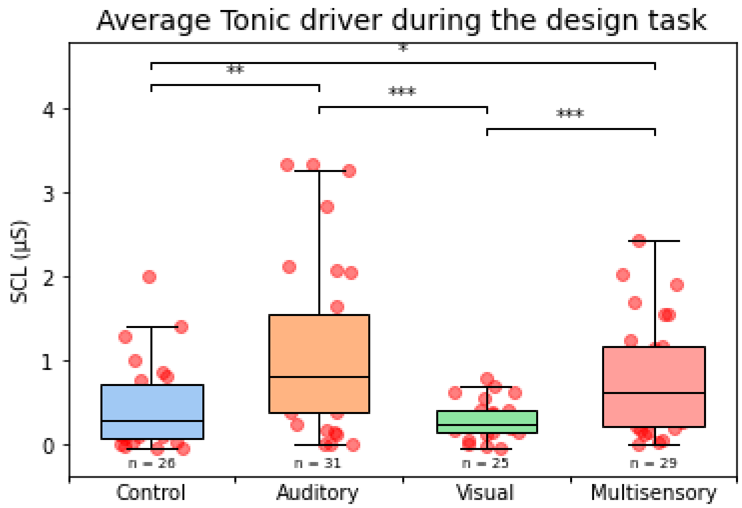

Table 46.

SCL during the design task.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
	C	26	0.456	0.521	-0.038	2.017	0.001	18.573	**0.0003***
SCL	A	31	1.150	1.012	0.002	3.351	0.003		
(task)	M	29	0.817	0.673	0.006	2.431	0.033		
	V	25	0.297	0.223	-0.046	0.790	0.170		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the design task, the mean SCL for the auditory group was significantly higher than the visual (*p* = 0.0008, Cohen's *d* = 1.109) and the control (*p* = 0.010, Cohen's *d* = 0.839) groups, with large effect sizes. Also, the mean SCL for the multisensory group was significantly higher than the visual group (*p* = 0.003), with a large effect size (Cohen's *d* = 1.007).

	C	I	M	V
C	1.000000	0.010414	0.096164	0.284585
I	0.010414	1.000000	0.284585	0.000772

M	0.096164	0.284585	1.000000	0.002690
V	0.284585	0.000772	0.002690	1.000000

Table 47.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within two hours of the experiment, baseline stress level and connectedness to nature. The model indicates that none of the potential confounders had a significant influence on the dependent variable (mean tonic driver during the design task).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
SCL (task)	C (intercept)	0.672	0.655	1.026	0.305	(-0.612, 1.956)
	A	0.517	0.233	2.212	**0.027***	(0.059, 0.974)
	M	0.060	0.240	0.251	0.802	(-0.410, 0.530)
	V	-0.051	0.246	-0.207	0.836	(-0.533, 0.432)
	Stress (pre)	0.185	0.086	2.161	**0.031***	(0.017, 0.353)

Table 48.

Number of SCRs during the TSST.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
nSCR (TSST)	C	29	467.2	146.5	145	757	0.990	1.469	0.227
	A	32	492.0	203.8	63	775	0.073		
	M	29	412.1	174.4	28	665	0.414		
	V	26	422.5	137.2	37	636	0.254		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.

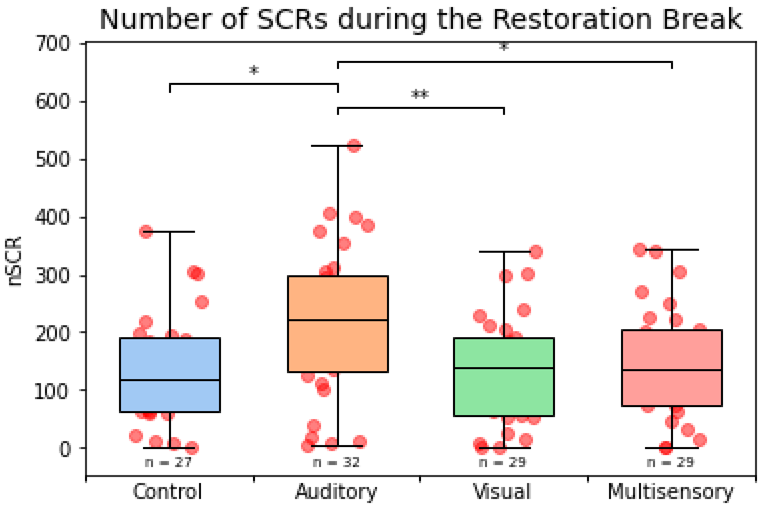

Table 49.

Number of SCRs during the restoration break.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
nSCR (rest)	C	27	137.6	96.9	2	375	0.197	4.331	**0.006***
	A	32	218.0	130.5	3	523	0.615		
	M	29	148.9	96.3	0	342	0.412		
	V	29	132.0	94.6	0	340	0.240		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the restoration break, the mean number of SCRs for the auditory group was significantly higher than the visual group (*p* = 0.030), with a medium to large effect size (Cohen's *d* = 0.749).

	C	I	M	V
C	1.000000	0.052779	1.000000	1.000000

I	0.052779	1.000000	0.092611	0.029541
M	1.000000	0.092611	1.000000	1.000000
V	1.000000	0.029541	1.000000	1.000000

Table 50.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within two hours of the experiment, time of the day (AM/PM), baseline stress level and connectedness to nature. The model indicates that none of the potential confounders had a significant influence on the dependent variable (number of SCRs during the restoration break).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
nSCR (rest)	C (intercept)	146.514	88.110	1.663	0.096	(-26.179, 319.207)
	A	55.146	30.732	1.794	0.073	(-5.087, 115.379)
	M	-10.338	31.616	-0.327	0.744	(-72.304, 51.628)
	V	-28.886	32.273	-0.895	0.371	(-92.141, 34.368)

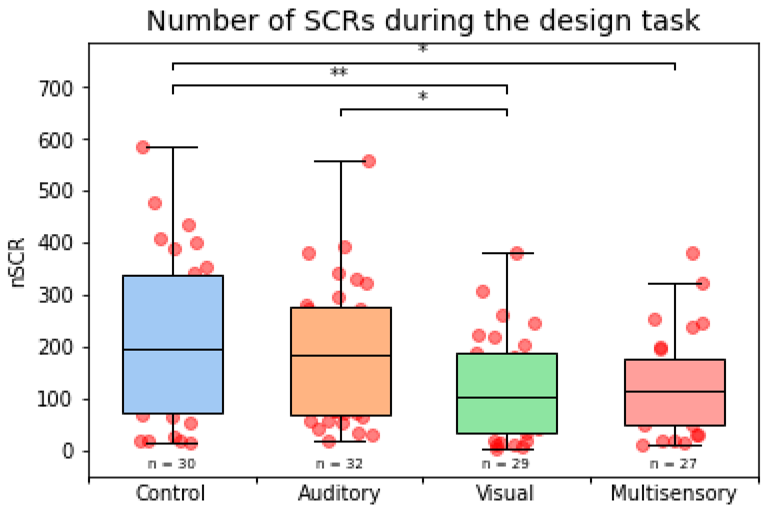

Table 51.

Number of SCRs during the design task.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
nSCR (task)	C	30	213.2	160.3	14	585	0.066	8.922	**0.031***
	A	32	185.4	135.6	17	558	0.012		
	M	27	128.5	97.7	9	381	0.055		
	V	29	115.8	101.8	1	381	0.013		

Note. Group: C – Control; A – Biophilic Auditory Experience; V – Biophilic Visual Experience; M – Biophilic Multisensory Experience. S-W *p* – Shapiro-Wilk *p*-value.

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the restoration break, the mean number of SCRs for the control group was significantly higher than the visual group (*p* = 0.044), with a medium to large effect size (Cohen's *d* = 0.723).

Table 52.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within two hours of the experiment, baseline stress level and connectedness to nature. The model indicates that none of the potential confounders had a significant influence on the dependent variable (number of SCRs during the design task).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
nSCR (task)	C (intercept)	405.860	96.0736	4.224	0.000	(217.553, 594.166)
	A	-21.439	34.247	-0.626	0.531	(-88.562, 45.685)
	M	-35.788	35.190	-1.017	0.309	(-104.758, 33.182)
	V	-80.650	36.106	-2.234	**0.026***	(-151.416, -9.885)
	Age	-12.409	3.623	-3.425	**0.001***	(-19.511, -5.307)

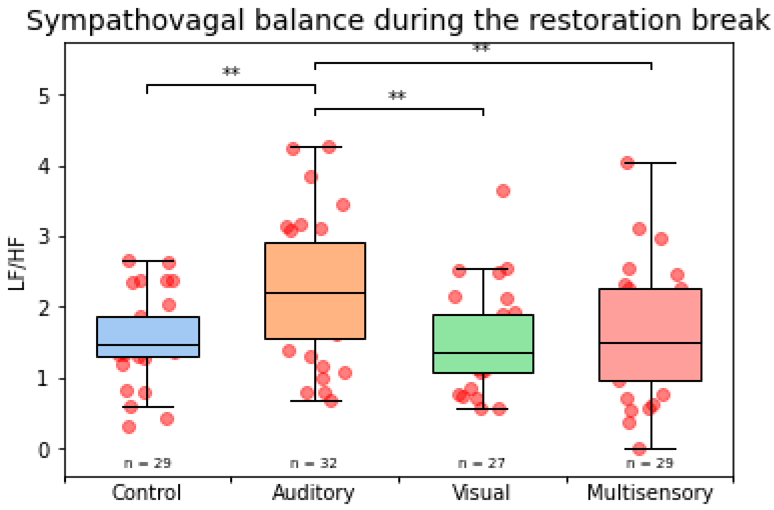

Table 53.

LF/HF during the restoration break.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
	C	30	1.607	0.660	0.334	2.939	0.471	5.238	**0.002***
LF/HF	A	32	2.255	0.974	0.699	4.269	0.435		
(rest)	M	28	1.637	0.885	0.373	4.032	0.202		
	V	27	1.507	0.720	0.566	3.642	0.298		

A post hoc T-test with a Holm-Bonferroni *p*-value adjustment indicated that during the restoration break, the mean LF/HF for the auditory group was significantly higher than the visual (*p* = 0.010, Cohen's *d* = 0.861) and the control (*p* = 0.017, Cohen's *d* = 0.773) groups, with large and medium to large effect sizes.

	C	I	M	V
C	1.000000	0.017407	1.000000	1.000000
I	0.017407	1.000000	0.053169	0.010139
M	1.000000	0.053169	1.000000	1.000000
V	1.000000	0.010139	1.000000	1.000000

Table 54.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within two hours of the experiment, time of the day (AM/PM), baseline stress level and connectedness to nature. The model indicates that none of the potential confounders had a significant influence on the dependent variable (LF/HF during the restoration break).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
LF/HF (rest)	C (intercept)	0.854	0.707	1.208	0.227	(-0.531, 2.239)
	A	0.824	0.248	3.324	**0.001***	(0.338, 1.310)
	M	0.108	0.260	0.418	0.676	(-0.400, 0.617)
	V	0.265	0.262	1.012	0.311	(-0.248, 0.778)

Table 55.

LF/HF during the design task.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
LF/HF (task)	C	30	2.198	1.055	0.467	4.839	0.565	6.053	0.109
	A	31	1.861	0.826	0.720	3.935	0.016		
	M	28	1.703	0.702	0.754	3.560	0.149		
	V	27	1.642	0.806	0.519	3.782	0.011		

Table 56.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within two hours of the experiment, time of the day (AM/PM), baseline stress level and connectedness to nature. The model indicates that none of the potential confounders had a significant influence on the dependent variable (LF/HF during the design task).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
LF/HF (task)	C (intercept)	1.907	0.279	6.824	0.000	(1.360, 2.455)
	A	-0.130	0.256	-0.509	0.611	(-0.631, 0.371)
	M	-0.493	0.264	-1.867	0.062	(-1.010, 0.024)
	V	-0.191	0.270	-0.705	0.481	(-0.721, 0.339)

Table 57.

Power at HF during the restoration break.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
HF (rest)	C	28	478.22	310.17	0.66	1204.3	0.414	3.880	0.275
	A	29	325.42	179.49	32.06	713.62	0.105		
	M	28	450.58	323.47	0.09	1139.4	0.111		
	V	27	351.90	237.68	68.85	896.30	0.013		

Table 58.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within two hours of the experiment, baseline stress level and connectedness to nature. The model indicates that age and baseline connecte had significant main effects on the dependent variable (power at HF during the restoration break).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
HF (rest)	C (intercept)	717.723	249.776	2.849	0.004	(222.170, 1201.28)
	A	-121.864	90.283	-1.350	0.177	(-298.815, 55.088)
	M	-88.237	92.588	-0.953	0.341	(-269.706, 93.232)

V	-111.047	93.997	-1.181	0.237	(-295.277, 73.183)
Age	-17.286	8.239	-2.098	**0.036***	(-33.433, -1.139)
NR-6 (pre)	61.126	29.281	.088	**0.037***	(3.736, 118.515)

Table 59.

Power at HF during the design task.

Measure	Group	*n*	*Mean*	*SD*	Min.	Max.	S-W *p*	*t*	*p*-value
HF (task)	C	27	98.492	79.741	0.013	318.40	0.059	2.601	0.457
	A	29	97.014	68.902	2.416	268.43	0.033		
	M	27	139.73	118.40	19.81	411.25	0.000		
	V	29	130.64	97.393	0.001	325.95	0.066		

Table 60.

Linear mixed effects model results. Adjusted for age, gender, caffeine consumption within two hours of the experiment, baseline stress level and connectedness to nature. The model indicates that none of the potential confounders had a significant influence on the dependent variable (power at HF during the design task).

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
HF (task)	C (intercept)	359.345	49.077	7.322	0.000	(263.155, 455.535)
	A	-10.279	41.591	-0.247	0.805	(-91.796, 71.238)
	M	17.921	43.011	0.417	0.677	(-66.378, 102.220)
	V	-18.830	44.035	-0.428	0.669	(-105.136, 67.477)
	Age	-10.546	3.709	-2.844	**0.004***	(-17.815, -3.277)

Incorporation of biophilic design (only rater 4)

Table 61.

Linear mixed effects model results. Adjusted for, age, gender, design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
P1	C (intercept)	0.904	0.649	1.393	0.164	(-0.368, 2.177)
	A	0.175	0.235	0.744	0.457	(-0.286, 0.636)
	M	0.017	0.244	0.070	0.944	(-0.460, 0.494)
	V	0.477	0.241	1.977	**0.048***	(0.004, 0.950)

Table 62.

Linear mixed effects model results. Adjusted for, age, gender, design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
P4	C (intercept)	1.636	0.686	2.386	0.017	(0.292, 2.980)
	A	0.057	0.248	0.228	0.820	(-0.431, 0.544)
	M	0.059	0.257	0.229	0.819	(-0.445, 0.563)
	V	0.485	0.255	1.903	0.057	(-0.015, 0.984)
	BD Knowledge	1.476	0.725	2.035	**0.042***	(0.054, 2.898)

Table 63.

Linear mixed effects model results. Adjusted for, age, gender, design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
P5	C (intercept)	0.100	0.827	0.121	0.903	(-1.520, 1.720)
	A	-0.271	0.300	-0.904	0.366	(-0.858, 0.316)
	M	-0.057	0.310	-0.184	0.854	(-0.665, 0.551)
	V	0.948	0.307	3.085	**0.002***	(0.346, 1.550)

Table 64.

Linear mixed effects model results. Adjusted for, age, gender, design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
P9	C (intercept)	2.216	0.522	4.246	0.000	(1.193, 3.239)
	A	-0.312	0.189	-1.648	0.099	(-0.682, 0.059)
	M	-0.098	0.196	-0.499	0.618	(-0.481, 0.286)
	V	-0.102	0.194	-0.525	0.600	(-0.482, 0.278)
	Age	-0.051	0.021	-2.455	**0.014***	(-0.092, -0.010)

Table 65.

Linear mixed effects model results. Adjusted for, age, gender, design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
P10	C (intercept)	1.662	0.638	2.603	0.009	(0.411, 2.913)
	A	0.070	0.231	0.301	0.764	(-0.384, 0.523)
	M	0.207	0.239	0.864	0.388	(0.263, 0.676)
	V	0.420	0.237	1.772	0.076	(-0.045, 0.885)
	Age	-0.068	0.025	-2.657	**0.008***	(-0.118, -0.018)

Table 66.

Linear mixed effects model results. Adjusted for, age, gender, design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
P11	C (intercept)	1.305	0.600	2.177	0.029	(0.130, 2.480)
	A	0.075	0.217	0.344	0.731	(-0.351, 0.501)
	M	0.204	0.225	0.906	0.365	(-0.237, 0.644)
	V	0.164	0.223	0.737	0.461	(-0.272, 0.601)
	BD Knowledge	1.251	0.634	1.973	**0.049***	(0.008, 2.494)

Table 67.

Linear mixed effects model results. Adjusted for, age, gender, design experience, biophilic design knowledge, pre- and post-experiment connectedness to nature.

Measure	Group	Model Estimate (β)	Std. Err.	z	*p*-value	95% CI
P14	C (intercept)	0.219	0.668	0.328	0.743	(-1.089, 1.528)
	A	-0.117	0.242	-0.484	0.628	(-0.591, 0.357)
	M	0.245	0.250	0.980	0.327	(-0.246, 0.736)
	V	0.813	0.248	3.279	**0.001***	(0.327, 1.300)