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Biophilic office design: Exploring the impact of a multisensory approach on human well-being

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ABSTRACT

Experiencing nature provides a multitude of health benefits. Biophilic design has emerged as a design approach that aims to reconnect occupants with the natural environment. We evaluated the impact of a multisensory biophilic environment on occupants' cognitive performance, stress, productivity, mood, connectedness to nature, and attention. Thirty-seven participants in three cohorts were exposed to three biophilic design interventions (visual, auditory, and a combination (multisensory)) and a baseline condition, with weekly variations over eight weeks. A wrist-worn stress sensor, daily surveys, and scheduled executive function tasks were administered. Cognitive performance improved in all biophilic conditions compared to baseline. Most satisfaction with workplace appearance, and visual privacy was reported in visual and multisensory conditions, and stress ratings were lower in the multisensory condition compared to baseline. The results demonstrate that immersive biophilic environments can improve occupants' satisfaction and cognitive performance, while reducing stress. The findings highlight the need to consider non-visual factors in biophilic design.

1. Introduction

Rapid urbanization of the modern world has contributed to a human experience now dominated by the indoor environment. In the global North, humans spend approximately 90% of their time indoors (Klepeis et al., 2001), resulting in reduced exposure to nature and measurable physiological and psychological impacts (Baggerly et al., 2015; Sandifer et al., 2015).

Research has previously demonstrated that experiencing nature provides a multitude of human health and well-being benefits such as stress reduction (Fuller et al., 2007; Park et al., 2009), increased productivity (Lohr et al., 1995; Kellert et al., 2008), and improved mood (Brown et al., 2013; Shibata & Suzuki, 2004). These few constructs, in addition to several others (Bratman et al., 2012; Hartig et al., 2014), overwhelmingly point to the benefit of being in contact with nature for physical and psychological health.

Previous studies have explored the concept of biophilia, describing our innate human desire for spaces that more closely resemble natural outdoor environments due to its evolutionary benefits (Wilson, 1984). However, the trend toward inhabiting primarily indoor spaces has contributed to a disconnect between humans and the natural world (Turner et al., 2004). This departure from the our environment of evolutionary adaptedness (EEA), has contributed to poor quality of life and potential negative health effects (Crawford et al., 2013; Grinde

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et al., 2009). Thus, strategies to reconnect humans to our natural environment might serve to mitigate such negative health effects.

Biophilic design has emerged in recent years as an architectural design approach that aims to reconnect building occupants to their EEA by integrating various natural elements, or evocations of nature, into the built environment (Gillis and Gatersleben, 2015). According to Browning et al. (2014), biophilic design components can be characterized in three ways: 1) *nature in the space*, which incorporates natural elements into the space including physical plants, natural sounds, scents and direct views of nature, 2) *natural analogues*, which elicit indirect evocations of nature in a space through the use of natural patterns, colors, shapes and materials, and 3) *nature of the space,* or indoor spaces that mimic natural landscapes through the layout of furniture and design elements that prompt feelings of security and comfortability, often referred to as prospect/refuge theory (Appleton, 1996), or the ability to withdraw and still observe the larger space (Browning et al., 2014).

The field of biophilic design has thus far primarily focused on the first of such characterizations, or *nature in the space*, emphasizing the impact of visual connections with nature (Franco et al., 2017). Such works include attempts to evaluate the impact of real and artificial nature on stress, with Beukeboom et al. (2012), measuring the stress of individuals in hospital waiting rooms under both conditions and noting lower stress levels for each, in comparison to a waiting room with no nature (Beukeboom et al., 2012). Similarly, participants from visual biophilic design studies have demonstrated lower self-reported levels of anxiety and nervousness, and improved heart rate recovery from low-level stress when exposed to a window view of nature, or indoor plants (Chang & Chen, 2005; Kahnet al., 2008). Others have replicated these findings when utilizing technological mediums to invoke feelings of nature, showing lower systolic and diastolic blood pressure, as well as lower skin conductance levels in virtual reality settings (Yin et al., 2019). Beyond measures of stress, some research has sought to understand the impact of visual nature on task performance in indoor spaces, with Shibata and Suzuki (2004) demonstrating that students, in particular, may show improved task performance when in the presence of indoor plants (Shibata & Suzuki, 2004).

While several such studies have investigated the impact of nature across a variety of indoor settings, very few introduce biophilic design that incorporate other sensory elements aside from visual, limiting our understanding of the potential effects of auditory, olfactory, haptic, and combined multisensory design approaches on human well-being. Much research has measured the impact of nature on human stress and anxiety in *outdoor* environments (Hansen et al., 2017; Park et al., 2009), drawing comparisons between these impacts in urban and forested environments (White et al., 2019). Additionally, virtual natural environments that mimic the multisensory outdoor experience by combining auditory, olfactory, and visual stimulation have also been linked with lower levels of stress and faster stress recovery (Annerstedt et al., 2013; Hedbloom et al., 2019). These findings highlight the benefits of immersive and holistic sensory environments, and the need to replicate and study these deep, natural connections in indoor settings through their non-virtual integration.

With the exception of (Determan et al. (2019)), who explored the impact of a biophilic designed classroom on students' test performance and stress recovery over a year-long exposure period (Determan et al., 2019), there is a paucity of studies assessing the *sustained* effect of having been in contact with natural elements (Tennessen & Cimprich, 1995). Living labs, or monitored spaces that seek to recreate everyday environments, offer the opportunity to address some of these limitations by constructing realistic, indoor environments that allow researchers to capture participants' responses over longer periods (weeks, months) as well as parse out the effects of different natural elements introduced to the space, such as the effects produced by visual versus auditory components, with a level of control that is not afforded by field studies (Aristizabal et al., 2019; Jamrozik et al., 2018).

While some research on multisensory experiences (Brown et al., 1969) has suggested that humans face difficulties in responding to multiple, simultaneous sources of sensory information when performing tasks that require attention, such as attending to auditory inputs while driving, more recent studies have shown that humans can monitor multiple sensory stimuli of different modalities with little cost if they engage different attentional resources (Spence & Driver, 1997; Wickens, 2002). Spence and Ho (2008), for example, have shown that multisensory stimulation, as opposed to unimodal stimulation, could be an effective strategy to capture attention and potentially help overcome the sensory decline that occurs with age (Spence & Ho, 2008).

To extend the existing body of literature on the positive impacts of multisensory biophilic indoor design, this research aims to measure the effects of visual and auditory natural elements on occupant well-being and performance in a simulated office environment. Three cohorts of participants were exposed to a baseline condition of an office without biophilic design elements, as well as three experimental conditions that include the following: visual, auditory, and combined visual and auditory biophilic design elements (hereto referred as multisensory). All participants experienced each condition for a one-week period, at two separate times, totaling a living lab occupancy of eight consecutive weeks. Comparisons between self-reported measures of stress, mood, perceived productivity, attention restoration, and cognitive performance, as well as continuous long-term monitoring of physiological indices of stress with wearable devices (heart rate and electrodermal activity) were performed across all biophilic interventions (visual, auditory, multisensory) with respect to baseline.

We posit that experiencing a multisensory biophilic environment, as opposed to an environment with solely visual or auditory elements, will lead to greater improvements in cognitive performance, mood, feelings of connectedness to nature, environmental satisfaction, and attention restoration, in addition to reductions in stress, when compared to an office with no biophilic design features. We also hypothesize that multisensory conditions will lead to greater levels of perceived productivity as opposed to visual or auditory conditions alone, alongside improvement in attention restoration and cognitive performance.

2. Methods

2.1. Overview of study design

This study used a within-subjects, prospective cohort design to examine the effect of nature on occupant experience in a simulated, open-office environment. The study was composed of three cohorts of participants, each with a duration of 10-weeks, which took place from September to November, January to March, and May to July, respectively. The lab space is located at the Well Living Lab, a facility where participants spent their workdays completing their typical job tasks. The office environment consisted of three combined, modular spaces that accommodated fifteen workspaces in total. To maximize the time participants spent in the experimental modules, one of the modules was set up as a shared break area, creating a sufficient space to comfortably accommodate the individuals for 10 weeks. After a two-week acclimation period, recruited participants were each exposed to the experimental conditions (visual, auditory, and multisensory) on a weekly basis, twice for a total of eight weeks. The order in which experimental conditions appeared (Table 1) were altered such that any conclusions that were drawn from analyses would account for ordering effects. Each participant had an assigned workstation so that the overall seating arrangement was held constant throughout the course of the study. Other environmental factors including temperature, relative humidity and light illuminance were kept constant throughout the study.

Experimental conditions consisted of 1) biophilic *visual* content including indoor plants and rotating, digital projections of nature that included fractal imagery and canopy-type plants, 2) biophilic *auditory* content reminiscent of the natural, regional environment including blowing wind, trickling water, and sounds produced by regional fauna,

Table 1
Order of experimental conditions.

Week	1 & 2	3	4	5	6	7	8	9	10
Scene	Acclima-tion	Baseline	Visual	Multi-sensory	Auditory	Baseline	Multi-sensory	Visual	Auditory

3) a *multisensory* combination of biophilic visual and auditory components, and 4) no biophilic interventions, serving as a *baseline*.

Throughout the workday, participants wore research-grade wrist-worn wearables to measure physiological indicators of stress, including changes in heart rate and electrodermal activity. Participants also completed surveys at multiple time throughout the workday, at the end of each workday, and at the end of each experimental condition to measure feelings of stress, environmental satisfaction, perceived productivity, mood, and connectedness to nature. Objective measures of participants' cognitive performance were also collected twice weekly. These validated executive function tasks consisted of a working memory test, inhibition control, and task switching (Diamond, 2013). Physiological and behavioral responses during the baseline conditions were compared to participants' responses in the visual, auditory, and multisensory conditions.

2.2. Participants

Eligible individuals were between the age of 18 and 60 and provided informed consent and relocated to the Well Living Lab for 10-weeks. They were asked to spend at least 80% of their workday in the office. This study was reviewed and approved by the Mayo Clinic Institutional Review Board. Potential participants were screened for cardiovascular, neurological, and psychiatric conditions, stress, or depression related medications, illegal or prescription drugs, alcohol dependency, and moderate to severe hearing and vision impairments. The 37 total participants were recruited across 3 consecutive cohorts: cohort 1 (6 Female, 7 Male, Mage = 41.85), cohort 2 (5 Female, 8 Male, Mage = 33.62), and cohort 3 (8 Female, 4 Male, Mage = 33.73). The lab space can accommodate 15 total workstations at one time, so the office was not at the maximum number of occupants for any of the three cohorts. In addition, all participants had been living in Minnesota for at least two years by the time the study began and were thus accustomed to the sounds introduced in this study. See Table A1 for a complete profile of participant's demographics.

Each participant completed a baseline survey to provide a profile of health and work habits in their regular work environment, in addition to demographic information such as age, race, ethnicity, gender, income, education and occupation. A health assessment (weight, height, blood pressure, body mass index, and heart rate) was also conducted prior to relocating.

2.3. Environmental exposure

We recreated an office layout with added visual and auditory biophilic analogues that when combined would resemble aspects of savanna-like environments, as previous research demonstrates that humans prefer this environment to others for its evolutionary advantages (Orians & Heerwagen, 1992). These analogues consisted of visual projections of greenery with canopy-type structures, water features, and artwork that was congruent with the sounds being introduced to the space. Workstations were located side-by-side and separated by 1.04 m low partitions on the front-facing portion of desks to allow for more access to daylight, and by 1.05 m tall individual file cabinets on either side of each desk. The office space had windows along the north and east facades with dimensions of 2.39 m × 1.76 m and 2.39 m × 4.27 m, respectively. Access to daylight and views varied slightly depending on desk location and whether the participant was in the break area. The outdoor visual content from every window was consistent with an urban-typical street scene (Elzeyadi, 2011) displaying a city street with occasional tree foliage (pictured in Figure B1). Motorized, roller mesh shades were opened completely at the start of each day for every condition, and participants were given the option to adjust the shade position using wall-mounted controls to minimize glare. Shade position data was collected throughout the study. Building system operational data, including ventilation, lighting, and audio systems, were saved to a repository in real-time and were reviewed to ensure systems performed as expected throughout the study. Other building system setpoints were kept consistent to maintain similar environmental conditions across cohorts.

Condition 1. *(control): Baseline office environment with no environmental aspects.* In this condition, no interior environmental interventions (visual or auditory biophilic features) were introduced to the space. Window access with outdoor views was not restricted in this condition.

Condition 2. *Experimental condition with biophilic visuals introduced to the office space.* A space with a visual connection to nature was designed by introducing live plants, visual projections of greenery, and artwork displaying nature scenes throughout the office space. Plants with low-light tolerance, minimal care requirements and no production of allergens were added around the periphery of the room (shown in Fig. 1). Plants were placed at different elevations to increase the visual exposure for all participants, and indoor palm plants were used as natural barriers to separate individual desk spaces. A list of plant types used in the study is shown in Table A1. Digital screens (27.8″ x 47.2″) were used to display scenes with shade trees, natural fractal patterns, flowering plants, savannah-like landscapes, meadows, and rain. Images transitioned every 2 min to maximize the potential for participants to view each of the included digital nature scenes.

Condition 3. *Experimental condition with biophilic sounds introduced to the office space.* This condition introduced biophilic ambient noises that reflected the regional environment (Naturespace, Skokie, ILL, United States). The specific sound files portrayed wind blowing through trees, gentle streams, chirping crickets, and sounds of birds native to the Midwest region of the United States. Soundscapes were intentionally designed to prevent distractions that may occur from hearing unfamiliar noises, for example sounds from fauna not native to Minnesota. Sound files were 6 h and 30 min long and were repeated on a long loop. To recreate a realistic natural environment and avoid repetitiveness, the start of the sound clip was modified with each workday. Multi-channel soundscapes were captured with spatial accuracy using proprietary microphone techniques. Ceiling speakers were tuned to evenly deliver the sound across the near field, the mid-field, and in the distance, to create a more immersive and realistic environment.

Condition 4. *Experimental condition with biophilic sounds and visual components introduced to the office space.* To explore the potential benefits of a multisensory biophilic approach on study outcomes, biophilic visuals were combined with biophilic sounds. In this condition, participants were exposed to both Conditions 2 and 3 described above in addition to a water feature in the form of a small indoor water fountain, providing participants with the ability to both hear and see water. The water feature was placed in the break area (see Fig. 1) and was thus only visible and audible from this space given it was separated from the remaining work area by a sound dampening curtain. All participants had an equal opportunity for exposure to the water feature and were not restricted from visiting the break area to access it at any given point. However, we cannot quantify the exact extent of exposure for each participant. Sound levels collected at the three desk locations closest to the water feature during a pilot phase of the multisensory condition

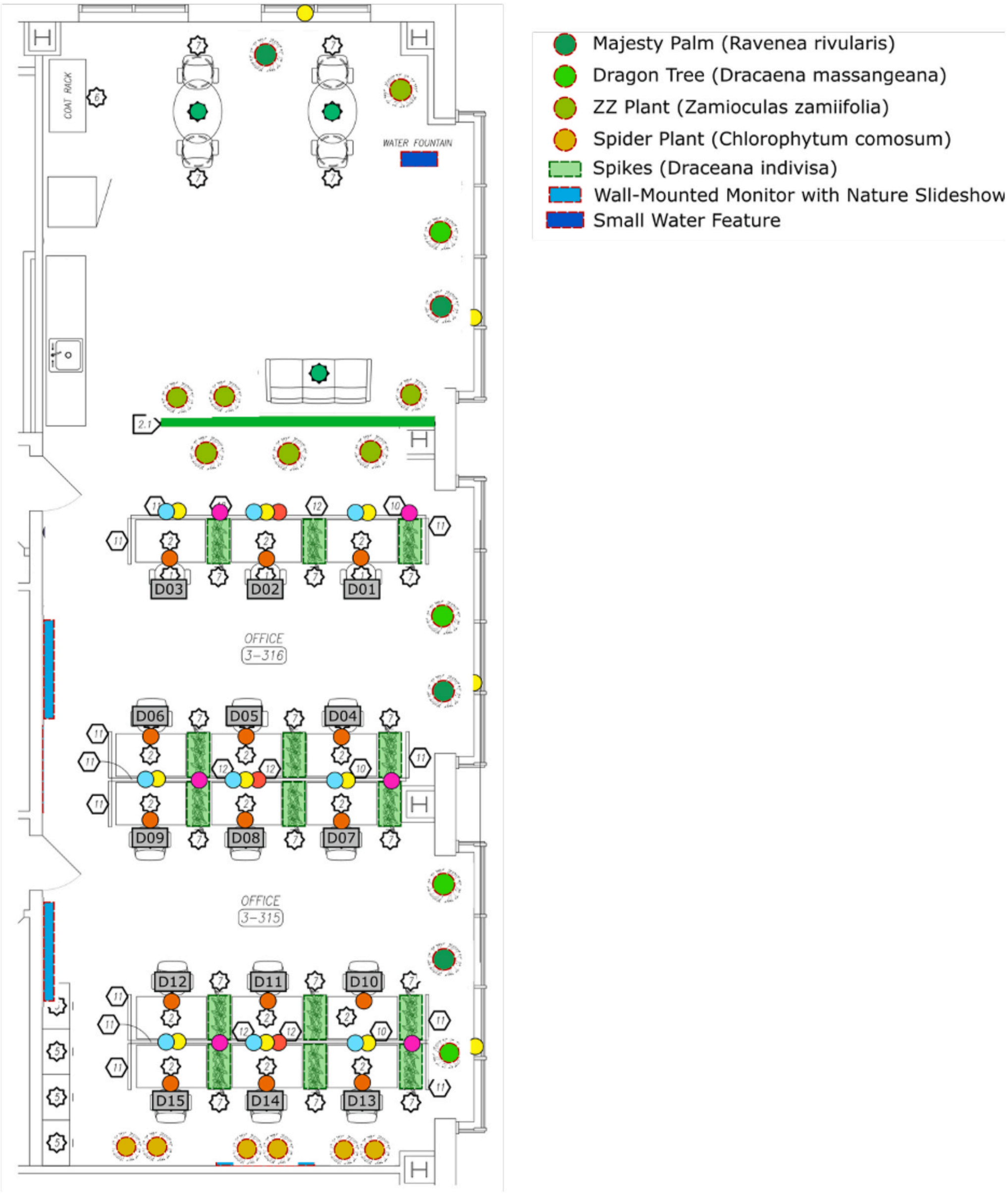

Fig. 1. Office layout with biophilic visual features.

showed that any changes in the water feature being on or off contributed less than 1 dBA for each of the three desks. We concluded that the water feature's auditory impacts were negligible when considering participants' seating location.

2.4. *Outcome measures*

2.4.1. *Physiological indicators of stress*

The human nervous system can be divided into two essential systems: the central nervous system (CNS) and the peripheral nervous system (PNS). The CNS consists of two main structures, the brain, and the spinal cord, and its main functions are to interpret sensory signals and conduct the signals to and from the brain (Everly and Everly, 1989; Noback et al., 2005). The PNS is an extension of the CNS and has two major anatomical and functional divisions: the somatic nervous system and the autonomic nervous system (ANS) (Guyton & Hall, 2016). The autonomic nervous system regulates body functions such as breathing, digestion, and heartbeat, and it can be divided into the sympathetic nervous system (SNS) and parasympathetic nervous system (PSNS) (Guyton & Hall, 2016). The SNS predominates during stressful reactions and strenuous physical activity, while the parasympathetic nervous system predominates during resting and recovery situations (McCorry, 2007).

In the presence of a stressful event, the body maintains its optimal equilibrium through a number of hormonal and physiological responses (Tsigos et al., 2000). The hypothalamus activates the sympathetic branch of the autonomic nervous system, which results in an acute stress response known as the “fight or flight” response (Hinson et al., 2010). The “fight or flight” response further leads to the secretion of catecholamines: epinephrine and norepinephrine into the blood by the adrenal medulla (Hinson et al., 2010). These hormones and the activation of the SNS, results in simultaneous activation of organs and tissues throughout the body, resulting in physiological changes such as the increase in blood pressure and heart rate (HR), decrease in heart rate variability (HRV), sweat gland activation, airway widening to increase oxygenation, and skin and intestine blood vessel narrowing to increase perfusion to major organs (Guyton & Hall, 2016). Sustained exposure to a stressor, leads to the activation of the hypothalamic-pituitary-adrenal

(HPA) axis, which results in the release of corticotropin-releasing hormone (CRH) and subsequently, adrenocorticotropic hormone (ACTH). ACTH further triggers the release of cortisol by the adrenal glands in the systemic circulation. The release of cortisol allows the body to stay in a "fight or flight" mode and maintain the body on high alert (Seaward, 2006). After the stressful event has passed, cortisol levels decrease and the PSNS counterbalances the body's arousal by slowing the HR and facilitating digestion through the action of the vagus nerve (Browning et al., 2017) to maintain homeostasis, conserve the body's energy and thus, facilitate stress recovery (Christensen et al., 2020; Guyton & Hall, 2016).

It is important to note that the psychological and physiological responses to a stressful or threatening event can vary between individuals. Previous research suggests that the stress response may vary according to trait characteristics (e.g., Stressors are more likely to trigger an emotional response from those demonstrating high trait perfectionism (Childs et al., 2014)) and genetic predisposition (Ebner & Singewald, 2017; Terenina et al., 2019), among other factors. These aspects can lead to an attenuated or amplified physiological response to an acute stressor (Xin et al., 2017). For example, Xin et al. (2017), showed that personality traits such as neuroticism, extraversion, and openness influence the way in which an individual appraises a stressful situation, evidenced by changes in cortisol activation as well as subjective affect in relation to the stress response.

Physiological measures such as electrodermal activity (EDA), respiration, and electrocardiography (ECG) derived measures such as HRV can reflect autonomic nervous system activity and therefore provide insights into a person's emotional reactivity to a stressor. Given that not every individual reacts to stressors in the same way, pairing physiological measures of stress with other self-report measures of stress, anxiety and mood can help provide a better picture of a person's overall stress reaction.

Previous research suggests that the visual environment plays an important role in the recovery from stress that prompts these physiological responses (Grinde et al., 2009). Environments that are perceived as aesthetically pleasing, such as those that include natural elements and fractal patterns, can have a positive impact on autonomic nervous system (ANS) functioning. Stress reduction theory (SRT) proposes that the experience of nature activates the parasympathetic nervous system (PNS) and mediates psychophysiological stress recovery (Ulrich et al., 1991). In addition, recent studies in neuropsychology have revealed that the human visual system has adapted to natural fractal patterns and can process them easily, otherwise known as *fractal fluency* (Taylor et al., 2016). This fluency generates positive feelings and reduction in physiological stress. Additional research is needed to elucidate the impact of different biophilic elements on stress beyond that of visual processes (Annerstedt et al., 2013; Alvarsson et al., 2010).

To measure the impact of visual, auditory, and multisensory biophilic design on stress, Empatica E4 device *(Empatica Inc., Cambridge, MA)* was used for continuous monitoring of physiological signals. Empatica E4 is a non-intrusive wearable for real-time data acquisition equipped with four embedded sensors: photoplethysmograph (PPG), electrodermal activity (EDA), a 3-axis accelerometer, and skin temperature (Garbarino et al., 2014). Participants were instructed to wear the device on their non-dominant hand throughout the workday to assess changes in skin conductance and HR associated with physiological-stress related events.

In this study, we primarily focused on EDA as it has been shown to be a reliable non-invasive biomarker of sympathetic nervous system activity (Christensen et al., 2020; Seoane-Collazoet al., 2015). Electrodermal activity, also known as galvanic skin response (GSR) is a measure of the change in the electrical conductance of the skin due to sweat production (Critchley, 2002; Edelberg et al., 1993). Although temperature control is the main function of sweat glands, they also play a role in emotional-evoked sweating, especially the eccrine glands located in the palmar and plantar sides of hands and feet (Kobielak et al., 2015; Posada-Quintero & Chon, 2020). Since there is no parasympathetic innervation of the sweat glands, EDA is considered to be a measure of sudomotor innervation of the eccrine sweat glands and thus, a measure of SNS arousal (Benedek & Kaernbach, 2010; Ellaway et al., 2010). As such, EDA has been widely used to measure the variability in physiological sympathetic arousal in the literature (Critchley, 2002).

The EDA signal is characterized by two main components: a slowing, changing component that reflects the tonic level of electrical conductivity of the skin, also known as the skin conductance level (SCL), and a phasic component that reflects fast changes in the EDA signal, known as the skin conductance responses (SCRs) (Boucseinet al., 2012). Non-specific SCRs (NS-SCRs) are the number of SCRs that occur over a period of time, and can be considered spontaneous changes in electrodermal activity that occur in the presence of a sustained stimulus. For this study, we computed the frequency and amplitude of non-specific SCRs (NS-SCRs) and SCL. NS-SCRs, SCL, and SCRs are sensitive to stress-related events and are widely used indicators of ANS activity during exposure to natural settings (Kim et al., 2018; Yin et al., 2019; Yin et al., 2020).

HR also changes in response to stressful events and is the most common, non-invasive clinical measure to assess the status of body functioning. Interactions between the SNS and PNS result in variations in HR values and alterations in HR properties, such as time fluctuations between successive heart beats (heart rate variability or HRV) (Ernst, 2017; Schubert et al., 2009).

2.4.2. Attention restoration and fatigue

Attention restoration theory was introduced by Kaplan and Kaplan (1989) and it proposes that our ability to maintain attention on tasks that require higher levels of focus (directed attention) can only be engaged for a limited amount of time (Kaplan & Kaplan, 1989). Exposure to nature can minimize directed attention fatigue by forcing humans to engage in soft fascination, or by having their attention captured in a less effortful way (Hartig et al., 2016; Kaplan, 1995). As in previous research, the Necker Cube Pattern Control task (NCPCT) was used in this study measure directed attention (Sahlin et al., 2016; Tennessen & Cimprich, 1995). Here, participants first see a blank computer screen with a line drawing of a three-dimensional cube, followed by a set of instructions in which they are told that their perspective on the cube will shift, with the front and back faces of the cube reversing their relative positions. They were then instructed to look at the cube and tap the spacebar when they perceived a pattern reversal. Frequent reversals occurring despite the effort to hold a pattern serves as an indication of directed attention fatigue. The number of reversals were recorded from two 30-s "free" periods where participants indicate any reversals they observed, and two 30-s "hold" periods where they were asked to focus on one pattern for as long as possible. The percentage difference between "free" and "hold" periods served as the dependent measurement.

2.4.3. Cognitive performance measures

Previous studies have shown that exposure to nature can positively impact cognitive performance (Berman et al., 2008; Yin et al., 2018; Yin et al., 2019). As described in Yin et al. (2019), convergent cognitive processes are further defined by attentional processing tasks, which have previously been measured using tests of attention restoration such as those described in section 2.4.2. To further understand the impact of indoor biophilic design on cognitive function, and more specifically, selective attention, other measures of executive function must be utilized (Yin et al., 2019).

Neuroscience and cognitive psychology research suggest that there are at least three executive functions that are suitable for assessing underlying performance across various work tasks (Jamrozik et al., 2019). The current research incorporates validated electronic tasks of working memory, response inhibition, and task switching. Participants performed the cognitive tests at their desks using a web application. Participants were reminded by email to complete the tests between 1 and 3 pm on Tuesdays and Thursdays.

In the Operation Span test (Foster et al., 2015; Unsworth et al., 2005) evaluating *working memory*, participants were asked to remember sets of letters while solving math problems. The Unit Score, defined as the proportion of letters participants can recall correctly in the appropriate order, was assigned as the dependent measure. Data from participants failing to maintain satisfactory math performance ($\geq$ 80%) were excluded from analyses (11.98% of cases) to follow standard practice for this task assessment.

Task switching was measured using the magnitude/parity test (Arrington & Logan, 2005; Kool et al., 2010). In this test, participants were instructed to answer as promptly as possible 1) whether a number is greater or less than five or 2) whether the number is odd or even, with the question they respond to depending on the color of the number shown (1–4, 6–9). Two categories, "Stay" or "Switch" trials, were used to distinguish each sequential trial. A trial following the same type of preceding trial (e.g., a greater or less than five trial followed by another greater or less than five trial) was categorized as "Stay". "Switch" trials were labeled when the trial type was different from the previous trial. The reaction time difference between the correct answers from Stay and Switch trials were defined as the dependent measurements for this task. To remove outliers, reaction times faster than 200 ms and slower than 3000 ms were excluded, then log-transformed to remove skew. To minimize practice effects that can arise with task switching (Kramer et al., 1999), participants completed these tasks multiple times throughout the acclimation period, at the beginning of the study.

The Stroop test was used to measure *response inhibition* (Besner et al., 1997). Participants were asked to respond as quickly as possible with the color of the words that appeared on the screen. Words were randomly presented with a congruent color (GREEN written in green) or incongruent color (RED written in blue). An initial test was used to determine if any of the participants were color blind, with no participants testing positive for color blindness. The reaction time difference between the correct answer from congruent and incongruent trials were defined as the dependent measurements. Outliers were removed and practice effects were minimized (Davidson et al., 2003) in a similar process as that mentioned for task switching.

2.4.4. Survey design and measures

Participants completed surveys reporting their daily experience at various times throughout the workday. *The Positive and Negative Affect Schedule* (PANAS) (Watson et al., 1988) was used, and consists of two, 10-item scales to measure each affect type, and each item is rated on a five-point Likert scale of 1 ("Not at all") to 5 ("Very much"). *The Job Stress Scale* (Lambert et al., 2007) was used once a week to assess participants' workplace stress, and consists of five questions using a five-point Likert scale from 1 ("Strongly disagree") to 5 ("Strongly agree"). To measure subjective "in the moment" feelings of stress, participants were asked to periodically rate their perceived stress using a seven-point Likert scale item from 1 ("Not at all stressed) to 7 ("Extremely stressed"). *The Connectedness to Nature Scale* (Mayer & Frantz, 2004) was used to measure individual's' feelings of emotional connectedness to the natural world. Participants were asked to rate their level of agreement with a set of 14 statements ranging from 1 ("Strongly disagree") to 5 ("Strongly agree"). *The State-Trait Anxiety Inventory (STAI)* (Spielberger et al., 1983) was used to measure trait-like levels of anxiety (20 items) at the start of the study and state-like feelings of anxiety (20 items) throughout the study, rated on a 4-point Likert scale (e.g., from "Almost Never" to "Almost Always"). Finally, a set of questions from an adapted version (Park, 2015) of the *Cost-effective Open-Plan Environments (COPE) survey* (Veitch et al., 2007) were given to participants at the end of each workday to assess their satisfaction with environmental features, including workstation characteristics, physical conditions, perceived productivity, and job satisfaction. All ratings were on a scale from 1 ("Very dissatisfied") to 7 ("Very satisfied"). The survey distribution schedule is shown in Table 2.

Table 2
Survey delivery schedule.

	Monday	Tuesday	Wednesday	Thursday	Friday
9:00 a.m.	DSS PANAS NCPCT	PANAS	DSS PANAS NCPCT	PANAS	DSS PANAS NCPCT
11:00 a.m.	DSS PANAS	PANAS	DSS PANAS	PANAS	DSS PANAS
1:00 p.m.	DSS PANAS	PANAS	DSS PANAS	PANAS	DSS PANAS
3:00 p.m.	DSS PANAS NCPCT COPE	PANAS COPE	DSS PANAS NCPCT COPE	PANAS COPE CNS STAI Job Stress Scale	DSS PANAS NCPCT COPE

Note. DSS: Dynamic Stress Scale, CNS: Connectedness to Nature, STAI: State-Trait Anxiety Inventory, COPE: Cost-effective Open-Plan Environments, PANAS: Positive Affect Negative Affect Scale, NCPCT: Necker Cube Pattern Control Task.

2.4.5. Environmental measurements and monitoring

Wireless environmental sensors were placed throughout the office as shown in Fig. 2. Desk-level air temperature and relative humidity (RH, n = 9), horizontal illuminance and CCT (n = 9), sound level (dBA, n = 3), and CO$_2$ (n = 6) sensors were placed on partitions between desks. Additionally, temperature and RH (n = 1), sound level (n = 1), and CO$_2$ (n = 1) were also measured in the break area, and vertical illuminance and CCT were measured on four externally facing windows (n = 4, height of 1.65 m), three along the east façade and one along the north façade.

A spatial and temporal assessment of temperature, RH, sound levels, illuminance, and CCT sensor data across all the conditions and study cohorts was conducted using the methodology described in the supplementary materials (see Section E.)

2.5. Data analysis and statistical analysis

2.5.1. Physiological indicators of stress

EDA signals retrieved from the Empatica E4 device were analyzed in the time domain using MATLAB® and Ledalab® (Benedek & Kaernbach, 2010). Continuous decomposition analysis (CDA) was conducted to extract tonic and phasic components of EDA during a typical office workday (8hr-period). The threshold for skin conductance response amplitude was set to 0.01 μS (Benedek & Kaernbach, 2010; Braithwaite et al., 2013) with default settings for filtering and smoothing from the software (Benedek & Kaernbach, 2010). The mean skin conductance level (SCL) and mean amplitude and frequency of non-specific skin conductance responses (NS-SCRs) per minute were computed, and the differences in these EDA measures for each experimental condition were compared to baseline using linear mixed effect models (lmerTest) package (Version 3.1-0) (Kuznetsova et al., 2015).

Analysis of HR data retrieved from the Empatica device was performed using Matlab® and R® with values below 40 and above 200 excluded. Linear mixed effect models (lmerTest) package (Version 3.1-0) (Kuznetsova et al., 2015) were used to assess potential differences between the HR values in the experimental conditions compared to baseline.

For each model, a covariate adjustment was made for time of day and a random intercept for participant was included to account for repeated measures. P-values were determined using Satterthwaite's approximation (Satterthwaite, 1946), *p*-values less than 0.05 were considered significant. To test for a potential interaction between biophilic condition and time of day for each of the 4 physiological variables of interest (SCL, NS-SCRs per min, NS-SCRs amplitude, and HR) we used a Scheirer-Ray-Hare test (Sokal & Rohlf, 1995), or essentially a non-parametric version of a two-way ANOVA with interactions (two-way Kruskal-Walis test). Tests were two-sided and *p*-values less than

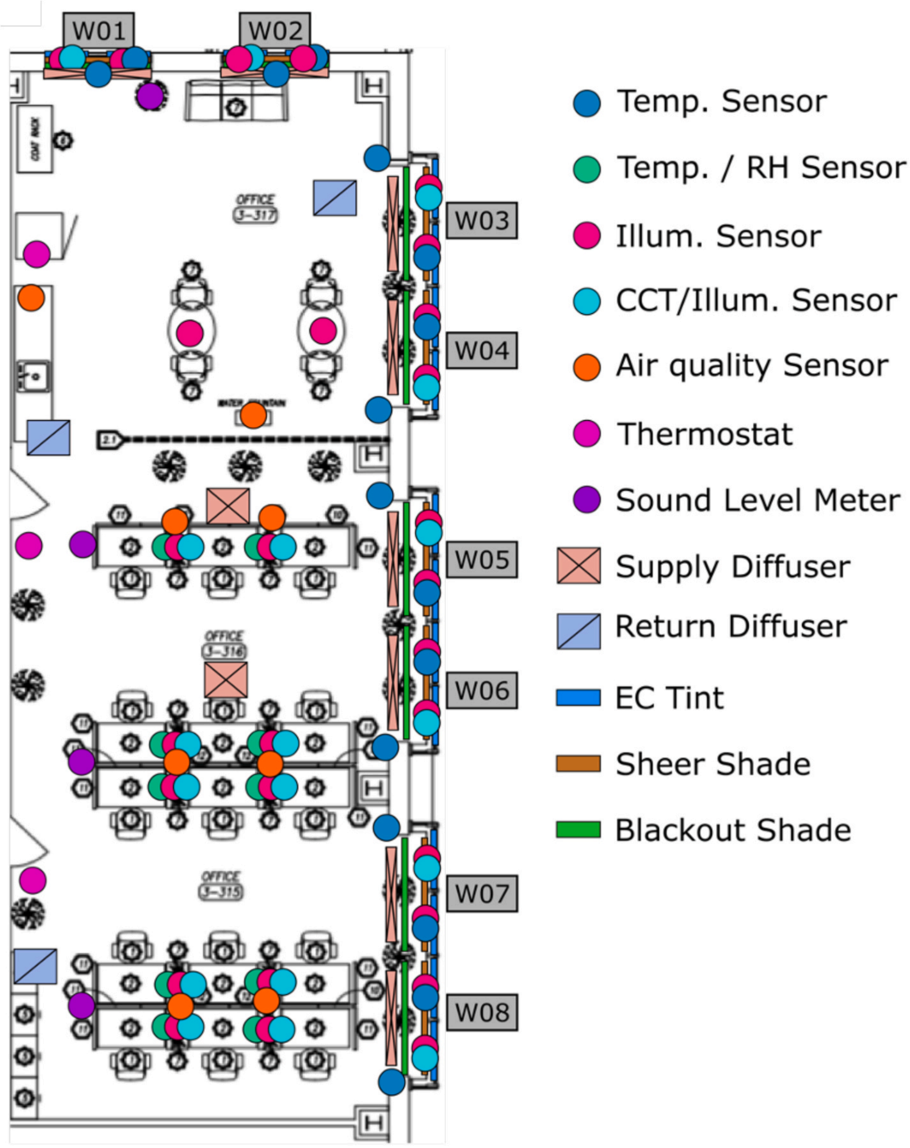

Fig. 2. Environmental sensor deployment map. W0## represent window numbers.

0.05 indicated significance.

2.5.2. Cognitive performance and survey measures

Linear mixed-effects analyses using the lme4 (Version 1.1–21) package in R (Version 3.6.1) were used to examine cognitive performance across all conditions (baseline, auditory, visual, multisensory). Random intercepts for participants were included in each model to account for repeated measures. The tests in the linear mixed effects models (lmerTest) package (Version 3.1-0) (Kuznetsova et al., 2015) were used to obtain p-values using Satterthwaite's approximation (Satterthwaite, 1946), and confidence intervals for the fixed effect estimates were obtained using the effects package (Version 4.1-1) (Fox & Weisberg, 2019).

Pairwise comparisons of the conditions were performed using the estimated marginal means (emmeans) package (Version 1.4) (Lenth et al., 2019). The covariates of interest have been shown to impact cognitive performance, which include caffeine intake (Barone & Roberts, 1996), amount of exercise (Andersen et al., 1999), amount of mindfulness practice (Carmody & Baer, 2008), positive affect, and negative affect (Watson et al., 1988) were separately tested for inclusion in each of the cognitive performance models.

Models of the Response Inhibition and Task Switching measures included additional fixed effects of trial type (e.g., Congruent vs. Incongruent) and trial sequence (within a task) to identify differences in the trial-specific effects on reaction time under different environmental conditions (i.e., if the difference between Congruent and Incongruent trials was smaller in the auditory condition than the baseline condition).

2.5.3. Environmental measurements

Statistical summaries of all environmental conditions were calculated for the hours of 6:00 am to 10:00 pm, which was the approximate range of time the office was occupied during the three cohorts. Mixed linear effects models were used to evaluate whether environmental conditions at each sensor varied significantly between experimental conditions and baseline. These models used each environmental parameter as the response variable and included cohort number and condition (baseline, auditory, visual, and multisensory) as independent variables.

3. Results

3.1. Physiological indicators of stress

Data from two participants (n = 37) were excluded from analysis due to their absence from the office for more than a week during the study period. The summary of heart rate measurements obtained across the remaining 35 participants are shown in Fig. 3(a). Mean HR observed in the baseline intervention was 79.3 (SD = 4.9). Similarly, HR mean and standard deviation during the visual, auditory, and multisensory condition were 80.6 ± 4.1, 80.6 ± 5.5, 79.3 ± 5.3, respectively. Among 35 participants, the average number of non-specific skin conductance responses (NS-SCRs) per minute elicited during the four conditions including baseline are shown in Fig. 3(b). The estimated average number of NS-SCRs per minute obtained during the baseline condition were 23.7 ± 4.8. Likewise, the average estimates of NS-SCRs per minute obtained during the biophilic interventions were 22.1 ± 8.3 for the visual, 23.2 ± 6.1 for the auditory, and 20.4 ± 6.1 for the multisensory condition. Similarly, the average amplitude of the NS-SCRs obtained for the baseline condition was 0.08 ± 0.02, 0.08 ± 0.04 for visual, 0.08 ± 0.03 for auditory, and 0.07 ± 0.02 for the multisensory condition (see Fig. 3 (c)). The skin conductance level (SCL) estimates were as follows: 0.6 ± 0.7 (baseline), 0.8 ± 1.2 (visual), 0.6 ± 0.9 (auditory), 0.6 ± 0.8 (multisensory), and are summarized in Fig. 3(d).

The results from the statistical analysis performed for the physiological indicators of stress are described in Table 3. SCL and HR were not significantly lower during any of the biophilic conditions compared to baseline. However, the *amount* of NS-SCRs per minute were significantly lower when participants were exposed to the visual ($p = 0.002$) and multisensory conditions ($p < 0.001$), and the *amplitude* of NS-SCRs was lower in the multisensory condition compared to the baseline condition ($p = 0.007$). No significant changes were observed in the auditory intervention.

Time of day effects across all conditions are summarized in Table 3. Participants' heart rate increased between 1 p.m. and 3 p.m. ($p < 0.008$) compared to the morning (9 a.m.–11 a.m.). Similarly, the average *amount* of NS-SCRs per minute was significantly lower in the morning compared to all other times of day (11 a.m.-1 pm ($p < 0.001$), 1–3 pm ($p < 0.009$) and 3–5 pm ($p < 0.001$)). Furthermore, the amplitude of NS-SCRs significantly increased at the end of the workday (3 p.m.–5 p.m.)

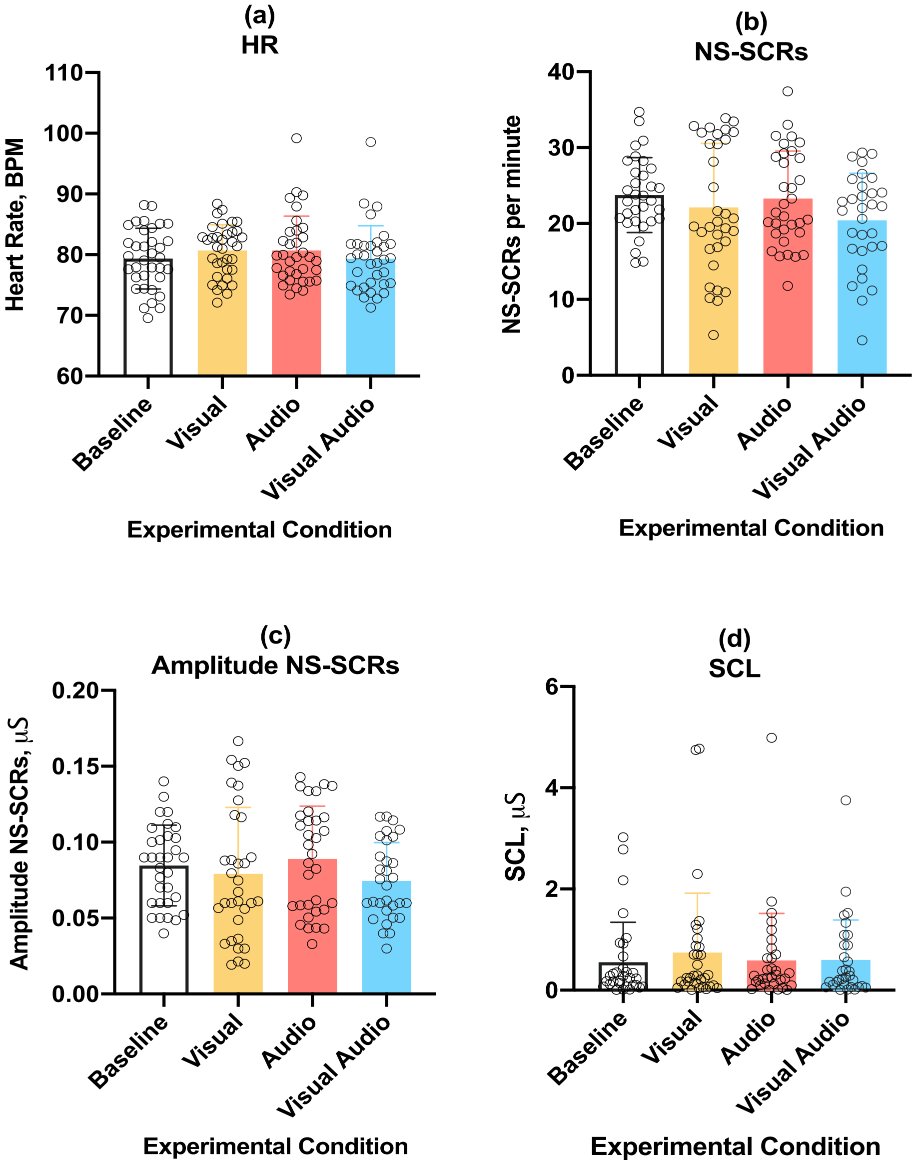

Fig. 3. Mean estimates of the (a) heart rate, (b) NS-SCRs per minute, (c) Amplitude of NS-SCRs and (d) SCL under four different experimental conditions. The error bars correspond to the standard deviation between thirty-five different participants.

Table 3
Mixed-effects model estimates over the different experimental conditions for mean measurements of SCL, NS-SCRs per min, NS-SCRs amplitude and HR. A covariate adjustment was made for time of day for each measurement. Significant differences are indicated by an *.

	Model Estimate (β)	95% CI	P-Value
Heart Rate			
Visual	1.176	(-0.290, 2.641)	.125
Auditory	1.492	(-0.068, 2.880)	.062
Multisensory	−0.126	(-1.611, 1.359)	.549
Time of Day			
11am – 1pm	0.325	(-1.193, 1.843)	.758
1pm–3pm	2.190	(0.679, 3.701)	.008 *
3pm–5pm	0.536	(-0.982, 2.054)	.650
Skin Conductance Level			
Visual	1.153	(0.907, 1.467)	.245
Auditory	1.124	(0.883, 1.431)	.343
Multisensory	1.159	(0.906, 1.483)	.241
Time of Day			
11am – 1pm	1.210	(0.948, 1.545)	.126
1pm–3pm	1.104	(0.863, 1.410)	.432
3pm–5pm	0.945	(0.735, 1.216)	.661
Skin Conductance Responses per Minute			
Visual	−1.451	(-2.350, −0.551)	.002 *
Auditory	−0.182	(-1.086, 0.723)	.694
Multisensory	−2.651	(-3.574, −1.727)	<.001 *
Time of Day			
11am – 1pm	1.992	(1.072, 2.912)	<.001 *
1pm–3pm	1.238	(0.316, 2.159)	.009 *
3pm–5pm	3.114	(2.171, 4.057)	<.001 *
Skin Conductance Responses Amplitude			
Visual	−0.362	(-0.917, 0.193)	.202
Auditory	0.491	(-0.068, 1.049)	.086
Multisensory	−0.789	(-1.359, −0.219)	.007 *
Time of Day			
11am – 1pm	0.085	(-0.482, 0.652)	.769
1pm–3pm	0.071	(-0.497, 0.638)	.807
3pm–5pm	1.478	(0.896, 2.060)	<.001 *

Note. Model effects of NS-SCRs amplitude are scaled by a factor of 100.

compared to the morning ($p < 0.001$).

For each of the four physiological measures, we did not find an interaction between biophilic condition and time of day (HR $p = 0.796$; SCL $p = 0.923$; NS-SCRs/min $p = 0.719$; NS-SCRs Amplitude $p = 0.226$).

3.2. *Attention restoration and cognitive performance measures*

There was a positive effect of biophilic interventions on cognitive function performance, however, not all three measures were similarly impacted (see Table 4 for model details and Table 5 for descriptive statistics).

Working memory, measured by the Unit Score, improved reliably in all biophilic design conditions compared to baseline (Fig. 4). The Unit Score improved by 8.7% in the auditory condition ($p < 0.001$), 7.6% in the multisensory condition ($p = 0.001$) and 7% in the visual condition ($p = 0.003$). This pattern of findings remained the same after including all covariates in the model (see Table C1).

The dependent variable for the task switching test was reaction time for each correctly answered trial, and the independent variables were experimental condition, trial type (Switch vs. Stay), and sequence number (the trial number within the task). Across all conditions, participants were 10.02% slower to respond to Switch trials than Stay trials ($p < 0.001$), displaying stability in the Task Switching effect. However, when comparing response time by biophilic interventions, task switching yielded mixed results. Compared to baseline, participants responded 1.37% faster during the auditory condition ($p = 0.002$). Response times during the visual condition did not change relative to baseline, and participants were 1.05% slower in the multisensory condition relative to baseline ($p = 0.014$). This trend remained the same after accounting for all covariates, a summary of which can be found in Table C2.

For response inhibition results, reaction time for each correctly answered trial was the dependent variable, while trial type (Congruent vs. Incongruent), condition, and sequence number (the trial number within the task) were the independent variables. People were 9.92% slower to respond to incongruent trials than congruent trials across all experimental conditions ($p \leq 0.001$). In addition, individuals' overall reaction time was not influenced by the sequence of each trial and session. The difference between incongruent and congruent trials, known as interference cost, was not significant when comparing each of the biophilic conditions against each other. However, there was a positive effect for each of the biophilic interventions when compared to baseline, with participants' reaction time improving by 1.47%, 2.95% and 1.85%

Table 4
Model summary of three executive function measurements.

	Unadjusted Univariate			Adjusted Multivariate*		
	B	95% CI	*p*	*B*	95% CI	*p*
Working Memory Unit Score						
Intercept (Baseline)	.801	(.751, .851)	<.001	1.079	(.923, 1.233)	<.001
Visual	.056	(.019, .093)	.003	.054	(.016, .091)	.006
Auditory	.070	(.031, .109)	<.001	.066	(.026, .104)	.001
Multisensory	.061	(.025, .098)	.001	.059	(.023, .096)	.002
ICC	.512					
Task Switching Reaction Time						
Intercept (Baseline)	6.8870	(6.8329, 6.9417)	<.001	6.6010	(6.4563, 6.7452)	<.001
Visual	.0009	(-.0075, .0093)	.838	.0017	(-.0067, .0102)	.685
Auditory	-.0138	(-.0224, −.0051)	.002	-.0140	(-.0222, −.0048)	.002
Multisensory	.0104	(.0021, .0187)	.014	.0109	(.0025, .0193)	.011
Switch trial (vs. Stay)	.0955	(.0896, .1014)	<.001	.0958	(.0899, .1017)	<.001
Seq	.0000	(-.0001, .0001)	.805	.0000	(-.0001, .0001)	.785
ICC	.204					
Response Inhibition Reaction Time						
Intercept (Baseline)	6.8140	(6.7653, 6.8620)	<.001	6.5560	(6.4358, 6.6774)	<.001
Visual	-.0148	(-.0230, −.0065)	<.001	-.0148	(-.0230, −.0065)	<.001
Auditory	-.0299	(-.0384, −.0213)	<.001	-.0304	(-.0390, −.0218)	<.001
Multisensory	-.0187	(-.0270, −.0105)	<.001	-.0192	(-.0275, −.0109)	<.001
Incongruent trial (vs. Congruent)	.0946	(.0888, .1004)	<.001	.0946	(.0887, .1003)	<.001
Seq	.0000	(-.0001, .0001)	.578	.0000	(-.0001, .0001)	.576
ICC	.177					

Note. *Models are adjusted for caffeine intake, level of exercise, mindfulness practice, positive, and negative affect.

Table 5
Descriptive statistics of cognitive performance tasks and surveys.

	Baseline		Visual		Auditory		Multisensory	
	M	SD	M	SD	M	SD	M	SD
Cognitive Performance								
Working Memory	0.812	0.200	0.860	0.159	0.872	0.178	0.877	0.165
Response Inhibition								
Congruent Trials (ms)	941.694	350.392	937.367	346.417	895.770	295.412	915.365	312.168
Incongruent Trials (ms)	1059.865	428.940	1046.753	435.996	1007.360	403.779	1020.492	408.181
Task Switching								
Stay Trials (ms)	1011.867	400.451	1031.492	423.911	993.849	393.557	1023.256	410.911
Switch Trials (ms)	1118.507	423.119	1116.350	422.468	1086.343	413.484	1113.468	412.262
Survey								
PANAS – Positive	29.140	10.846	29.193	11.083	28.430	11.295	29.187	11.363
PANAS – Negative	11.974	3.133	12.147	3.890	12.086	3.612	12.042	3.139
Dynamic Stress Scale	2.081	1.331	1.992	1.362	1.879	1.243	1.904	1.203
Job Stress Scale	11.841	4.052	11.787	3.873	10.766	3.434	11.679	4.282
Connectedness to Nature Scale	3.625	0.590	3.609	0.709	3.625	0.632	3.628	0.585
State Trait Anxiety Inventory	37.364	11.406	37.875	13.195	36.638	9.449	37.365	11.682

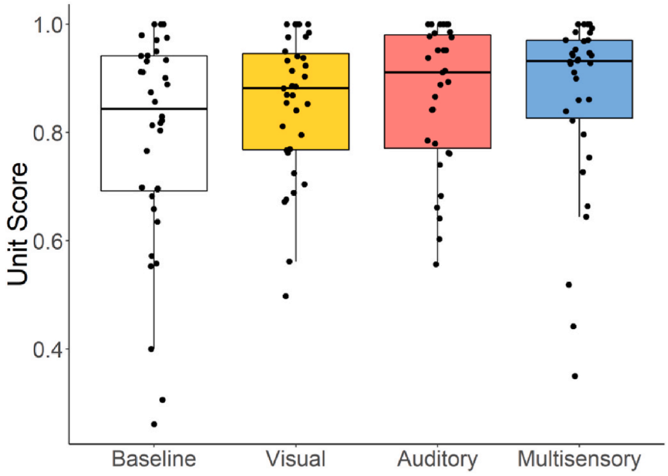

Fig. 4. Working memory unit score by experimental condition.

in the visual, auditory and multisensory conditions, respectively ($p < 0.001$ for all). Similar to results from the task switching tests, the auditory condition showed the most significant effects. The main effects remained when including covariates in the model. Covariate effects can be seen Table C3. Despite significant differences observed across executive function measures, no significant differences were observed for directed attention when comparing each biophilic intervention to baseline.

3.3. *Survey measures*

Model summary and descriptive statistics for all survey measures are summarized in Tables 5 and 6, respectively.

3.3.1. *Connectedness to nature*

Participants' feelings of connectedness to nature did not vary across the conditions, or in comparing conditions to participants' feelings from the baseline acclimation survey.

3.3.2. *Positive Affect Negative Affect Scale (PANAS)*

Compared to baseline, participants' positive affect remained the same in all biophilic conditions, while negative affect scores increased in the auditory condition (β = 0.267, 95% CI [0.04, 0.50], $p = 0.023$). Additionally, participant positive affect scores decreased significantly at the end of day (β = −0.869, 95% CI [-1.32, −0.42], $p < 0.001$) compared to the beginning of the workday.

Table 6
Model summary of survey measurements.

	Unadjusted Univariate		
	B	95% CI	*p*
PANAS – Positive			
Intercept (Baseline)	28.996	(25.856, 32.135)	<.001
Visual	.007	(-.451, .465)	.975
Audio	-.261	(-.723, .201)	.268
Multisensory	.112	(-.344, .568)	.629
ICC	.762		
PANAS – Negative			
Intercept (Baseline)	11.950	(11.203, 12.696)	<.001
Visual	.175	(-.053, .403)	.132
Audio	.267	(.036, .497)	.023
Multisensory	.149	(-.079, .376)	.200
ICC	.412		
Dynamic Stress Scale			
Intercept (Baseline)	2.110	(1.768, 2.453)	<.001
Visual	-.055	(-.147, .037)	.242
Audio	-.143	(-.236, −.051)	.002
Multisensory	-.126	(-.217, −.034)	.007
ICC	.607		
Job Stress Scale			
Intercept (Baseline)	12.306	(10.910, 13.710)	<.001
Visual	-.637	(-1.319, - 0.049)	.071
Audio	-.966	(-1.647, −0.285)	.006
Multisensory	-.706	(-1.364, −0.045)	.038
ICC	.857		
Connectedness to Nature Scale			
Intercept (Baseline)	3.569	(3.356, 3.781)	<.001
Visual	-.005	(-.152, .143)	.953
Audio	-.001	(-.149, .147)	.989
Multisensory	.046	(-.097, .189)	.529
ICC	.713		
State Trait Anxiety Inventory			
Intercept (Baseline)	38.201	(34.366, 42.074)	<.001
Visual	-.562	(-3.277, 2.167)	.687
Audio	-.532	(-3.249, 2.188)	.703
Multisensory	-.604	(-3.243, 2.040)	.656
ICC	.706		

3.3.3. *Perceived stress*

Participants reported stress on Mondays, Wednesdays, and Fridays every 2 h between 9 am and 3 pm. Compared to baseline, significant differences in stress were observed in the auditory (β = −0.143, 95% CI [-0.24, −0.05], $p = 0.002$) and multisensory conditions (β = −0.126, 95% CI [-0.22, −0.03], $p = 0.007$).

3.3.4. Job stress scale questionnaire

The Job Stress scale (Lamber, Hogan, Camp, & Ventura, 2006) was distributed on Thursdays at 3 pm. Compared to baseline, all biophilic conditions showed a positive effect on participants' workplace stress. Participants experienced less job-related stress in the auditory ($\beta = -0.966$, 95% CI [-1.65, −0.29], $p = 0.006$) and multisensory ($\beta = -0.706$, 95% CI [-1.36, −0.05], $p = 0.38$) conditions, and marginally less job stress in the visual condition ($\beta = -0.637$, 95% CI [-1.32, 0.05], $p = 0.071$).

3.3.5. Environmental and work-related satisfaction

Overall, participants reported being more satisfied with the workplace in the biophilic conditions than in the baseline condition (see Fig. 5). Participants reported higher levels of satisfaction with the aesthetic appearance of their work area and visual privacy for conversation in the visual and multisensory conditions (all demonstrating $p \leq 0.001$) compared to baseline. Similarly, participants reported feeling less frequently distracted by other people and more satisfied with the background noise in the visual condition ($p \leq 0.001$ and $p = 0.002$, respectively). There were no changes in ratings of visual privacy and distractions from other people in the auditory condition. However, satisfaction with the aesthetic appearance of the work area decreased ($p \leq 0.01$) when participants were exposed to the auditory intervention.

Participants displayed significant changes in the extent to which they felt their work area supported their personal productivity in the multisensory ($p = 0.002$) and visual conditions ($p = 0.068$) compared to baseline.

Air quality and circulation rates were not changed during the study. Nevertheless, participants reported higher satisfaction with air movement in the visual ($p = 0.015$) and multisensory ($p = 0.031$) conditions. Similarly, when asked about the cleanliness in their work area, participants reported feeling less satisfied in the auditory condition ($p = 0.002$) compared to baseline. See Table D1 for model details and descriptive statistics.

3.4. Environmental measurements results

Statistical summaries of environmental parameters across all sensors for each condition are included in supplemental materials, section F.

4. Discussion

The main goal of this work was to measure the extent to which visual, auditory and multisensory biophilic design, similar to what one would experience in nature, reduces stress, improves mood, and increases perceived productivity, cognitive performance, and directed attention in office environments. Previous studies have demonstrated the potential for visual and auditory stimulation to more quickly prompt stress recovery, as measured with HRV (Annerstedtet al., 2013). In this study, when participants were exposed to both visual and a combination of auditory and visual biophilic elements, phasic reactions associated with sympathetic nerve activity decreased compared to the baseline condition (Fig. 3 (b, c) & Table 3). An increased frequency and amplitude of individual SCRs and tonic conductance level is typically associated with greater emotional arousal during a stressful situation vs. a non-stressful situation (Braithwaite et al., 2013; Sarchiaponeet al., 2018). Our results

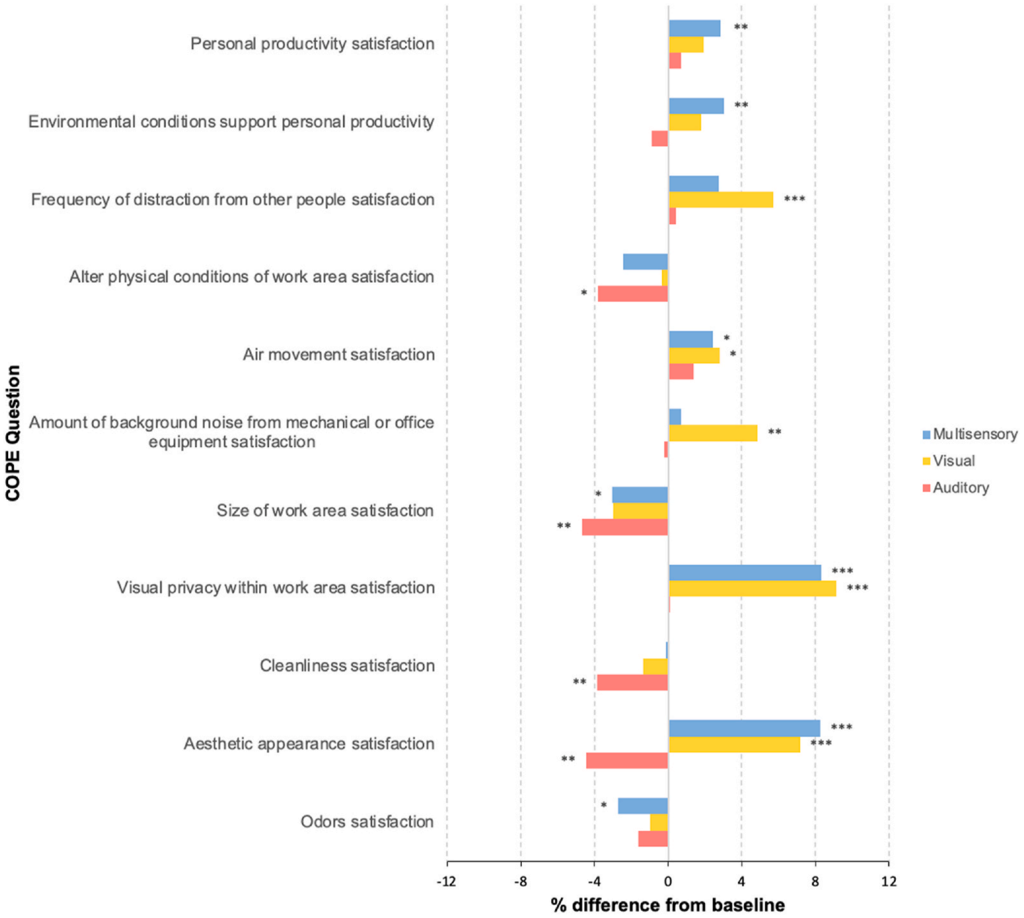

Fig. 5. Differences between work environment satisfaction and workday experience ratings for the three biophilic experimental conditions (visual, audio and multisensory) in comparison to baseline. Each bar represents percentage increase or decrease from Baseline. Only questions with significant statistical differences are shown in this figure- *$p < 0.05$. **$p < 0.01$. ***$p < 0.001$.

indicate that the multisensory condition in particular, showed a reduction in both NS-SCRs frequency and NS-SCRs amplitude, suggesting lower stress when compared to the other experimental conditions against baseline. This would suggest that multisensory biophilic interventions have the most potential to positively mitigate the experience of stressors. This is consistent with previous studies, demonstrating that physiological recovery from stress (skin conductance) was greater after exposure to real and simulated natural environments (Hedblomet al., 2019; Li & Sullivan, 2016; Ulrich et al., 1991). Importantly, self-ratings of stress were consistent with the above-mentioned results. Participants felt less stressed in each of the biophilic conditions, especially in the multisensory intervention, but with no significant changes to SCL and HR (Fig. 3 (a, d) & Table 3). When considering the time of day impacts on NS-SCRs frequency and amplitude, results indicate that participants felt more stress towards the end of the workday, consistent with our PANAS results showing a decrease in positive affect at the end of the workday. These findings were consistent regardless of condition.

In addition to stress, participants' cognitive performance improved in all biophilic conditions compared to baseline. Their ability to hold information in their mind while performing a certain task (working memory) and suppress dominant responses (response inhibition) improved across all biophilic interventions, particularly in the auditory and multisensory conditions. Conversely, participant's' ability to shift attention between tasks (task switching) improved in the auditory condition and worsened in the multisensory intervention (see Table 4). This finding suggests that introducing multiple biophilic design stimuli may in fact result in distractions for employees whose jobs require them to alter between multiple tasks at once. Future studies should further examine the impact of biophilic conditions on executive function by studying those with varying job requirements.

We did not observe an impact on participants' attention when exposed to biophilic interventions. Previous studies have shown that directed attention can be restored by being exposed to nature, such as walking in a park or forest, or viewing nature images (Berman et al., 2008; Crossan & Salmoni, 2019; Kaplan & Berman, 2010; Tennessen & Cimprich, 1995). While the biophilic interventions introduced in the study might have had a restorative effect, we may not have seen a difference in attention from the NCPCT given temporal limitations. This was a long-term study and directed attention recovery has been typically quantified in the short-term, occurring as soon as 40 s after experiencing nature (Lee et al., 2015). The Necker Cube Pattern Control Task (NCPCT) may not have measured recovery from directed attention fatigue as participants spent most of their working day in one single environment, and these tasks were administered intermittently throughout the week. Future studies with longer exposure times in indoor environments could benefit from continuous measures of directed attention fatigue, including eye-tracking technology to measure gaze attention.

Fig. 5 summarizes participants' workplace satisfaction by condition. Participants were more satisfied with the aesthetics of the office when plants and projections of greenery were present in the office, which may have contributed to decreased stress. They were also more satisfied with the visual privacy in the office, and reported experiencing fewer visual distractions in the space in those same conditions (visual and multisensory). During these interventions, planters served as desk dividers, which provided participants with a natural privacy barrier. Although air movement and lighting conditions were not changed, participants felt more satisfied with those environmental factors in the visual and multisensory conditions. This could result from human's experiencing environmental factors in a more holistic manner, rather than individually isolating each factor, as previously described in (Jamrozik et al., 2018). Additionally, feelings of connectedness to nature may not have significantly varied across conditions in a similar manner as that of their visual preferences, as participants collectively reported feeling highly connected to nature at the outset of the study. Participants also felt more productive when visual and multisensory natural elements were present in the space. These findings are consistent with previous research, and suggest that workplace productivity increases as a result of visual biophilic design architecture's impact on cognitive performance, satisfaction, and feelings of psychological support by the workplace (Al Horr et al., 2016; Ayuso Sanchez et al., 2018; Lohr et al., 1995).

These findings offer promising evidence for the adoption of office multisensory biophilic features. Our results indicate that immersive interventions, including sounds that are reminiscent of nature as well as visuals that incorporate indoor plants and projections of greenery, have a positive impact on executive functioning - specifically response inhibition and working memory. A multisensory approach also provides stress reduction and satisfaction with the indoor environment, perceived productivity and workplace conditions. Visual features alone provide slight improvements for stress, cognitive performance and satisfaction with the work environment, consistent with previous studies. Future work should explore the extent to which individual design components (i.e., physical plants or digitally rotating natural images) contribute to the improvement of wellbeing and performance in office environments. Auditory features had the strongest impact on working memory and response inhibition, no effect on stress reduction and mixed benefits on occupants' satisfaction and workday experience were observed. In contrast to previous studies showing that nature sounds introduced via headphones can be effective in masking attenuating distractions and improving cognitive performance (Jahncke et al., 2016), an improvement in satisfaction with background noise was not observed in the current study. Given the multisensory benefits demonstrated here, future research could expand on this work by combining biophilic visuals with auditory interventions via headphones, which provide the occupant with the ability to adjust audio settings and select their preferred nature sounds. This could allow us to better understand the generalizability of these results across different auditory conditions. In addition, future studies might also consider implementing a "water wall" which could have a greater auditory and visual impact given that the scale of the water-based intervention would be much greater than the water feature incorporated in this work.

There are several limitations to this study. Beyond self-report, we did not have a method to accurately monitor the amount of time participants spent in the space. This may have introduced variability in the results as not everybody spent the same amount of time in the office for each condition. Future experiments could include real-time locating systems (RTLS) to track the location of participants and estimate the amount of time they are exposed to environmental conditions. Second, we did not measure blood pressure, which has been previously shown to decrease when individuals are exposed to natural elements (Park et al., 2009), nor gaze characteristics, which could provide continuous monitoring of directed attention. Future studies might also consider substituting other objects that were taken up by plants or biophilic visuals for non-visual conditions, as this may have impacted the participants' overall experience of the space. Additionally, we did not collect information regarding participants' job tasks, limiting correlations that can be drawn between the benefits of biophilic interventions and particular job types. Further, the biophilic auditory elements included in the natural soundscape for the auditory and multisensory conditions are those typical of multiple seasons, winter notwithstanding. The birds and crickets interspersed throughout the recording were originally recorded outdoors during late summer and early fall. As such, our auditory soundscape was not aligned with the outdoor natural environment for each cohort who participated at various times of the year (Fall, Winter, and Spring), because the recording remained consistent across all cohorts. Lastly, the order in which the experimental conditions were presented in the study was not fully randomized. Although analysis revealed that the order of conditions may have contributed to learning effects over time, the second baseline period still had worse cognitive scores than the biophilic conditions which would suggest that biophilic interventions had a stronger effect on performance than an improvement over time. Future work should use a randomized design for condition assignment to avoid any possibility of experimental bias.

The aim of the current study was to evaluate the benefits of biophilic sounds combined with visual features on occupants' mood and feelings of connectedness to nature and stress, as well as perceived productivity, attention restoration, and cognitive performance. This study suggests that an immersive biophilic indoor environment can improve occupant satisfaction and aspects of cognitive performance, and reduce stress in office settings. Results show that some benefits were present only when visual biophilic features were combined with their auditory complements. These findings could help architects, designers, and organizations understand how the implementation of multisensory biophilic design, as opposed to solely visual components, could translate to improvements in worker performance, productivity, and overall well-being.

4.1. Research directions

The study presented in this paper addresses a gap in the literature regarding sustained exposure to biophilic elements in indoor environments, such as residential and office settings, by utilizing a living lab approach (Aristizabal et al., 2019; Clements et al., 2019; Jamrozik et al., 2018). The benefits provided by a multisensory design approach also speak to how easily it may be replicated in built environments outside of a research context, given the relatively low-tech approach used to introduce biophilic sounds and visuals in this study. The living lab methodology permits researchers to closely control the environment through manipulation of different design features. As a result, researchers can confidently distinguish between the effects of various natural elements while studying the potential long-term effects of biophilic design on human health. Moreover, future studies in living labs could explore the benefits that result from biophilic design features characterized as *nature of the space* (Browning et al., 2014). This methodology would also allow for the introduction of olfactory and haptic environmental components, which are also critical to recreating an immersive natural experience indoors.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2021.101682.

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