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Evaluating the Restorative Impact of Nature Through Multimodal Mobile Sensing of Neural, Physiological, and Behavioral Activity in Ambulatory Settings

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ABSTRACT

One of the fundamental principles of neuroergonomics is that human cognition is profoundly shaped by the environment in which it operates. In the modern world, this environment can often be highly artificial, noisy, barren, and intentionally distracting. On the other hand, natural environments compare favorably as they may offer not only an appreciation of beauty but a rich array of sensory and contextual information which can be undemanding to the observer. Attention Restoration Theory (ART) proposes that exposure to natural environments can provide various benefits to stress, health, and cognition. Understanding how the brain responds to natural environment presentation poses a crucial hurdle to using traditional neuroimaging techniques as many approaches necessitate highly controlled and resultingly, low-fidelity stimuli presentation to mimic the environmental effects of nature. Functional near-infrared spectroscopy (fNIRS), a non-invasive brain monitoring technology that relies on optical techniques to detect changes in cortical hemodynamic responses to human perceptual, cognitive, and motor functioning, is an ideal candidate tool for understanding the brain in natural environments. In this paper, we will describe an experimental setup that involves the integration of mobile fNIRS systems with simultaneous wrist-based optical heart rate monitoring (OHRM) and electrodermal activity (EDA) recordings that can record the cognitive and physiological responses of individuals to natural settings.

Keywords: Neuroergonomics, Mobile neuroimaging, Nature, Beauty, Attention restoration theory (art), Environmental exposure

INTRODUCTION

Humans living in the modern world occupy vastly different spaces than evolution may have prepared them for. Presently, 55% of the world's population lives in urban areas and this number is expected to increase to 68% by the year 2050 (*World Urbanization Prospects*, 2019). The rise of highly urbanized spaces has been accompanied broadly by the declining availability of green spaces and an overall reduction of natural settings in everyday life (Beyer et al., 2018, p. 29). Living within urban spaces involves significant exposure to noise, pollution, information overload, and other factors which may require individuals to alter their attentional processing to co-exist with the environment (Linnell et al., 2013). In addition to burdens imposed by urban settings, work in modern office settings has been associated with increased burnout, reduced productivity, and a variety of stress-induced illnesses such as depression and anxiety (An et al., 2016). As the costs of sustained stress and attentional demands mount, researchers have explored the benefits of using nature exposure sessions as an antidote (Bratman et al., 2021).

A notable framework attempting to describe both the negative impacts of attention-grabbing environments as well as the restorative quality of nature derives from the neuroscience of attention. Attention Restoration Theory (ART) (Kaplan, 1995) proposes that directed attention can be modeled as a muscle, wherein the sustained attentional demands of urban environments or prolonged focus on work-related tasks results in significant mental fatigue which requires rest to recover from. Here, effortful attention is considered to be the purview of the dorsal attention network and fatigue may induce deficits similar to frontal cortex impairment including difficulty in planning, socializing, and impulse control (Foster et al., 1994; Holtzer et al., 2010; Kaplan and Berman, 2010). On the other hand, natural stimuli are considered to be optimally restorative because they are able to be "softly fascinating" and with which the brain can effortlessly attend while the ability to direct effortful attention is restored. The automatic ventral attention network takes over and is able to engage loosely with these complex, coherent, but undemanding stimuli and promote attentional recovery (Williams et al., 2018).

Another prominent framework advocates psycho-physiological stress as the primary means by which urban environments impact individual physiology and well-being (Ulrich et al., 1991). Ulrich suggests that mental fatigue from prolonged directed attention is also accompanied by an accumulation of physiological and mental stressors which negatively affect the individual. In this framework, unthreatening natural stimuli offer a psychological benefit rooted in an evolutionary and aesthetic preference for nature (Meidenbauer et al., 2019). Accordingly, spending time in visually pleasant environments can help reduce stress and improve mood by promoting parasympathetic activity. Together these two frameworks propose that natural environments are offer significant advantages as a means of restoring an individual's cognitive wellbeing in contrast with urban environments (Kjellgren and Buhrkall, 2010).

Although the cognitive benefits of nature exposure have been studied under a variety of circumstances (Stevenson et al., 2018), neuroimaging studies of nature exposure under real-world contexts are few and far between with the vast majority focusing on virtual or static natural images as a means of nature immersion. Environmental settings in lab research are often purposefully reduced to eliminate experimental variability, these controls can also overlook the negative impacts of barebone environments (Ayaz and Dehais, 2019; Tognoli, 1973). Nature immersion draws on a of number auxiliary non-visual stimuli which are difficult to recreate within the laboratory environment (Mollazadeh and Zhu, 2021). In order to understand how our mind responds to nature, we cannot substitute the experience for a cardboard cutout.

NEUROERGONOMIC ASSESSMENT OF RESTORATIVE ENVIRONMENTS

Neuroergonomics is a research field that aims to study the brain at work and in everyday life (Ayaz and Dehais, 2021; Parasuraman, 2003). This approach asserts that an understanding of human brain function is critical to understanding how individuals operate within society and human-systems. Key to this philosophy is the idea that the environment profoundly shapes the nature of cognition and accordingly, cognitive processes should be studied "in the wild", under realistic contexts which closely match the systems being studied (Curtin and Ayaz, 2018; Dehais et al., 2020). This form of study has been made feasible in part by the proliferation of mobile neuroimaging technologies which has in turn freed researchers from static laboratory experiments. These advances have allowed researchers to study the brain under a wide variety of circumstances including individuals walking outdoors (McKendrick et al., 2016), attending class (Barreto et al., 2021), performing surgery (Shewokis et al., 2017), and even during flight piloting aircraft (Gateau et al., 2018). The ability to study the brain in context is especially important in studies of environmental reception where environmental context is the defining feature.

In addition, neuroergonomics highlights the need for integration of wearable neuroimaging with non-invasive physiological monitoring to provide multi-modal neural and peripheral physiological activity (Curtin and Ayaz, 2018). Early neuroimaging works often have taken the view that peripheral physiological responses to stimulation represent purely nuisance signals which should be filtered to better understand the specific cortical response without assessing the relationships between physiology and the brain. However, physiological response offer unique insights into the underlying brain states and greatly assist in state-related classification (Liu et al., 2017; Mark et al., 2018). Parsing the restorative properties of nature exposure may explicitly require both an understanding of the cortical response from the active dorsal attention network as well as peripheral measures of physiological stress. In this work, we outline a comparative protocol for studying the environmental effects of nature using mobile neuroimaging and non-invasive physiological monitoring.

fNIRS and Nature Assessment

In order to assess cortical function, we will employee functional near-infrared spectroscopy (fNIRS), a non-invasive neuroimaging technique which has emerged over the last two decade (Ayaz et al., 2013). fNIRS uses near infrared light to monitor changes in oxygenated and deoxygenated hemoglobin at the outer cortex of the brain (Hoshi et al., 2003). By employing wearable light sources and detectors, photons are emitted over the scalp that pass by layers of tissue and detectors then collect the fraction of them that return. Because most tissue is transparent to light between 700–900 nm and because absorption is minimal within this optical window, fNIRS systems use multiple wavelengths within this near infrared range. fNIRS is able to measure optical density fluctuations caused by metabolic changes in neural activity through a mechanism called neurovascular coupling (Cauli, 2010) and can measure the hemodynamic response in a similar fashion to functional magnetic resonance imaging (fMRI). However, fNIRS sensors are wearable, portable, low-cost and possess a higher temporal resolution then fMRI. fNIRS allows subjects to freely move in natural postures while monitoring cortical regions such as the prefrontal cortex or motor cortex in a way that is compatible with research surrounding cognitive and motor tasks (Ayaz et al., 2022).

EDA and Nature Assessment

Evaluation of psychophysiological interaction using conductance change of the skin is a classic measure of stress and stimuli reception. Early research in the study of nature presentation is predominately based on stimuli-induced changes in conductance (Perrins et al., 2021; Ulrich et al., 1991). Electrodermal activity (EDA) is a non-invasive, portable sensor that measures the changes in electrical properties of the skin. The electrical property changes occur due to the electrolytes inside sweat when sweat secretion occurs by the eccrine sweat glands (Sharma et al., 2016). Eccrine sweat glands play a key role in regulating thermoregulation and are activated by sympathetic activity of the autonomic nervous system (ANS). ANS activity is responsible for fight-or-flight response, which reflects bodily arousal and is associated with emotional expressions and behaviors in humans (Sequeira et al., 2009). Hence, EDA is considered as an indicator of emotional arousal and processes (Caruelle et al., 2019; Shi et al., 2007) and has been utilized in diverse applications in ambulatory settings (Topoglu et al., 2020).

HRV and Nature Assessment

In addition, peripheral physiological activity will be assessed via wrist-based integrated optical heart-rate monitoring (OHRM). OHRM employs a similar principle to fNIRS but uses different wavelengths and focuses on capturing pulsatile variations in blood concentrations associated with the heartbeat. Increases in heart rate and changes in heart-rate variability (HRV) are often taken as peripheral measures of exertion and engagement (ChuDuc et al., 2013). Increased HRV is associated with increased cognitive flexibility and decreased autonomic activation, whereas decreased HRV is associated with increased autonomic activity and inhibition of the prefrontal cortex (Thayer et al., 2012). These measures can also be used to help control for changes in functional measures observed in fNIRS which may result from peripheral changes in addition to local cortical activation. The addition of HRV to prefrontal measures from fNIRS and autonomic activity via EDA will help tie together the relationships between cognitive burden and physiological responses to stress to which nature exposure is expected to mediate (Scott et al., 2021).

Protocol

In order to study the role of different environments on brain and body measures, participants will be asked to perform an environmental mindful presence task in several locations located throughout a local botanical garden (Longwood Gardens, Kennett Square, PA). Participants will freely walk between multiple environmental locations, each representing different forms of natural beauty and built-environment settings (Office, Italian Garden, Indoor Garden, Outdoor Meadow, Outdoor Forest) (Fig. 1). In each environment, the participant will be asked to freely observe the environment during which the participant's prefrontal cortex will be monitored using a mobile fNIRS system (fNIR Devices 1100). In addition, participant HRV and EDA responses will be monitored using a mobile actigraph (Empatica E4). Following the 5 minute exposure tasks, participants will be surveyed on their perceptual responses to the environment including the Perceived Restorative Scale (PRS) (Pasini et al., 2014) as well as scales related to the experience of the environment and aesthetic qualities.

Participants will be guided through the different environments according to a counter-balanced order. Data will be analyzed to determine the evoked and sustained responses to environmental immersion with attention paid to variations in resting HRV, intracortical prefrontal connectivity from fNIRS, and interactions between cortical responses and responses from peripheral measures of physiology (EDA, HRV). In addition, participant neural signals

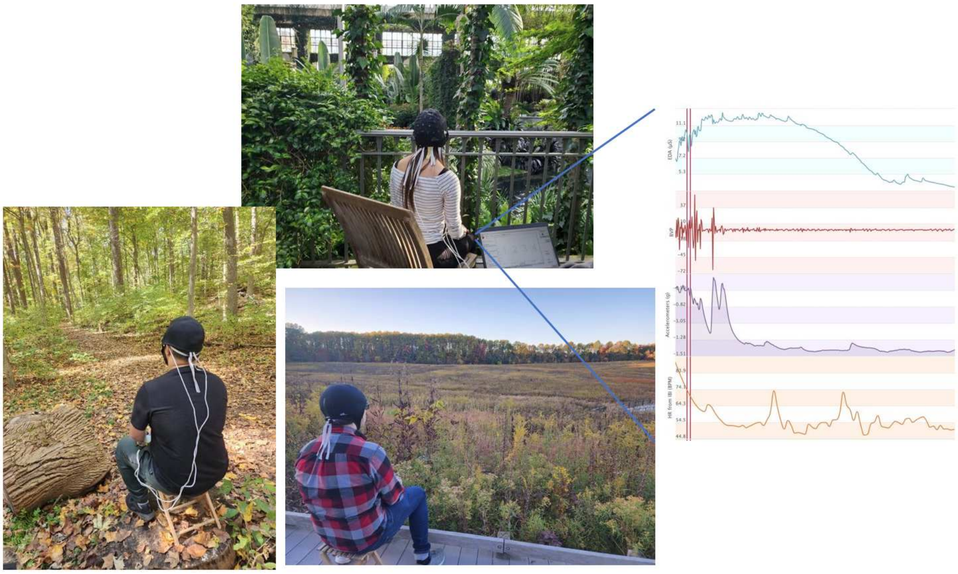

Figure 1: Nature Immersion Task under different environments and example peripheral physiological response.

will be compared using qualitative measures from survey to establish the relationship between presented environmental properties, received aesthetic qualities, and self-evaluation of the restorative properties via the SRS. Together, this study will offer a real-world insight on the neural and peripheral physiological effects of nature immersion as well as a window into the mechanisms behind its asserted restorative potential.

CONCLUSION

While the demanding nature of the modern world can be taxing for the individuals who inhabit it, exposure to natural environments has been suggested to induce a number of beneficial effects including reductions in stress as well as inducing improvements in mood. While competing theories exist as to the mechanisms by which these effects may operate, there is convergent agreement that the mind and body work in tandem. This protocol proposes one means of investigating the inter-relationship of psychological, neural, and peripheral responses to nature immersion with an eye towards understanding how these may be beneficial to society at large.

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